Plant breeding, often described as the art and science of altering the genetic makeup of plants for the benefit of human-kind, has had a major role in increasing crop productivity and improving quality. Plant breeders are expected to play a central role in preserving and enhancing the quantity and quality of the world’s food, feed, fiber, and energy supplies, while society is challenged to meet the needs of an expanding human population estimated to reach nine billion by the year 2050 (FAO, 2009). If envisioned improvements in crop productivity, stress tolerance, resource utilization, and product quality are to be realized, plant breeders skilled in modern science and knowledgeable about local production practices must be prepared for these ongoing challenges and opportunities.

Currently, too few breeders are being prepared to meet global demands of expanding private sectors and continuing needs of public sector research centers, universities, and nongovernmental organizations in both developed and developing countries (Morris et al., 2006; Traxler et al., 2005; Frey, 1996). Comparison of information from Frey (1996) to data in the paper by Traxler et al. (2005) raises concerns about declining capacity in U.S. universities and state agricultural experiment stations for preparing plant breeding education programs should incorporate new scientific knowledge and emerging technologies while retaining core knowledge and essential practices and skills.
plant breeders to meet not only internal public and private sector demands but also diverse global needs. This declining capacity is underscored by reduction in plant breeding faculty in U.S. universities (Gepts and Hancock, 2006) and in other developed countries (Bliss, 2007).

Many developing countries are in dire need of more breeders and better support for current ones. The number of people devoted to plant breeding is being rapidly diminished as experienced breeders retire or are drawn to better opportunities elsewhere (Guimaraes et al., 2006; Bliss, 2007). Additionally, developing countries face declining funding and dispersal of educational resources, all of which contribute to decreased breeding research and development on crops which impact hunger and poverty (Morris et al., 2006). The widespread lack of plant breeding capacity and unmet demands for improved cultivars (Guimaraes et al., 2006) reinforce the need for universities and other educational institutions to consider how best to provide education and experiential training for breeders intending to work in and/or develop cultivars for developing areas. Fortunately, some countries, including Brazil, the Philippines, Japan, Korea, China, and India, have increased educational capacity for plant breeding, and some universities elsewhere are striving to improve institutional capabilities (Bliss, 2007; Morris et al., 2006).

Modern plant breeding is more than just the application of classical genetic principles through visual selection and biometrical procedures. Components of genetics, genomics, statistics, molecular and cellular biology, plant physiology, and agronomy along with highly specialized technology are being used to develop improved varieties (Gepts and Hancock, 2006; Lee and Dudley, 2006). Furthermore, Tester and Langridge (2010) point out that it will be difficult to utilize evolving breeding technologies without people well trained to use current technology in field settings. The multidisciplinary nature of plant breeding and likelihood that a breeder will work at different breeding activities during his/her professional career underscores the need for breadth and depth in education (Lee and Dudley, 2006; Morris et al., 2006). Ideally, crop improvement programs engage multidisciplinary teams, involve field components, and focus on breeding as a central role (Baenziger, 2006). In addition, it may be that preparation and skills for breeders working in developing countries differ for a multitude of reasons from those engaged elsewhere (Baenziger, 2006). The need for a broad curriculum base and the fact that regional specifics are likely to change throughout an individual’s career present a compelling challenge for universities and training centers striving to craft plant breeding curricula.

Preparation for work in either the public or private sector usually differs only by a matter of degree rather than with sharp distinctions, but some differences do exist. In the book Revolutionizing Higher Education in Agriculture, authors Kunsel, Maw, and Skaggs posit that “the most important step in implementing the needed fundamental changes in higher education in agriculture and natural resources is to gain a perceptive understanding of the society and the industries for which our graduates must be readied” (Kunkel et al., 1996, p. 156). Similarly Bliss (2006, p. 45) states, “education and training of future breeders should be relevant to the employment prevalent in the profession as well as prepare them to meet changes that will most certainly occur throughout their career. So the goal should be to provide the best preparation options for a diverse group of students enrolled in a degree program.” An idea of similarities and differences that characterize work in different sectors will help faculty design programs and concordant courses, dissertation topics, seminars, practicum, internships, etc. To successfully meet those aspirations will require not only scientific acumen of faculty and administrators, but also opinions, insight, and wisdom from practicing breeders along with collaboration of employers and other decision makers.

