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COMMENTARY

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The many-faced Janus of plant breeding

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Societal Impact Statement

Plant breeding is crucial for improving agricultural crops for human use. However, an urgent rethink is needed to ensure the next generation of plant breeders have the necessary breadth of skills to provide ever more efficient, nutritious, profitable, and environmentally sustainable crops. Plant breeding is a multifaceted endeavor, which intersects with many other disciplines and professions. To help ensure that future plant breeding efforts are sustainable and relevant to the needs of society, it is vital that the interdisciplinary nature of the plant breeding profession is adequately reflected in student training and development.

Summary

Breeders need to have many faces to understand not only genetics but also environmental, social, and economic factors that are relevant for maintaining or improving crops for human use. In the United States, there is a long history of public involvement in agriculture and plant breeding. However, recent changes in the social systems underpinning public agriculture (i.e., funding structure) necessitate a rethinking of how agriculture education, specifically plant breeding education, should be facilitated. To provide viable plant breeding programs, it is necessary to explicitly acknowledge that breeding has been an interdisciplinary, long-standing public endeavor to increase food system stability. Acknowledging this complexity has important pedagogical implications: the core of plant breeding resides in genetics, but the changing nature of this profession requires breeders to embrace a much broader training. Here, we suggest specific curricular objectives for plant breeders.

KEYWORDS

interdisciplinary, food system, public goods, plant breeding programs, societal preference

> *My sides are many, my angles aren't few. I'm the Dodecahedron, and who are you?*
> -The Dodecahedron outside digitopolis from the Phantom Tollbooth (1961), Norton Juster

In the United States, public plant breeding is in crisis. Its funding model has eroded. Large-scale commercial farmers primarily grow varieties bred by the private sector and the number of lines released by public programs (e.g., Universities and USDA) has substantially diminished over the last 25 years (Shelton & Tracy, 2017). In effect, outputs from public programs have shifted away from cultivars and more toward publications and other forms of intellectual property. The public sector has seen decreases in capacity both in terms of the number of breeders and the budgets that those workers have

(Shelton & Tracy, 2017). The movement toward privatization has been in part due to the economy of scale that is possible within the private sector and the resulting increase in availability of positions compared to the public sector. However, the decline in public plant breeding has come at a time when we may need it more than ever. Under significant societal and environmental pressures, agriculture needs to transition toward forms of production that deliver greater levels of ecological services in addition to crop yield (Mehrabi, Ellis, & Ramankutty, 2018; Ramankutty et al., 2018). Crops that deliver more to society will require new targets for selection that are not typical of data currently collected in breeding programs (e.g., yield, disease resistance, insect tolerance), and will also require breeders to acknowledge the interconnected nature of simultaneously improving cropping systems and the crops that are placed in them (van Bueren, Struik, Eekeren, & Nuijten, 2018). The risks of developing such agricultural systems are generally too high for the private sector to do the trial and error work of exploring an infinite solution space of system configurations. The agricultural production challenges we face are public goods problems, and therefore a highly functional national public plant breeding system is best suited to address them.

Here, we are concerned with the specific skill sets that current and future public breeders need in order to rebuild viable public plant breeding programs that generate crops/cultivars that are widely adopted by farmers and consumed by the public. To address this, we first must understand the social contract that exists between the public and agricultural sciences. It is a long-held belief that the public sector has a duty to help maintain and improve agricultural crops for human use and prosperity. In the United States, the social contract associated with agriculture grew out of the merging of the extension service (Smith-Lever Act, 1914) and the land grant university system (Morrill Act, 1862), which led to a synergy between basic and applied research that increased agricultural productivity, as highlighted by Wendell Berry (2009) in his book *Bringing it to the Table: On Farming and Food*:

> Agriculture must mediate between nature and the human community, with ties and obligations in both directions. To farm well requires an elaborate courtesy toward all creatures, animate and inanimate. It is sympathy that most appropriately enlarges the context of human work. Contexts become wrong by being too small - too small, that is, to contain the scientist or the farmer or the farm family or the local ecosystem or the local community - and this is crucial.

Food production is a perennial issue that every generation must address because maintaining a healthy population is central to functioning societies. Human preferences for how food production should occur and what foods are desired are constantly changing and are influenced by the interplay of societal values (e.g., humanitarian, national defense, social stability, environmental; Moon, Chang, & Asirvatham, 2017).

Fulfilling a social contract between food producers and society requires breeders to gain expertise across several disciplinary boundaries. Plant breeding has been described as having many faces: a natural science face that engages in genetics, computational biology, and statistics; an engineering face, applying scientific methods to designing and building new crops and cultivars; a social science face that considers the economics of new crops and cultivars, consumer psychology, marketing, and farmer/consumer education; an artistic face that is expressed in the process of selection; and a community organizing face, through which breeders support communities in food advocacy. The appropriate face of a plant breeder depends on the specific position, task, and project. Table 1 describes the many faces used to delineate some of the major contours of plant breeding. This list of skills defines areas in which breeders need to continue professional development and education in order to fulfill their social contract and develop a sustainable agriculture industry, as well as disciplines they need to be able to commutate with and learn from. Plant breeding is inherently an interdisciplinary process. Breeding teams include pathologists, agronomists, entomologists, computer scientists and molecular biologists. The breeder is often at the center of these different viewpoints and needs to know enough about the latter disciplines to make decisions and facilitate communication.

