The art and science of plant breeding

John Sylvester Gladstones

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Whether he has known it or not, man has influenced the evolution of plants throughout his whole existence. In the pre-agricultural state he collected fruits and seeds from plants chosen for their useful or desirable qualities, and dispersed them wherever he went. With the neolithic revolution and the development of agriculture, some of these plants were taken into cultivation.

Consciously or unconsciously he selected types with higher yield, which germinated readily when planted, and whose seeds stayed in the head at maturity rather than being shed as in the wild grasses and legumes. Over thousands of years this "guided evolution" produced our crop plants as we know them; many so changed that their relationship to their primitive ancestors can hardly be recognized.

The classical civilizations of the Mediterranean and Middle East had a rich variety of field crop, forage and horticultural plants. From Roman and early Greek writers we know that plant varieties were then well recognized and to some extent systematized. The principle of "like begets like" was known, and growers deliberately selected seed from their best plants and even the best individual ears for sowing next season.

In this way cultivators throughout the early-agricultural world—in the Mediterranean, East Africa, the Middle East, South and East Asia, and Central and South America—over a long period evolved varieties of the main crop plants specially adapted to their own conditions.

In mountainous regions, where travel and commerce were limited, even adjacent valleys often evolved their individual ranges of crop varieties in isolation from each other. Such regions became centres of quite remarkable crop diversity, a fact first properly recognized by the great Russian botanist, N. I. Vavilov.

From 1915 until his death in Siberia about 1941, Vavilov undertook and organized collecting expeditions to nearly every part of the world. Together with their successors organized in many countries.
expeditions greatly enriched the modern plant breeding.

Today, began in the 18th and early 19th centuries. It developed greatly with the discovery of genetic principles from the late 19th century onwards. We now have many technological aids which add precision and help to define problems, needs and appropriate procedures. Advancing knowledge of plant physiology, in particular, is making possible a better understanding of how plants function, pointing the way to achieving higher yields and other desirable qualities.

Plant breeding has become a science. Yet it remains an art as well. Many of a plant breeder's crucial decisions—this plant rather than that—have to be made in advance of scientific proof, and must depend on his insight. Practical decisions have to be made in areas where scientific knowledge is often lacking. The test of success is practical results, in the form of new and better plants.

It is also true that plant breeding can function on many levels. Professionals are sometimes blinded by their science and overlook the obvious. The observant amateur and the breeder without scientific training can and still do make valuable contributions.

The basic principles of plant breeding are in fact not hard to grasp. Their application in practice, on the other hand, usually entails much work, time, patience, and insight into the plant and the needs for which the breeding is done.

To give an idea of how our present improved plants evolved or were bred, and how we go about trying to breed better ones, let us examine the major steps and methods in a plant improvement programme as they might apply in southern Australia.

Deciding priorities and objectives

Deciding priorities and objectives is easier to recommend than to implement. Ideally, it consists of a kind of cost/benefit analysis, in which these three components have to be balanced against each other. (1) What are the potential benefits? (2) How much will it cost? (3) What are the chances of success?

Existing major crops obviously enjoy priority because even a small gain (for instance, one bushel per acre in wheat) will mean an immense return over a whole industry. On the other hand, the more highly bred a crop already is, the harder it usually is to make further advances. Small advances that may be made will need extensive and perhaps costly testing to be established beyond reasonable doubt. By contrast, in a presently undeveloped crop such as lupins, major and obvious advances may be attainable quite simply.

Deciding objectives and priorities is complicated by the normal 10 to 15 years it takes to go through the full process of breeding, testing, bulking and release of a new variety, and perhaps several years after that before it reaches full commercial use. Given a commercial life of a variety of, say, 10 years, this means that planning must look to the needs of at least 10 to 25 years hence.

Who can see as far ahead as that? Day to day or even year to year market pressures give little guide. Decisions are probably best based on long-term market and technological trends, or on the need to meet technical problems of a permanent nature. The plant breeder must try to think of future needs because he cannot be sure that others will do it for him, and in any case it is he who ultimately must put the priorities into practice. Desirably he should be familiar with the whole agronomic and economic context into which his crop fits, as well as its genetics, physiology and ecology.

Future uncertainties point also to the wisdom of always maintaining a programme on a broad front, keeping open as many options as possible. This makes it possible to bring into prominence or to de-emphasize particular lines of breeding as needs progressively dictate. Unpromising lines can be put aside (seed stored under suitable conditions will stay viable for many years) and taken up later if required. Also, a broad and diverse programme will often contain plant material which can be extracted and developed quickly for particular purposes should a sudden need arise.

Evaluation and introduction of new varieties

It is pointless to undertake a long and necessarily expensive breeding programme if suitable or superior varieties already exist. In any case a thorough evaluation of the material already available is essential to plant breeding, as this is the raw material on which further progress must be based.

Introduction and evaluation of existing varieties are not necessarily the direct responsibility of the breeder. If not, he needs to remain in close and familiar contact with the work, seeking new genetic material to meet particular breeding aims and indicating what further kinds of genetic material are required.