The need to strengthen public plant breeding programs for research and cultivar development and to produce more plant breeders has been emphasized in several position papers (e.g., Stalker and Knauft, 2008; Miller et al., 2010). Education and preparation of plant breeders and other well-trained professionals is a primary goal of the business plan for the Global Initiative for Plant Breeding Capacity Building (2009). Universities and training centers can meet these needs by critically evaluating educational offerings and revising curricula to ensure that dynamic programs attract the best and brightest students. Successful graduate programs and supplemental professional improvement courses should integrate new technologies and methods that are revolutionizing the life sciences as well as expand breadth and depth in basic and applied subject matter. Furthermore, students need practical experience in breeding and other supporting activities common to real-world programs for them to be well prepared for success in the workplace (Gepts and Hancock, 2006).

Several papers have provided information about subject matter and types of training likely to be needed (Duvick, 1998; Coors, 2006; Lee and Dudley, 2006; Bliss, 2007), but we are not aware of systematic studies aimed at understanding what type of preparation professional plant breeders may need in different job settings. Considering the strong demand for breeders and knowledgeable professionals to fill many jobs that use plant breeding, this is an opportune time to research and assess what is needed for a contemporary plant breeding education to prepare students for careers in crop improvement. The need for this study became apparent from the discussions and findings of the symposium entitled “Plant Breeding & the Public Sector: Who Will Train Plant Breeders?” held at Michigan State University, 9–11 Mar. 2005 (Hancock, 2006).

To collect information about knowledge, experiences, and skills to be mastered during plant breeder education, we conducted a Delphi study to obtain opinions from
diverse expert stakeholders who have first-hand experience in plant breeding and related matters. This paper provides analysis and consideration of the responses from public and private responders from developed and developing countries. It is intended to guide educators in integrating courses and experiences that will provide knowledge and skills beneficial for future breeders in multiple settings.

MATERIALS AND METHODS

Delphi Method

Utilizing the Delphi method described in Total Design Method (Dillman, 2000), this study sought to identify priorities for curriculum planning of graduate-level education in the field of plant breeding. The Delphi method is commonly used to garner expert opinion and experience regarding a particular issue, allowing for input from geographically dispersed individuals with no opportunity for face-to-face exchange. The study's methodology builds consensus among such experts using a Web-based anonymous survey response technique, avoiding issues of dominance of one or two voices (Rice, 2009).

Participant Selection and Demographics

Groups including the Plant Breeding Coordinating Committee, National Council of Commercial Plant Breeders, and Global Partnership Initiative for Plant Breeding Capacity Building along with academic and industry experts submitted suggestions for individual participants. Study participants (stakeholders) were purposely selected based on their expertise in plant breeding. To encourage an expansive range of ideas and to differentiate curriculum needs, the study solicited replies from three groups of stakeholders in plant breeding: (i) professionals employed in the public sector in developed countries; (ii) professionals employed in the private sector in developed countries; and (iii) professionals employed in developing countries. Stakeholders who identified their main area of work in developed countries; and (iii) professionals employed in developing countries. Stakeholders who identified their main area of work in or associated with developing countries or emerging markets will be designated by “DEV,” those working in or with the public sector of developed countries will be designated “PUB,” and those in or with developed countries in the private sector, “PRI.”

Utilizing this list of sources and recommendations for participants based on the three stakeholder groups, 107 PRI individuals, 110 PUB, and 106 identified as DEV were emailed personalized invitation letters asking for their participation in this Web-based Delphi study. The first invitation was sent by email in fall 2009 to stakeholders as defined above; 172 respondents participated in Round I, representing 31 countries, 35 companies, and 50 universities, of whom 29 were female and 142 male. From this initial pool 67% (115) participated in Round II, and 88% (101) participated from Round II to Round III. This spectrum of respondents met our goal of broad representation.

Data Collection

In Round I of this Delphi study, each participant was asked to respond in short answer form with up to 10 unique responses to the following questions:

1. What knowledge (topics or subject matter) is essential to have obtained at the completion of a graduate degree in plant breeding?
2. What experiences should a student have while pursuing a graduate-level plant breeding degree that will contribute to his/her future success?
3. What skills and competencies should a student obtain by the completion of a plant breeding graduate program?

