EDUCATING THE NEXT GENERATION OF PLANT BREEDERS: THE NEED AND THE CHALLENGE

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SUMMARY

Plant breeding is critical to the future of productive agriculture, food security, and economic prosperity. Increasingly, many plant breeders are working in industry or governmental agencies that do not include education of the next generation of plant breeders as part of their mission. At the same time, many educational institutions lack resources and programs of sufficient size and scope to adequately educate students in applied plant breeding. Furthermore the technology of plant breeding is changing, so established plant breeders need ongoing opportunities to develop new skills to take advantage of the new tools such as genomics. Two key questions facing our science are: 1. Do we have the capacity to educate the numbers of plant breeders that will be needed in the future? and 2. Do we have the approaches to continue to educate modern plant breeders in these changing times? Globally, in many developed and developing countries, it appears that the answer to both questions is “no”. However, both questions are being asked by so many companies, non-governmental organizations, governmental agencies, and universities that we can reasonably predict that a consensus on the need and challenges for plant breeding education is forming with the expectation that the capacity and approaches will be developed. Just as the science of plant breeding is rapidly changing, so should be educational approaches to educating plant breeders. The diversity of approaches will include internships at major companies and international centres, the establishment of virtual and single location educational centres, systematic life-long learning, and a much more fluid workforce that moves globally and from private to public sector positions seamlessly. The education will necessarily be broad since it must prepare students for positions that simply do not occur today.

Key words: crop improvement, genomics, global capacity

THE MANY CAREERS OF PLANT BREEDERS

Plant breeding education must meet the needs of the science and industry that it supports. The science extends from genomics to measuring diversity and germplasm enhancement to quantitative genetic theory to prebreeding and finished line, clone, population, or hybrid plant improvement. Similarly, depending upon the crop, the industry may extend from genomics to finished product development, but often has the majority of its resources in finished product development. For the purpose of this paper we will concentrate on germplasm enhancement to prebreeding and finished line, population, and hybrid plant improvement with the full understanding that plant breeders must understand the continuum of this research to most effectively focus on their specific part of the continuum. Plant breeding on a global scale is

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being done by scientists in international centres (part of the Consultative Group on International

Agricultural Research (CGIAR) centres); national agricultural research services (NARS), universities, cooperatives and nongovernmental organizations, and private companies. The proportion of plant breeders in each of these groups will vary with the country and with the crop. Furthermore, while many previous publications have concentrated on Ph.D. level scientists who remain the lead scientist in most plant breeding endeavours, plant breeding involves researchers with many different levels of education each working with diverse educational and experiential knowledge. Hence, the emphasis of plant breeding education varies with organization, position within the organization, country, and crop.

The responsibilities for plant breeding have shifted in the last several decades. For example, maize (*Zea mays* L.) in most developed and many developing countries is largely bred in the private sector because the sale of hybrid seed is very profitable. Similarly soybeans (*Glycine max* (L.) Merr.) which is often grown in rotation with maize is largely bred by private companies because hybrid maize producers purchase seed annually and soybean seed is difficult to maintain on farm. However, wheat (*Triticum spp.*) in Europe is mostly bred by private companies, whereas in the United States it is bred by public (more common in the western U.S.) and private breeders (more common in the eastern U.S.). Australia is in the process of moving from large public wheat breeding programs to largely private breeding companies. In many developing countries, wheat, rice (*Oryza sativa* L.), and maize are largely developed by CGIAR centres and NARS. Fruit, vegetable, and turf crop breeding programs were relatively plentiful at U.S. land grant universities and European research institutes and universities in the middle of the 20^{th} century as most breeders developed germplasm for several crops (sometimes in excess of 10) for regional use. Today most of those positions have been redirected to more discipline-oriented research endeavours and the remaining breeders are focused on one or a few crops. Private companies now breed most of the seed-propagated vegetables, while breeding of clonally-propagated vegetables (e.g. potatoes [*Solanum tuberosum* L.] and sweet potatoes [*Ipomoea batatas* (L.) Lam.) and fruit continue to be bred by public breeding programs, although their numbers have dwindled too. With this in mind and using the U.S. as an example (where the authors have the most experience and knowledge), Morris et al. (2006) reported that in 2001 there were 424 plant breeders at universities, 161 plant breeders in the ARS-USDA (the national agricultural research effort), and 1545 plant breeders in industry. In 1994, the previous survey, the number of plant breeders at universities, ARS-USDA, and industry were 528, 177, and 1497, respectively. Hence the plant breeding activity in the public sector declined and that in industry increased. Furthermore, over 70% of all plant breeders were in the private sector. It is expected that most of these surveys concentrated on senior plant breeders/breeding program managers and may not have included the many technical support people that are providing crucial input to breeding programs. If the full cadre of plant breeders at all levels were considered, the proportion of researchers in plant breeding in industry would be even higher as industry tends to have well staffed teams. Reviewing these data:

1. Plant breeding education must continue to educate scientists capable of working in universities, CGIAR centres, NARS, nongovernmental organizations, and private industry.
2. While the number of plant breeders working in the private sector is increasing, the number of plant breeders working the public sector and specifically in plant breeding education is decreasing. The capacity to educate the next generation of plant breeders will likely decline further if current trends continue.