The many faces of plant breeding require not only explicit acknowledgment of the way breeding has been pursued, but also the implicit social contract that has been a part of breeding institutions since this became a formalized discipline in the 19th Century. Every variety requires breeding to maintain or improve its use to humans. Understanding the many faces of plant breeding allows us as a culture to turn the implicit social contract into explicit traits that can be used to create a more efficient, nutritious, profitable, and environmentally sustainable food system. Acknowledging complexity in the training needed for becoming a breeder has important pedagogical implications. The base of plant breeding has, and will continue to be, genetics, but the changing requirements of this career necessitates a more interdisciplinary approach to plant breeding education. At both the undergraduate and graduate levels, plant breeding students should be challenged to interact with, and interpret not only the natural sciences from which the discipline has traditionally grown, but also a wide range of social sciences, including economics, sociology, and business.

For plant breeding programs to be financially sustainable, they need to produce crops that satisfy unmet market needs and can generate sustainable revenue for the program. To establish sustainable research programs, plant breeders need to rigorously evaluate potential crops based on the full value chain of getting the crop to market (from breeder, to farmer, to value added producer, to final customer). Critically, estimating costs, benefits, modes of delivery to consumers, and on-going engagement with customers will be essential. There are many well developed business models that could be incorporated to achieve stability in future funding. For example, business models such as the Lean Start Up (Reis, 2011) which rely on a process of validated learning, involving setting a vision, building a product from that vision, measuring potential consumers' responses to the product, and then learning from consumers to update the initial product. This *build-measure-learn* framework has been widely adopted by the NSF, NIH, and other

TABLE 1 The many faces of plant breeding, a generalist discipline. In order for plant breeding to be relevant for changing societal needs for food, fuel, fiber, and ecosystem services, students of this subject must be exposed to, interact with, and learn from professionals with a diverse set of expertise

Face	Skill set
Scientist	Plant breeding is an attempt to systematically understand the genetic variation within a plant species. Genetic variation is the raw material that a breeder seeks to use to benefit humans; understanding and experimenting with how inheritance occurs is central to improving plants for human use
Engineer	Breeding has a set of known challenges, particularly biotic (e.g., leaf blight) and abiotic (e.g., drought); to overcome these challenges standard methods have been developed. In this sense, breeding is an engineering problem that requires identifying the right pieces and assembling them
Artist	Breeders live with their plants and develop a deep sense of their ideal phenotype; creating the latter through selection is as much a labor of love as it is of practicality
Computer scientist	The last 25 years have witnessed an explosion of data that better define our environment, our genome, and the response of plants to both of these factors. Breeders are increasingly trying to combine, manipulate and explore these data, which necessitates large computation infrastructure and training in analysis of big scale data
Genomicist	Genetics has been the heart of plant breeding since this discipline originated. It has long been recognized that understanding qualitative and quantitative genetic variation is the best way to get the phenotypes that humans want
Statistician	Agriculture and breeding has been a fertile place for the development of statistical techniques, starting with those by R.A. Fisher who designed methods to understand variation in traits and to assemble a desired suite of the latter
Conservator	Plant breeders save seed in the form of a personal storage chamber of genetic stocks and germplasm that looked good, bad, or were unusual. This living library is the raw material for future gains
Economist	One of the driving forces of breeding has been the development of plants that are profitable for farmers or companies. Traits contributing to profitability may include higher yields, better taste, and improved chemical properties. Understanding the economic drivers that define desirable phenotypes by crop producers and consumers helps breeders develop cultivars that are more likely to be adopted
Sociologist	Societies have ever changing tastes, and preferences are often regionally/culturally influenced. Breeders need a solid understanding of factors that influence their end-consumers to better identify which phenotypes should be prioritized
Marketer	Change is difficult. People may need to be convinced that qualities of a new cultivar are beneficial, especially if they are unfamiliar. This means that product development, breeding cycles and marketing efforts need to be coordinated in order to maintain a breeding program
Community organizer and advocate	Food is culture; everyone has a story about a family heirloom plant. Breeders are integral to creating and maintaining a community's favorite types of plants
Ecologist	There is a need to produce more food for an ever growing population. This is occurring under increasing competition for land and resources. Understanding the interplay between sustainability and important traits, including ecological (e.g., carbon dynamics) will become increasingly important

federal agencies through the Innovation Corps program. In order to help resolve the funding crisis plant breeding is facing and increase the ability of public programs to be self-sustaining, there is a need to embrace the interdisciplinary nature of the discipline so that the public sector can be flexible and responsive to public goals and desires.

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