In addition to the survey questions, participants were asked to provide demographic data including place of employment, age, gender, highest degree earned, number of years in the field, and the location (developed or developing country) that is the focus of their work.

The research team (authors) used the constant comparative method to distill and cluster participants’ Round I suggestions into logical categories (Strauss, 1987). For example, “Intellectual property rights understanding” and “Breeding–IP management” were collapsed with others into “Intellectual property rights as it relates to plant materials, plant improvement technologies, etc.” As suggested by Smagorinsky (2008) to address issues of validity, at least two researchers reviewed all data, representing both the field of plant breeding and that of curriculum development.

In Round II, participants were presented with a list of all unique suggestions made by their peer group and were asked to score the importance of each on a Likert-type scale, with 1 being Unimportant, 2 being Somewhat important, 3 being Neither important nor somewhat important, 4 being Important, and 5 being Very important. Based on the results of the second round, the research panel elected to eliminate statements with a mean rating of <3.75 in an effort to elicit consensus on items rated as Important in Round II. Statements with a standard deviation above 1.0 were eliminated unless the distribution of scores for that given item held 51% or greater within the 4 and/or 5, Important and/or Very Important values.

In Round III, participants were asked if they still agreed with their initial ratings, and if not, to adjust their ratings. They were provided with the group mean ratings and their previous personal ratings from the second round. Data were collected and analyzed in Microsoft Excel (Microsoft Office 2007, Redmond, WA). Results from Round III, the final round, are represented as mean scores with standard deviations (SD). Mean scores and SD were calculated for each individual statement.

RESULTS

Analyses of responses to the three survey questions show that PUB, PRI, and DEV stakeholders generally agree about knowledge, experience, and skills required in graduate programs. However, when comparisons were made regarding what was very important (rated 4.5–5.0) to each stakeholder group, there were several differences. Disparities were also observed in broad categories among the three groups.

Knowledge

From the 145 stakeholder suggestions rated 3.75 or above, 18 knowledge categories were formed. Ten categories included suggestions from all three stakeholder groups (Fig. 1). Among the 10 shared categories, 50 plant breeding, 16 statistics, and 16 genetics suggestions encompassed the
Figure 1. Knowledge categories (small white ellipses) identified by developing (DEV), private (PRI), and public (PUB) sector stakeholders surveyed in the Delphi-based study at Univ. of California Davis, 2009. Large ellipses include unique categories: DEV (blue), PRI (yellow), and PUB (pink); two-sector categories: DEV/PRI (green), DEV/PUB (purple), and PRI/PUB (orange); and categories shared by all three sectors are in red. Numbers in the small ellipses indicate the number of suggestions from the DEV (left), PRI (center), and PUB (right) sectors in each category.

Figure 2. Mean scores of knowledge category suggestions rated very important (black line at mean rating 4.5) to developing (DEV), private (PRI), and public (PUB) sectors surveyed in the Delphi-based study at Univ. of California Davis, 2009.
majority of the knowledge responses. Twenty-two knowledge suggestions were rated very important, 4.5 or above, by at least one stakeholder group (Fig. 2). Two categories, biotech and business, were shared by DEV and PRI. Three categories, scientific communication, plant diversity and evolution, and funding were shared by DEV and PUB. One category, plant reproductive biology, was shared by PRI and PUB; and two categories, genomics and management, were unique to the PUB sector. Stakeholder suggestions within categories identified by either one or two sectors are listed in Table 1. A list of all knowledge suggestions tendered can be found in Supplementary Table S1.

**Experience**

From the 109 stakeholder suggestions, rated 3.75 or above, 16 experience categories were formed. Nine categories included suggestions from all three stakeholder groups (Fig. 3). Among the nine shared categories, 22 communication, 17 breeding, 17 practical experience, and 13 data suggestions encompassed the majority of the experience responses. Fourteen experience suggestions were rated very important, 4.5 or above, by at least one stakeholder group (Fig. 4). Two categories, computers and experimental design, were shared for DEV and PRI. Two categories, germplasm and field visit, were shared for DEV and PUB. One category, management, was unique to PRI, and two categories, extension and funding, were unique to the PUB sector. Stakeholder suggestions within categories identified by either one or two sectors are listed in Table 2. A list of all knowledge suggestions tendered can be found in Supplementary Table S2.