Do We Have the Capacity To Educate the Next Generation?

There are two critical aspects of plant breeding education capacity. The first aspect is whether we attract and educate enough students to meet future needs? The second aspect is whether those programs that educate plant breeders have sufficient resources, size, scope, and equipment, etc. to educate students for working in the different career paths described above? Again using the U.S. as an example, Guner and Wehner (2003) surveyed 71 U.S. Land Grant Universities and found that 409 Ph.D. and 361 M.S. degrees were awarded in plant breeding between 1995 and 2000. The total number of 770 students trained (later revised to 783 as additional information became available; see http://cuke.hort.ncsu.edu/gpb/publications/gradtraining.html) is an overestimate as some students receiving an M.S. degree continued their education and joined Ph.D. programs. Of these students, 47% were domestic (U.S.) students and 53% were international (non-U.S.) students. In a recent informal assessment of the number of plant breeders that need to be educated (http://cuke.hort.ncsu.edu/gpb/publications/gradtraining.html) using estimated needs from Bliss (2006), it was concluded that we are currently educating enough students to meet the current needs, but with two major concerns. The first is the informal estimate included 10% of the students beginning a program would not complete the program or after completing the program would leave the country (e.g. return home or go to another country). The second concern is that Bliss (2006) estimated a 2 to 5% replacement rate is needed which translates to 45 to 110 plant breeders need to be trained each year to maintain current numbers. Commercial companies are very concerned that they will have too few plant breeders to meet their needs. Anecdotally, recent job announcements for plant breeders are extensive, and numerous additional positions are advertised only through informal channels (e.g. by "word of mouth"). In addition, some companies have described holding back promotions of plant breeders to management positions because there is no one to replace the breeder . These anecdotes suggest that, in fact, more plant breeders need to be educated to meet current needs, and that of those being trained, their education needs to improve to enhance their skills. Basically, you can enlarge the pool of skilled plant breeders by having more educated or by having more of those educated being skilled in the requisite fields currently needed.

As for the many positions in plant breeding that are held by those with a B.S. or B.A. degree, we currently do not have an estimate of how many graduates are needed. Anecdotally, we believe the demand is again larger than the numbers being educated.

The second, equally important concern related to plant breeding education capacity is whether those programs involved in education have the resources, size, scope, and equipment, etc. to educate students for working in the different plant breeding career paths. Guner and Wehner (2003) surveyed 71 universities, so the number of universities is sufficient to educate the next generation of plant breeders, however, Guner and Wehner (2003) did not assess the quality or scope of education at the surveyed universities.

As plant breeding requires continuous funding to be successful in creating new products and new knowledge (Goodman, 2002, Baenziger et al., 2006), so must be the funding support for plant breeding education be continuous. Guner and Wehner (2003) noted that the many of the surveyed plant breeding programs were becoming smaller in size, or switching to more basic research (effectively becoming smaller in their field, forest, or greenhouse research) or other crops where resources were easier to obtain. Remembering that at least 70% of U.S. plant breeders work in industry which often has large breeding programs, being educated in a smaller program means that often the student will not be exposed to state of the art equipment and research infrastructure (data acquisition and analyses, etc) that they will be expected to use in their careers. The consolidation of educational programs due to poorer funding, often into smaller use crops where there is little private effort and away from the highly privatized crops, will certainly lead to more breeders changing crops from their graduate studies to their professional careers and more learning on the job. Morris et al. (2006) described that 55% of all U.S. plant breeding resources were in eight crops, maize, soybean, cotton (*Gossypium spp*.), wheat, tomato (*Solanum lycopersicum* L.), alfalfa (*Medicago sativa* L.), sorghum (*Sorghum spp*.), and potato. These changes may be a benefit in that fresh ideas brought from one crop may be applied with positive results to a different crop. However as many of the most heavily researched crops have very well-established breeding approaches, there may be a concern that a plant breeder with one crop experience may not be fully efficient for some time to effectively apply their skills to a different crop. For example, it may take years for a wheat breeder experienced with inbred line cultivar development to learn the germplasm, and understand heterosis and heterotic gene pools, combining ability, hybrid development, and the use of tester lines. Similarly, those trained to create new hybrids, might not fully understand how best to inbreed and which traits to select for in creating new inbred lines in a new crop.

