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Participatory plant breeding and organic agriculture: A synergistic model for organic variety development in the United States

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Abstract

Organic farmers require improved varieties that have been adapted to their unique soils, nutrient inputs, management practices, and pest pressures. One way to develop adapted varieties is to situate breeding programs in the environment of intended use, such as directly on organic farms, and in collaboration with organic farmers. This model is a form of participatory plant breeding, and was originally created in order to meet the needs of under-served, small-scale farmers in developing countries. A robust body of literature supports the quantitative genetic selection theory of participatory plant breeding, and helps to explain its increasing prevalence among organic breeding projects in the United States. The history of the organic farming movement in the United States highlights the cultural relevance of engaging organic farmers in the breeding process, complementing the biological rationale for participatory plant breeding. In addition, limited private investment in organic plant breeding encourages the involvement of plant breeders at public institutions. This paper synthesizes the biological, cultural, and economic justifications for utilizing participatory plant breeding as an appropriate methodology for organic cultivar development.

Introduction

In recent years, organic farmers have increased their usage of organic seeds on their farms. A 2014 survey of organic farmers conducted by the Organic Seed Alliance showed that organic farmers are, on average, planting 69% of their acreage to organic seed, an increase from 58% in 2009 (Hubbard and Zystro, 2016). Certainly the widespread availability of commercial organic seed, as well as certifier requests that growers source more organic seed, has contributed to this increase. But when asked why organic growers are purchasing organic seed, nearly 80% said they wanted their organic seed purchase to support organic plant breeding (Hubbard and Zystro, 2016).

At the most literal level, organic seed in the United States (US) is seed that has been produced according to the organic production standards set forth by the United States Department of Agriculture's (USDA) National Organic Program (NOP). Seeds from most conventionally bred vegetable and crop varieties can be produced and certified as organic seed, with the exception of varieties that are genetically engineered (GE) or developed using some forms of cell fusion. Certified organic seed, however, does not mean that the variety was bred organically, and thus may not possess the genetic traits that will enable it to thrive in organic management systems. Organic seed that has also been bred for improved performance under organic production can serve as an important tool to help farmers produce successful crops. Indeed, research indicates that cultivars that perform well in conventional systems are not necessarily the best producers when grown in organic conditions (Murphy et al., 2007; Reid et al., 2010). In order for organic agriculture to continue to grow as a viable sector of the food system, varieties must be bred with adaptations to the unique soils, nutrient inputs, management practices and pest pressures found in organic farming systems.

But who will breed these new varieties and how will they do so? The conventional seed sector experienced a 1,300% real increase in research and development investments from 1960 to 1996 (Fernandez-Cornejo, 2004). The result is a steady supply of new varieties adapted to conventional production systems each year. For the organic farming community, however, both external and self-imposed restrictions limit the resources available for investment in research and development for new varieties. As a result, expansion of the conventional seed industry over the past 85 years does not provide an applicable model for expected growth in the nascent organic seed sector. Indeed, many organic advocates prefer very different models – ones that incorporate regionally adapted varieties, a diversity of seed companies, farmer engagement in the breeding process, and shared access to genetic resources. As a result, many organic breeding projects in the public sector incorporate some form of participatory plant breeding (PPB) or participatory varietal selection (PVS).

The following synthesis explores the reasons why PPB has become such a prevalent methodology for organic breeding in the US. From its roots in international development work, PPB has become formalized as a methodology by public breeders working in low-input systems in the developing world and low-external input systems such as organic agriculture in the developed world. But to fully understand its application for organic systems, this paper reviews how the history of the organic farming movement encouraged the engagement of farmers in the organic breeding process. Finally, this synthesis shows that limited private investment in organic plant breeding necessitates involving plant breeders at public institutions and provides fertile ground for this methodology to fully take root.

History of participatory plant breeding

Plant breeding, as a practice, is as old as agriculture itself, with crops such as barley and emmer wheat domesticated by farmers approximately 10,000 years ago (Harlan, 1992). Plant breeding, as a scientific discipline, can be traced more recently to Mendel's experiments in the early 1900s on the inheritance of genetic traits. Plant breeding is a "science-based technology" that aims to deliver improved cultivars to farmers through selection in genetically variable plant populations (Tracy, 2004: 26). PPB is just one of numerous methodologies that has been developed to achieve this goal. Specifically, PPB is a process in which farmers and formally trained breeders collaborate throughout various stages of the breeding process, often situating breeding plots in farmers' fields rather than on agricultural research stations, and selecting for agronomic and quality traits tailored to the farmers' specific requirements. PPB grew from critiques that began in the 1950s of the ineffectiveness of development projects aimed at introducing modern agriculture technologies to areas lacking these resources. For example, Apodaca (1952) explains the failed attempt of a USDA extension agent to replace the low-yielding traditional corn variety used by a farming community in New Mexico with a high-yielding hybrid, which was unacceptable because of its taste, texture and color. Interdisciplinary approaches such as Farming Systems Research and the Farmer-Back-To-Farmer model (among others) were created as an attempt to incorporate experimentation on farmers' fields throughout the research process, encouraging feedback from farmers at various stages of the project (Rhoades and Booth, 1982; Jones and Wallace, 1986). The theory behind these methods is that farmers are more likely to adopt new agricultural technologies (including new varieties) when they have actively participated in their development. This process is particularly relevant for resource poor farmers, especially in developing countries, whose diverse and complex needs are often underserved by agricultural innovations designed for larger commercial farms (Merrill-Sands et al., 1989).