**Skills**

From the 228 stakeholder suggestions rated 3.75 or above, 21 skill categories were formed. Thirteen categories included suggestions from all three stakeholder groups (Fig. 5). Among the 13 shared categories, 39 intrapersonal, 38 practical breeding, 22 experimental design, 21 scientific communication, 15 analytical aptitude, 13 field work, 11 statistics, and 10 data management suggestions encompassed the majority of the skill responses. Thirty skill suggestions were rated very important, 4.5 or above, by at least one stakeholder group (Fig. 6). Two categories, leadership/teamwork and interdisciplinary, were shared for DEV and PUB. Three categories, funding, pests/disease, and regulatory, were unique to DEV; and three categories, genomics, lab techniques, and genetics, were unique to the PUB sector. Stakeholder suggestions within categories identified by either one or two sectors are listed in Table 3. A list of all knowledge suggestions tendered can be found in Supplementary Table S3.

**DISCUSSION**

Grouping opinions and suggestions from expert stakeholders with diverse backgrounds and experience into consensus categories provides a clear idea about which knowledge, experience, and skills are important core components of plant breeding graduate curricula. By consolidating this information into PUB, PRI, and DEV groups, important categories of knowledge, experience, and skills that are more relevant for future breeders working in the public or private sector of industrialized or developing countries were identified.

Many public sector plant breeders will be responsible for not only conducting research and developing cultivars but also educating and mentoring students aspiring to become plant breeders. It is critical that faculty know what is needed for success in employment areas outside academia. Most breeding positions in industrialized countries are in the private sector, so opinions from experts in the PRI sector are very important to meet needs and assure relevance. Also, it is important for faculty to know the knowledge and skills that are important in both industrialized and developing regions because students may likely come from either and return to positions in either.

If plant breeding is described as an art and science, it seems appropriate that a well-prepared breeder would be one skilled in both the art and science of breeding. Skills should be acquired

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**Table 1. Mean scores of suggestions contained within knowledge categories that were identified as important by either one or two stakeholder groups from developing (DEV), private (PRI), and public (PUB) sectors surveyed in the Delphi-based study at Univ. of California Davis, 2009.**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Knowledge suggestions</th>
<th>Knowledge categories</th>
<th>R3 mean†</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUB</td>
<td>Genomics tools for plant breeding</td>
<td>Genomics</td>
<td>4.4</td>
</tr>
<tr>
<td>PUB</td>
<td>Project management</td>
<td>Management</td>
<td>3.8</td>
</tr>
<tr>
<td>PUB</td>
<td>Scientific and technical writing</td>
<td>Communication</td>
<td>4.2</td>
</tr>
<tr>
<td>DEV</td>
<td>Scientific and technical writing</td>
<td>Funding</td>
<td>3.8</td>
</tr>
<tr>
<td>DEV</td>
<td>Writing a grant</td>
<td>Management</td>
<td>3.9</td>
</tr>
<tr>
<td>PUB</td>
<td>Plant genetic resources (e.g., collection</td>
<td>Plant diversity</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>management, maintenance, management,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>characterization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PUB</td>
<td>Plant diversity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEV</td>
<td>Plant genetic resources (e.g., collection</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>management, maintenance, management,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>characterization)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRI</td>
<td>Topics in applied biotechnology</td>
<td>Biotechnology</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Biotechnology tools and methods</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>DEV</td>
<td>Principles of biotechnology</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>PRI</td>
<td>Seed business (e.g., from research to delivery</td>
<td>Business</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>of varieties)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEV</td>
<td>Seed business (e.g., from research to delivery</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>of varieties)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PUB</td>
<td>Mating systems and their uses</td>
<td>Plant reproductive</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>biology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRI</td>
<td>Understanding of floral biology</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Mating systems and their uses</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
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</tbody>
</table>

† Range of SD = 0.61–1.05.
through the marriage of knowledge with experiences related to plant breeding. Competence in science knowledge and skills built on information and experience is of unquestionable importance, but a successful breeder must also possess professional effectiveness that involves personal attributes, interactions with coworkers, leadership, and management ability.