This scenario makes a strong case to support the need for excellent graduate education. Beyond the requirement for strong and continuously supported plant breeding programs to both create the new knowledge needed for scientific advances and to educate new graduates, it is equally important that the educational community has the capacity to educate the next generation of plant breeders with life long learning tools so that they can take advantage of the scientific revolutions that are expected to occur during their careers. Currently many plant breeders are learning how to use the information from the "omics" revolutions. In the past, there were revolutions in mechanization, global markets, and information technology which required considerable additional education during their career.

The question of life-long learning is important because it may provide a glimpse of how plant breeding education is evolving. This is evidenced by the increasingly important role of education in and by the private sector aimed at the company workforce (again remembering that at least 70% of the U.S. trained plant breeders will find positions in the private sector). Regarding scientific education and using cereal breeders as an example, Morris et al. (2006) reported that there were 124 (13%) university, 61 (6%) ARS-USDA, and 766 private industry (81%) plant breeders. Again, these numbers represent the senior plant breeders/project leaders and most likely underestimate the proportion of researchers in plant breeding in the private sector. Clearly the accumulated wisdom of the private sector provides a large reservoir of experiential learning though it must be remembered that some of the experiential learning will be considered proprietary and sequestered within individual companies. It is this information that will be used to educate the company's breeders. For comparison, large plant breeding companies will have more plant breeders than most if not all major universities and possibly more than the total public sector research combined. Since the private sector has larger breeding programs, usually with better technology platforms, the potentials for data mining, and understanding the mechanisms of successful plant breeding are huge and will largely be available only to those working within the company.

As described by Bliss (2006), there are scientific skills that are needed, but there are also many personal skills that are required for success in the private sector. It may be that the public sector will provide the initial education for plant breeders, while the private sector will provide the life long education, at least in part. Similarly the private sector will most likely provide opportunities for additional education for those areas that are valued more highly in the private sector than in the public sector.

Encouraging Students to Enter Plant Breeding

If we have both the need and the capacity to educate the next generation of plant breeders, will we have enough students with the requisite qualities entering the field? This question is an old one (Baenziger 1990). Every scientific field has its peaks and valleys for student recruitment, and plant breeding has seen both. As fields related to plant breeding develop, they attract plant breeding students and lessen the pool of applicants in the field of plant breeding. These new technologies often are portrayed as something more precise and efficient, and sometimes as replacements for plant breeding (e.g. Simmons, 1993; Goodman, 2002). However the following quote from Harlan (1957) describing the effect of genetics on plant breeding is worth remembering:

"The field of plant breeding actually suffered in a way from the greater knowledge we have acquired. Mendel's work was quickly accepted as an enormous advantage in plant science. It was a definite, tangible thing that seemed to take plant breeding from the arts and place it as a science overnight. It captured the imagination of all workers, and genetics at once became a field offering prestige that both soothed and satisfied. A genetic paper gave new dignity to the author. We boys began to get our hair cut and our shoes shined. The effect on plant breeding was calamitous. Good varieties were still produced, but explorations in the field of practical plant breeding were wholly neglected. A few of us eventually realized that there would come a day when the world would recognize the difference between a good geneticist and a poor one, so we went back to thinking about plant breeding. We have undoubtedly lost the resources of many good minds from this field for a time, but they will be back."

However, we believe that many previous authors on this topic have erred by not recognizing the full breadth and interdependence of plant breeding activities. As such, we recognize that plant breeders as defined in this paper enter the field by many different paths. For example, many come from agriculture or biology-based high school and undergraduate programs that then lead to specializations at the graduate level. However, others come from more diverse educational backgrounds and only discover plant breeding after they do an internship or some form of national or international service (in the U.S. this might be the Peace Corps); or they take a position with a breeding or related program and discover they really like what they do, and decide this is a career and more than a job. Similarly within an organization, individuals hired to have one position may be asked to take on more responsibility and will need additional skills in plant breeding. With the number of individuals exposed to plant breeding at different times during their lives, there is a large pool of individuals to fill the potential breeding positions. This raises several questions: Are we missing opportunities to attract people to our field? Are we creating the right environment to attract the needed students? With potential plant breeders coming to the field from all levels and from different entry points, the logical question is "Do we have the educational tools to meet these diverse needs?"