Direct use of introduced varieties is of greatest importance with pasture plants, where normal breeding procedures pose special problems. Nearly all our improved pasture plants in W.A.—for instance the sub. clover strains and various perennial grasses—are either direct introductions or were collected from locally naturalized stands which originated as chance introductions.

Even among cereals we still find introductions which are directly useful. Beecher barley, from the U.S.A., was one such variety. In general, however, the more advanced the breeding of a crop for the local environment, the less likely it is that introduced varieties will compare favourably in all respects. They nevertheless remain essential for breeding, whether they be highly bred varieties useful as genetic sources of yield or quality characteristics, or primitive varieties which may be unique sources of genetic factors for, say, disease, drought or cold resistance.

There is a wider and perhaps more crucial reason why plant collecting and the preservation of plant varieties is necessary. Particularly with staple crops, the old primitive
Plant breeding has in a sense been varieties. Unlike many of the pasture plants, these varieties cannot survive outside cultivation. Once gone they are lost permanently, and with them the store of genetic diversity which enabled them to survive and produce under varied conditions in the past. Much of their diversity is still unexplored for current breeding. If preserved it could be invaluable in breeding for the unknown conditions of the future.

**Simple selection in plant breeding**

*Predominantly self-pollinating crops*

Assuming the resources of existing varieties and introductions to have been exhausted, the next step is to explore genetic variation that might exist within varieties. In predominantly self-pollinating crops such as wheat, oats and barley, this stems from three main sources. (1) The varieties may be mixtures. (2) New types may result from natural cross-pollination with other varieties. (3) New types may arise as rare natural mutations, or “sports”. Cross-pollination and natural mutation, followed by selection of superior variants, were the means by which our crop plants evolved over the thousands of years they have been in cultivation.

The first modern breeders of the 18th and early 19th centuries found the old cultivated varieties of most crops to be very mixed, and deliberately set out to select the best of the lines within them. In the case of predominantly self-pollinating crops, an individual plant selected in this way will usually breed true. The breeders of this time developed improved cereal varieties many of which persisted well into the 20th century, and feature in the ancestry of most modern varieties.

Simple selection of true-breeding lines features less in the breeding of self-pollinated crops than it used to, largely because there is less scope left for it. Nevertheless it still plays a valuable part where opportunity allows. Bungulla wheat, bred by Dr. A. J. Millington, was selected as an early-heading variant of Bencubbin. More recently Mr. Jack Reany selected “Gambee” wheat as an off-type in Gamenya. Uniwhite, Uniharvest and Unicrop lupins were based on naturally-occurring mutants selected in older lupin varieties.

In case anyone should feel inspired to emulate these examples, I should warn that simple though the method is, it has pitfalls for the inexperienced.

Firstly, the off-types or “strangers” in commercial crops mostly turn out to be admixtures of other existing varieties. Only when they differ in having some character well outside the normal range can we be reasonably sure of their novelty, and then even if they do breed true they are usually no more than use­less freaks.

Within the normal range of types, even the experienced eye can seldom discern the real novelty from the admixture, so detailed comparison of progenies is necessary. Then, having discarded existing varieties, the remainder have to be thoroughly tested for yield and other qualities. The prospect of a chance variant being superior to the best varieties already available becomes increasingly remote as the crop is more highly bred.

The second warning introduces the distinction, extremely important in all phases of plant breeding, between genotype and phenotype. A selection will breed true and different from its parent only to the extent that it is genetically different: that is, it carries different genetic factors (“genes”) which are passed on to its progeny.

Even in a genetically pure variety, not all plants will be identical in appearance. Some are larger or smaller, more or less advanced in flowering, or differing in various ways due to external factors such as nutrition or moisture, whether or not they happen to have been grazed or attacked by insects or diseases, and so on. These differences are of course not inherited. The external form and appearance of the plant is its phenotype. Its heritable genetic constitution is called its genotype.

Distinguishing between that part of the phenotype due to external causes and that due to its genotype is one of the most difficult arts of plant breeding, and depends on a complete familiarity with the crop and its responses to its environment. Even the most experienced breeder can distinguish only up to a point, and must rely on extensive testing in succeeding generations to identify superior lines. But by careful eye selection he can often improve the chances of isolating the best genotypes, particularly in less developed crops where differences may be more obvious and the scope for improvement greatest.

**Selection in open-pollinated crops**

Cross-pollinating crops, such as rye and maize, present a different set of problems. “Varieties” are not genetically uniform, as they now generally are in self-pollinating crops. Instead, they consist of freely interbreeding populations which may be reasonably uniform in appearance and most practical qualities, but which contain much genetic diversity.

The situation and methods of selection closely parallel those of animal breeding. As with animals, continued selection of small plant numbers and interbreeding only amongst them soon leads to inbreeding and loss of vigour and yield. Development of pure lines as with naturally self-pollinated (and therefore inbreeding) crops is usually out of the question.