Knowledge
Most knowledge categories identified by PUB, PRI, and DEV stakeholders as being important or very important were similar and emphasized plant breeding and breeding methodology, basic and quantitative genetics, statistics, and experimental design. Prevalence of these knowledge suggestions...
should come as no surprise since they provide much of the core curriculum for today’s plant breeding education programs. However, several category topics of shared importance, such as ethics and policy and law, may be novel to current programs. Business, important to PRI and DEV, and management, important to PUB, are not likely emphasized widely in traditional plant breeding curricula.

The PUB and DEV sectors provided unique suggestions indicating a need for advanced statistical knowledge beyond that of private company breeders, who in large organizations at least, may have access to statistical consultants. Many students who will claim jobs as PUB plant breeders eventually become the educators of future plant breeders. They may need more extensive knowledge of statistics because of the underpinning methods used for crop improvement such as selection, rate of gain, and heritability; molecular marker development; and evaluation of germplasm, improved populations, elite lines, and new cultivars that involve various types of comparisons. In contrast to PRI breeders who are more likely to have access to consultants knowledgeable about statistics and experimental design, DEV breeders are often isolated with limited access to specialists and therefore must rely more on their own knowledge and skills.

The PUB and DEV sector respondents rated knowledge about plant diversity and evolution as important topics of graduate curricula. Better characterization and wise use of diverse germplasm for breeding have become increasingly important as population growth and increasing per capita consumption contribute to the unsustainable exploitation of Earth’s biological diversity (Rands et al., 2010). The DEV stakeholders may emphasize plant genetic resources because of not only the continued importance of diverse genetic materials for developing new cultivars but also that many developing regions view their native plants as rich natural resources of strategic importance. Collection, maintenance, management, and characterization of germplasm collections require substantial resources and specialized training but offer limited upfront business incentives to private companies. It is more likely that these activities will be done largely in the public sector of developed and developing countries. The PUB and DEV respondents also mentioned the importance of writing grants to obtain program funding. This has become critical in both those sectors for success and, in some cases, for survival. This was not rated as important in the PRI sector because there, funding is usually provided upfront rather than on a competitive basis.

Knowledge about project management, which includes activities such as managing personnel and budgets, establishing goals and timelines, maintaining relationships among multiple organizations, etc., was identified as important by PUB. Although not mentioned as important knowledge by PRI, they did rate management experience as important (Fig. 3) and personnel management as an important skill (Fig. 5). Thus, it appears that better preparation of breeders in several areas of management is important to both sectors.

It is not surprising that PRI emphasized knowledge about biotechnology and seed business, both of which have discernible roles in private sector business activities as important or very important. Knowledge about a broad topic like the seed business may require not only information from several sources integrated into a course but also activities such as visits to commercial companies. It may be that optional offerings from a school of business along with hands-on experience through internships in the private sector can provide the knowledge–experience–skills combination being sought. Interestingly, the DEV sector also emphasized biotech and seed business. This may be due to the new and rapid integration of biotech crops that developing countries are now facing.

Communication was identified as important by PUB and DEV but not so by PRI respondents. While good communication skills are surely valuable to most if not all breeders for presenting program goals and outcomes, it may be that for those in the public sector, scientific communication is more critical to professional success because they frequently make more presentations to a wide range of people outside of their respective organizations. However, both sectors rated skill in communication as important (Fig. 5). These differential ratings provide an example of some disconnect among how people view knowledge, experience, and skills. The public sector identified knowledge and experiences in communication as important, while the private sector did not. Logically, for a person to become a skilled communicator one might...
Figure 5. Skill categories (small white ellipses) identified by developing (DEV), private (PRI), and public (PUB) sector stakeholders surveyed in the Delphi-based study at Univ. of California Davis, 2009. Large ellipses include unique categories: DEV (blue), PRI (yellow), and PUB (pink); two-sector categories: DEV/PRI (green), DEV/PUB (purple), and PRI/PUB (orange); and categories shared by all three sectors are in red. Numbers in the small ellipses indicate the number of suggestions from the DEV (left), PRI (center), and PUB (right) sectors in each category.

Figure 6. Mean scores of experience category suggestions rated very important (black line at mean rating 4.5) to developing (DEV), private (PRI), and public (PUB) sectors surveyed in the Delphi-based study at Univ. of California Davis, 2009.
learn fundamentals (knowledge) then practice both oral and written delivery (experiences).