Evolving Approaches to Educating the Next Generation of Plant Breeders

Historically plant breeders were educated at universities where many crops were once being bred by large numbers of plant breeders, by today's standards (Guner and Wehner, 2003; Morris et al., 2006). Even as plant breeding had greater private sector involvement, educating the next generation remained largely the role of universities that use a degree granting model of education. What is not fully recognized by some is the diversity of approaches that universities have used to educate advanced degree students. Most American and Canadian universities and those modelled on their educational system include a large number of courses in their graduate programs. However, European universities and those modelled on their educational system often have few, if any, courses after the diploma or honours programs, but rely upon individual readings, independent studies, and mentoring. As the authors are most familiar with the American system, we will discuss the evolution of approaches in the course-based instruction for plant breeders. The system of mentoring clearly has been successful, but can be discussed by those more knowledgeable in its approaches.

To accommodate the life long learning needs of largely site bound plant breeders, education models became more flexible and short courses such as the Illinois Corn Breeders School (http://imbgl.cropsci.illinois.edu/school/table_of_contents.html) or the Summer Institute in Statistical Genetics (http://sisg.biostat.washington.edu/index.php?menu=main&location=seattle) have been offered. However, many of these schools provide short, intense, focused learning experiences as would be appropriate for students who already have a broad knowledge base and can only afford to take short periods of time away from their position. They do not provide extensive learning experiences that can lead to college degrees, nor are they amenable to "learning at your own rate" with a consistent mentor over time. With the revolutions in information technology, distance education has become a compelling way to educate plant breeders because it meets the following needs:

1. Distance education is not site bound as bricks and mortar campuses are. Many plant breeding stations are not located near major plant breeding universities, but have excellent internet access providing local delivery of the information.
2. It can be offered for college credit or for non-credit to fit the student needs and interests. Many students are interested only in the information and not in the college credit.
3. Most distance education courses are offered asynchronously so that students can take them as their schedule allows. This asynchronous delivery is particularly useful for courses that have a global reach (crossing time zones where students in the same class may be in Japan, India, Turkey, Ireland and the U.S.)
4. It allows classes where there are relatively few students in any one campus to be taught. Most universities have a minimum enrolment in order for a class to be taught. However, by combining resident and distance students the minimum enrolment requirement can be more easily met.
5. Distance education provides a healthy competition in the marketplace of ideas. For example, students may learn that one instructor may teach an outstanding self-pollinated crop breeding course, but another instructor may teach a better cross pollinated crop breeding class. For the student, it would be an easy decision to take the courses from the better instructor regardless of where they (the student or the instructors) are physically

housed. In mentor-based education systems, accessing a few courses may be very useful to help student have the knowledge to better understand their readings.

6. Finally, while most universities remain bricks and mortar campuses and deliver their courses only for resident students or possibly from their campus to a resident or distance community of learners, there is a huge potential for intercampus courses where the students are global as are the instructors. When properly structured, the instruction could be from outstanding educators any and everywhere in the world, as would be the students. This may also be an opportunity to involve the wisdom of the commercial plant breeders who cannot commit to lengthy teaching roles, but could provide great insights from their experiences.

All universities recognize they have their strengths and weaknesses and most recognize that for a comprehensive curriculum they cannot do it all. Hence intercampus curricula are expected to become more important in the future. For those worried about where the degree will be granted in the evolving virtual campus, it could be from that institution where 51% of the courses were taken or where the research, if required, was completed.

Working toward a Common Goal

The goal of this paper has been to identify the common concerns associated with plant breeding and to provide a plan for educating the next generation of plant breeders (Table 1). Given the continued need for plant breeders at all levels of education with most positions being in the private sector, public breeding programs that historically have educated many of the next generation of plant breeders are becoming smaller and rarer, the wealth of private sector information is often sequestered within the company due to being proprietary or sharing this wisdom is not an business objective, life long learning is increasingly important, and we have the information technology to deliver courses anywhere the worldwide web exists. With this in mind, there are synergisms about the global plant breeding community that should be explored.

First we must continue to attract people to our science. With the number of young people exposed to plant breeding through detasseling crews, working in breeding projects, etc. we need to make sure they have a favourable view of our science. Similarly, we need to have plant breeding examples woven into high school, vocational, undergraduate, and graduate education in non-agricultural areas. Furthermore, we need to make sure any person showing an interest in plant breeding can be properly mentored whether that means identifying meaningful part time jobs for them while in high school or college, finding internships or research experiences to expand their horizons to the breadth of plant breeding, and working with industry to offer scholarships to students who they have identified as excellent performers. In the U.S., many plant breeding companies have summer interns and invariably any intern who worked two summers with the same company has already been recognized for their potential. The second summer of work is critical because they are only offered a return experience if they are good performers. Universities may also need to develop flexible strategies to allow students who came late to plant breeding from other fields or who performed poorly in their initial education to make up courses and continue their education with a new found enthusiasm. Often in these cases they became enthused while working in a plant breeding company and now wish they had done better in their college education perhaps in a different major.