The procedure adopted is “mass selection”, analogous to very heavy culling in animal breeding. Apparently superior individuals are selected, interbred and their progeny in turn grown out and allowed to interbreed amongst themselves. Further selection is carried out within this population, and so on through successive generations. The population size has to be kept large enough to prevent a serious degree of inbreeding. In time the desirable genetic factors become increasingly concentrated in the “elite” selected population. Rate of progress depends largely on how much of the phenotype variation among plants is due to genotype, and therefore heritable, and how much is due merely to environmental influences.

Mass selection was the main method of maize breeding up to the development of “hybrid” vari-
eties, and still remains important in that crop. It was the means by which Canadian breeders developed low erucic acid rape varieties. Locally, Dr C. M. Francis has recently developed a low-oestrogen red clover variety, “Redwest”, by repeated selection for low formononetin content. Mass selection remains a major method in breeding pasture grasses, nearly all of which are cross-pollinating.

One important point about mass selection is that to a degree it happens anyway. If a cross-breeding population is transferred to a different environment, certain elements of its variable population may be favoured and others not. The former will steadily gain as a proportion of the population and the latter diminish, until in time the character of the population may have changed substantially. In effect a new variety will have evolved. Ryegrass has undergone this kind of differentiation in Australia, giving rise to fairly distinct types such as the two Kangaroo Valley strains.

Selection in vegetatively propagated plants
For crops normally propagated vegetatively by cuttings, budding etc., for instance most of our fruit and vine varieties and ornamental shrubs, the situation is different again. All individuals of a fruit or grape variety are, in effect, parts of the original plant and remain genetically identical with it except insofar as they may undergo sporting: a fairly rare occurrence. Such a variety is known technically as a “clone”.

Grafting on to a rootstock of a different variety may alter the phenotype to some extent through the effects of nutrient uptake and growth hormones produced by the roots of the other variety. The vigour or dwarfing effects of some rootstock varieties are well known and exploited in apples and a number of other fruit trees. However, if the scion variety is again grown on its own roots it reverts to its original form, genetically unchanged.

Simple selection has accounted for the great majority of our vegetatively propagated varieties. It is based on two natural sources of variability.

The first source is seedlings. Nearly all vegetatively propagated plants are cross-pollinated insofar as they set seed at all, and not a few are self-sterile. That is, they will not set seed if fertilized by their own pollen, and sometimes will only set seed if pollinated by a widely unrelated variety. For this reason fruit varieties very seldom breed true from seed, and any seedlings produced will vary greatly amongst themselves despite coming from the one tree.

As with other crop plants, fruit varieties already represent the best of selections that have been made over hundreds or even thousands of years. The likelihood of chance recombinants of varieties being better than their parents is therefore very small.

Nevertheless, it can occur, especially in a new environment where the qualities for which the parents were selected may be to some extent irrelevant. A superior individual if detected can be propagated vegetatively by budding, etc., and its genetic identity as a new variety will be maintained indefinitely.

The second source of exploitable variation is mutation or sporting. This takes place at any stage of growth and may affect a whole branch, twig, or merely a leaf, fruit or part of a fruit descended from the cell in which the change took place. An observant orchardist or nurseryman will occasionally find a few mutations if he looks hard enough.

Changes due to mutation are normally simple and affect only one or two characteristics of the variety in which the mutation took place. The fruit may be a different colour, or ripen at a different time, but in other respects the variety will be essentially unchanged. Some such changes, taking place in an already adapted variety, may be commercially valuable and can be propagated indefinitely as is done with new seedling varieties.

One disadvantage with vegetatively propagated plants is that they can progressively accumulate viruses. Once a tree, vine or shrub is infected, the virus is transmitted in buds or cuttings taken from it. Infections can also be acquired from rootstocks on which it is budded or grafted. Over many years and propagations the accumulation of viruses can be such that the variety seriously loses vigour, despite efforts that may be made to select only the healthiest individuals from which to propagate. This is the commonest cause of “running out” of varieties.

Virus transmission does not commonly occur through seeds, however, so a new seedling variety usually starts off healthy. For the same reason, plant types normally propagated by seed are not subject to this kind of varietal degeneration, despite popular legend to the contrary.

I have dealt so far with plant improvement by simple selection among the range of variability naturally available. But this is often not enough. As the breeding of a crop proceeds there is a progressive decline in potential improvement through selection among what already exists, or arises through natural mutation and natural unguided crossing. Also, developing agricultural technology and the improved conditions of nutrition, weed and pest control, and sometimes irrigation under which crops are grown, increasingly calls for plant types far removed from those which evolved in traditional agriculture. The developing technology of handling and processing agricultural products calls for new qualities often not present among the old varieties.

For these reasons, and to meet the accelerating rate of change and growth of food needs, the old simple methods have for some time been no longer adequate on their own. They retain a place as basic steps and as main breeding methods for relatively unimproved crops and pastures. For our main agricultural crops, however, plant breeding since the beginning of the 20th century has turned to the more sophisticated methods of purposeful cross-breeding, artificial mutagenesis, and the creation of “hybrid” varieties. These and special problems of disease resistance breeding, breeding of pasture plants, and the testing and release of new varieties will be discussed in the next issue of the Journal of Agriculture.