Experiences

Many suggested experiences, similar to knowledge and skills, were given comparable ratings by stakeholders in all sectors. Categories containing the most experience suggestions included breeding, practical experiences, scientific communication, and handling data. The PUB, PRI, and DEV noted great value in students gaining practical field knowledge through data collection and analysis and other hands-on activities, preferably with guidance from and interaction with experienced breeders. There was some divergence between the PUB and PRI groups on the level of importance stakeholders placed on oral and written presentations and on mentorship. Mentorship was rated very highly by PUB respondents. It is already engrained to some degree in many advanced degree programs because a student is expected or even required to work directly with a faculty member as an academic advisor throughout their studies. These experiences provide students necessary guidance during their growth as a plant breeder to sharpen their ability to clearly communicate scientific studies and results as well as integrate knowledge acquired in different formats. Interestingly, it was not rated as highly by PRI, even though many companies assign new junior breeders a mentor or colleague for guidance in a new position.

Experiences with extension programs were unique to the PUB sector. This may relate to the mandate of a land grant university to apply research for the public good. Therefore, students interested in working in the public sector may want to gain experience by participating in farmer field days and other extension activities within the community. Both the PUB and DEV sectors suggested student go on field visits. Field trips to breeding programs could easily be integrated in a plant breeding course and would provide the students with an opportunity to see the diversity in different types of breeding programs. The PUB and DEV sector respondents also thought that experience with germplasm was important, which is congruent with the importance of knowledge about plant diversity and evolution that they identified.

The PRI and DEV sectors emphasized experience with experimental design, and although the PUB sector did not, all three groups rated knowledge and skills with experimental design as very important. This underscores the broad importance of experimental design throughout nearly all plant breeding activities whether engaged in fundamental or applied research, developing new technology, or cultivar development, testing, and distribution. Almost without exception, it is critical that students know how to design, organize, establish, and then properly analyze lab, greenhouse, and field experiments. This is consistent with the emphasis on knowledge of advanced statistics. Much of this experience and skill building can be accomplished through a student's thesis research and by observing and helping other students and faculty.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Skill suggestions</th>
<th>Skill categories</th>
<th>R3 mean†</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUB</td>
<td>Perform genetic analysis of plant traits</td>
<td>Genetics</td>
<td>4.6</td>
</tr>
<tr>
<td>PUB</td>
<td>Assess genetic diversity</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>PUB</td>
<td>Conduct linkage analysis</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>DEV</td>
<td>Breed plants for disease and insect resistance</td>
<td>Pest and disease</td>
<td>4.3</td>
</tr>
<tr>
<td>DEV</td>
<td>Evaluate plant disease and insect resistance</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>DEV</td>
<td>Identify and diagnose insect and disease damage</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>PUB</td>
<td>Understand approaches for leveraging genomic information</td>
<td>Genomics</td>
<td>4.0</td>
</tr>
<tr>
<td>DEV</td>
<td>Approach plant breeding from an interdisciplinary perspective</td>
<td>Interdisciplinary</td>
<td>4.4</td>
</tr>
<tr>
<td>PUB</td>
<td>Develop interdisciplinary approaches to provide plant breeding solutions</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>PUB</td>
<td>Develop team leadership skills</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>PUB</td>
<td>Communicate with growers and extension scientists</td>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>PUB</td>
<td>Establish a plant breeding team and function as a leader of the team</td>
<td></td>
<td>3.9</td>
</tr>
<tr>
<td>PUB</td>
<td>Demonstrate and articulate results orientation and leadership track record</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>PUB</td>
<td>Establish working groups including different disciplines</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>PUB</td>
<td>Work in an interdisciplinary team</td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td>PUB</td>
<td>Work as part of decision-making team</td>
<td></td>
<td>4.1</td>
</tr>
<tr>
<td>PUB</td>
<td>Leadership and teamwork</td>
<td></td>
<td>3.9</td>
</tr>
<tr>
<td>PUB</td>
<td>Foster team working/building skills</td>
<td></td>
<td>3.9</td>
</tr>
</tbody>
</table>

† Range of SD = 0.57–1.11.