Since plant breeding is done in complex teams of people having various skills, we will need to broaden our plant breeding education to reach all levels of students from vocational, to undergraduate, to graduate education and beyond to life long learning. As part of this education, there should be exposure to both global and team thinking. Professional degrees in plant breeding might also include exposure to project management, budgeting, and human resource education.

As companies become the main provider of improved plant products and the public sector become smaller, there will need to be more collaboration between the public and private sector to provide the students with necessary breadth and scope of modern plant breeding. Internships are common for undergraduates, but internships in companies are currently rarer for graduate students. We expect this to change as companies become more competitive in searching for talented new plant breeders, want to have a better way of learning about the skills of the future employee, and also want to allow a future employee to learn how private sector breeding is done so they can be sure this is the right career for them. Having experience in the private sector will be valuable for those who decide that is the right career for them, and equally important for those who will work in the public sector to educate those who will become private sector plant breeders. Plant breeders who have worked in many areas of plant breeding will be better educators. Similarly, mechanisms need to be developed to allow highly skilled plant breeders in the university, NARS, international centres, and private sector to move among these organizations to the enrichment of all. Obviously plant breeding is a long-term endeavour (Goodman, 2002) and it is difficult to make many changes without affecting productivity. However, it is difficult to believe that most workers know which career path they want when they complete there initial training and begin their life-long learning.

Table 1. A plan for educating future plant breeders: Requirements for future success and the role of education in meeting those requirements

Attribute required	Educational role
Adequate numbers of capable individuals to sustain private and public sector plant breeding programs	1- Raise the profile of plant breeding in society (jointly with plant breeders in all sectors) 2- Introduce elements of plant breeding into high school, vocational, undergraduate, and graduate education – outside of formal plant breeding education
Capacity to provide adequate plant breeding education	1- Vocational, undergraduate, and graduate curriculum in plant breeding 2- Active, large-scale university plant breeding projects to mentor student education 3- Internships with industry, government, and NGO plant breeders for students at all levels 4- Continuing education and distance education programs to provide life-long learning opportunities for practicing

	plant breeders around the world 5- Expansive dialog among university plant breeders and with industry, government, and NGO plant breeders, with the crop production community (public and private), and with consumers
Personal and management skills	1- Formal targeted training and exposure to global and team thinking 2- Partnerships with private, government and NGO breeders to provide students with their management experiences

One question that arises in these new models of public-private collaboration, especially in countries where crop breeding has been privatized, is whether public sector breeding programs need a significant field, forest or greenhouse (depending on the crop) program to support their research and educational goals. In some countries the decision has already been made and it is believed that only the private sector needs effective field, forest or greenhouse programs. This conclusion has led to virtually all field, forest or greenhouse breeding research being done in cooperation with private companies. The drawbacks of this approach are that only research of mutual interest will be supported by the company due to the cost of doing field, forest or greenhouse research, and that some lessons learned will not be shared with other breeders as they are treated as proprietary. Hence there is less freedom to pursue ideas in the public sector. The other drawback is that where trials have a commercial and a research component, it is possible that the commercial component will be dominant to the research component. For example in a mapping population where the two goals are to release new cultivar and map yield QTLs, the trial may not be sprayed with a fungicide to remove the confounding affect of disease because disease resistance is an important commercial goal. We recommend that plant breeding education maintain field, forest or greenhouse breeding programs, as appropriate, despite their expense and even though their products may never be commercial, because creative research in plant breeding requires the ability to pursue ideas in the most appropriate research setting (e.g.. field, forest or greenhouse).

Commitment to the Next Generation:

One final comment on educating the next generation of plant breeders would be what is the appropriate role and commitment of this generation of plant breeders to the next generation. In most annual crops, it takes between 7 and 12 years to release a cultivar (Baenziger et al., 2006), so it is a long-term, continuous effort. Every breeder understands that one of their goals is to leave the next breeder with a better program. As such, it is common for breeders to make as many crosses the year they retire as they did during their peak. Although they will not make the selections from this material or release them as cultivars, they want the next person to have germplasm to work with. When it comes to education, there must be the same level of commitment. Those who have benefited from being a plant breeder and educator, should continue to teach, write, give seminars, deliver guest lectures, and mentor the next generation to ensure the science of plant breeding is of better quality and more robust than when they first entered the field.

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