Respondents provided many more suggestions of diverse experiences important for preparing new breeders. For some universities, especially if they have only a few breeding programs, it may be difficult to meet those aspirations. Experiences such as hybridizations, pollinations, and visual
assessment of traits can be taught in a lab course or by hands-on contact with breeding programs on campus or at nearby companies. Other techniques including planting, phenotyping, and harvesting can be experienced through internships with full-scale breeding programs. Becoming more skillful in scientific communication can come from participating in seminars, conferences, lab meetings, and journal clubs, as well as writing grants, reports, or scientific papers with evaluation and guidance from colleagues in a community of practice. Graduate programs are finite and it is challenging for students to meet the varied academic requirements in a timely manner. It will be important to integrate experiences as much as possible with required courses, research for a dissertation, and other nonacademic activities such as short-term workshops and online activities. Equally important will be the revision of courses to integrate new knowledge and methods with classical procedures rather than simply adding new courses to an already crowded curriculum.

Skills
Skill in a particular area usually is acquired by integrating knowledge and information with multiple experiences wherein that knowledge is put into action and the outcomes are evaluated. The many shared skill categories indicate that there is considerable agreement among sectors over the types of scientific and professional effectiveness skills that are important. Stakeholders placed equal emphasis on skills related to experimental design, analytical aptitude, data management, and statistics. Despite this agreement, there were relatively few similar knowledge and experience suggestions given for how to acquire these skills.

Among skills that PUB and DEV rated more important were those relating to interdisciplinary studies and leadership and teamwork (Fig. 6). This confirms reports from the 2005 symposium hosted by the Michigan State University Plant Breeding and Genetics Group (Gepts and Hancock, 2006; Ransom et al., 2006) and echoing calls by Applegate (2002) for a shift in research goals toward more interdisciplinary work. Strong emphasis on these categories may reward plant breeding education programs that provide opportunities for their students to develop these skills. Encouraging students to work across disciplines and/or with other colleagues and institutions on collaborative projects that require effective communication may better prepare them for future plant breeding.

The PUB sector found lab techniques, genomics, and genetics to be useful skills for a graduate student to acquire. The large volume of genomic information being created for most crop plants mandates the need for knowledge and skills that facilitate one’s ability to actively participate in molecular as well as whole-plant research applicable to breeding. Students aiming for careers in most areas of plant breeding will need to be able to manage genomic information and apply it along with standard breeding methods to research and cultivar development.

Other studies have identified topics that are not currently found in plant breeding curricula, such as an understanding of policy, business, and ethics (Morris et al., 2006; Nyquist and Woodford, 2000). Our study similarly identified nontraditional topics such as ethics, writing skills, and seed business. The DEV respondents gave a high level of importance to policy and law and regulatory issues. This may be due to a need for resource protection and for supporting legal and regulatory infrastructure. Educators preparing students for work in developing settings may want to take these differences into account.

Although it may seem that these skills would naturally ensue from subject matter competency, cognition research indicates that knowledge learned in formal classroom settings may not transfer easily to other settings (Rose, 2004; Lave and Wegner, 2003; Rogoff, 2003; Brown et al., 1989). Holistic skills that can be applied in multiple breeding contexts require integration of experiences with classroom learning to “activate” what scholars describe as inert knowledge acquired from textbook and lecture (Brown et al., 1989). Even lab experiences, when extracted from the planning, objectives, and issues of a real plant breeding program, may be difficult for students to apply without scaffolding. That is, the complexity of the context in which students encounter problem-solving situations must be carefully increased to build on past experiences (Hatan and Inagaki, 1986). Stakeholders’ emphasis on field experience under skills is an excellent example of such contextual learning, and indicates the need to balance field, classroom, and lab experiences in the curriculum. Gepts and Hancock (2006) raise this concern, noting the decline of field experience in plant breeding programs.

IMPLICATIONS
There are strong, continuing demands for well-prepared plant breeders in the public and private sectors of industrialized and developing countries worldwide. Therefore, plant breeding education and curricula must remain relevant, stimulating, and cutting edge to attract students and prepare new professionals for productive careers in widely diverse settings. Regardless of where plant breeders are employed and types of work their jobs entail, expert stakeholders from different sectors identified many similarities in knowledge, experience, and skill categories that are important components of graduate education. Even so, differences likely to be encountered by breeders working in different settings will favor different skill sets that can be gained by emphasizing particular categories of knowledge combined with connected experiences.

It is unrealistic to expect future breeders to be equally well versed in all breeding-related knowledge and skills. Thus, their educational preparation should balance breadth of knowledge and skills along with depth through specialization and experience. Educators should seek ways to evaluate effectiveness of education. To address student preparedness one might have skill workbooks in which major professors or student advisors assess competency of students in designated topics. This would
be a litmus test to determine what each student is capable of and areas where more effort and accomplishment are needed. For instance, students could be evaluated in generalized areas—communication, lab techniques, field techniques, experimental design, and data storage and management sometime during their graduate education. Then not only would a student be graded for knowledge and comprehension of topics but also application of this knowledge to skill sets. Specific areas could be emphasized differentially depending on each student’s area of emphasis and/or desired career path.

Much of the basic knowledge needed for public and private sector jobs will be the same, but stakeholders also identified some different needs between the two. Faculty at colleges, universities, and institutes are responsible for most of the formal education of plant breeding students and much of the research related to crop improvement. Students interested in public breeding may eventually become the educators of future plant breeders and therefore should have excellent scientific communication and mentorship skills. These skills may be gained through experiences such as oral and written presentations, teaching assistantships, and lab mentorship. Students interested in private breeding may need more agronomic knowledge and a better business sense, which may be gained through private internships and business classes.

Most work at seed-related businesses in the private sector is aimed at developing, testing, and selling new cultivars. Because most breeding jobs in developed regions are in the private sector, private companies can play important roles in preparing future plant breeders for productive careers. Some large seed industry companies are beginning to offer graduate-level funding through fellowships or scholarships for plant breeding students. Private breeding companies may also provide support for current employees to acquire more formal training through professional development courses in areas in which they may need greater expertise (Miller et al., 2011).

Graduate education programs committed to preparing students for work in developing countries should carefully consider some differences in needs mentioned here. In scientific knowledge and skill these include attention to: plant genetic resources and plant diversity, biotechnology, and breeding for pest and disease resistances. In terms of professional effectiveness, stakeholders in developing countries emphasized networking and collaborative work, within and across disciplines and sectors. They also noted the importance of understanding policy and law, funding, and scientific communication.

Curriculum planners may consider the cognitive apprenticeship model, outlined in a seminal work by Collins, Brown, and Newman in 1989. Cognitive apprenticeship involves modeling, coaching, scaffolding, and reflection, and a well-designed program would integrate both classroom and field experience (Collins et al., 1989). For example, an instructor might model how to create a rigorous field experiment (including problem solving of real experimentation), coach students as they create one themselves, and provide scaffolding as students transition into being able to plan and implement experiments based on certain objectives. Such programs function best when they include “communities of practice,” that is, groups of students who form a community characterized by evaluating and reflecting on the experience of plant breeding. The community of students should participate, at least peripherally, as part of a larger community of plant breeders working professionally, who function as “old timers” teaching the “newcomers” (Lave and Wenger, 2003; Wenger, 1998). Thus, the experimental design example might also incorporate an internship in which students are working with experts as they problem-solve their own experiments.

Research in higher education indicates different ways to approach curriculum revision. For example, some universities have made substantial progress in preparing graduate students in practical career experience, and their techniques may provide an example of how plant breeding graduate programs could be organized to expose graduate students to skills and experience outside of traditional academic curriculum (Pruitt-Logan and Gaff, 2002). These suggestions include for-credit graduate seminars, less formal seminars and workshops, certificate programs, and formal mentorship, all of which provide an avenue for discussion, mentorship, and training in areas important to enculturation into the plant breeding profession (DeNeff, 2002; Committee on Science, Engineering and Public Policy, 1995).

All students can benefit from curriculum that bridges skills and knowledge by integrating carefully planned experiences into graduate programs. Knowledge gained in the classroom can be supplemented with practical experience in lab and field settings to provide students with the skills needed to attain an ideal proficiency level. Education programs committed to the preparation of exceptional graduates for plant breeding work in varying, diverse settings now have access to consensus data from expert stakeholder groups to guide their process in curriculum enrichment.

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References