Some scholars suggest that these early methods of farmer engagement still treated farmers as mere research subjects, rather than true collaborators (van de Fliert and Braun, 2002). Nonetheless, they stood in stark contrast to the dominant model employed at international research centers such as the Consultative Group of International Agricultural Research (CGIAR), which were based on the structure of the public agricultural research system in the United States. Described as the "central source model" by Biggs (1990: 1481), the goal of these centers was to develop agricultural innovations that would reach the farmer only after being transmitted to national research systems and then extension agents. In this model, "there is an unambiguous, one-way progression in the research, extension and adoption process" (Biggs, 1990: 1481). The Green Revolution of the 1960s is perhaps the best example of this model, in which high yielding wheat and rice varieties were bred at international research centers in Mexico and the Philippines, promoted by national governments, and distributed by extension agents to farmers. Some farmers benefitted from these new varieties, however others did not because they were unable to adopt the new methods of seeding, fertilizing and irrigating required to achieve high yields with these varieties (Griffin, 1972; Perkins, 1997).

Despite this institutional culture, some public researchers at CGIAR centers were concerned that their work was not relevant for small-scale farmers and began to use interdisciplinary methods to better understand their needs. Social scientists, especially anthropologists, played a critical role in developing participatory research, a remarkable accomplishment given the dominant structure which viewed their work as "an extension type activity of limited relevance to a CGIAR center" (Thiele et al., 2001: 432). In the mid-1970s, the International Potato Center (CIP) in Peru was one of the first centers to actively promote the idea that farmer knowledge was as valuable as formal research to achieving its mission (Biggs, 1990). Other centers that housed small groups of researchers using participatory methods included the International Center for Tropical Agriculture (CIAT) in Colombia and the International Rice Research Institute (IRRI) in the Philippines (Chambers, 1989).

By the early 1990s, a diverse group of national agricultural research stations, non-governmental organizations and farmers' organizations in developing countries were utilizing participatory research models with success. Trialing an array of advanced breeding lines on farmers' fields, with input from farmers on their preferences, was a straightforward application of this participatory process. Maurya (1989) and Ashby et al. (1989) give examples of farmers selecting adapted rice varieties in rain-fed upland areas of India and improved bush-bean and cassava varieties in Colombia, respectively. Using the term "participatory varietal selection," Sperling et al. (1993: 510) demonstrate that Rwandan bean farmers successfully identified superior bean varieties for their particular farms by evaluating on-station research trials. In addition, the farmer-selected varieties outperformed local mixtures 64–89% of the time, while the breeder-selected varieties did so only 34–53% of the time (Sperling et al., 1993). According to Walker (2006), the acronym PVS was first used for participatory varietal selection at a 1995 workshop hosted by Canada's International Development Research Center (IDRC), as was the acronym PPB. Witcombe et al. (1996: 450) describe both of these methods for the first time in the peer-reviewed literature, specifically referring to PPB as "a logical extension of participatory varietal selection," in which farmers are involved in the earliest stages of selection from segregating populations.

With a growing number of successful participatory projects, the CGIAR began to recognize the value of participatory research and formalized its commitment to this process with a systems-wide initiative on Participatory Research and Gender Analysis (PRGA) in 1996 (Thiele et al., 2001; van de Fliert and Braun, 2002; Walker, 2006). By 2000, a recommendation made to the CGIAR Technical Advisory Committee suggested "that PPB become an integral part of each CGIAR center's plant breeding program" (Vernooy, 2003: 55).

PPB methodologies have now been thoroughly documented in the scientific literature, and vary significantly based on the project's resources and goals (Figure 1). All share a commitment to meaningfully involve farmers in the breeding process. PPB is often presented as a continuum of participation in which farmers can engage at various points of varietal development, such as setting breeding goals, making initial crosses, selecting among diverse progeny, evaluating experimental varieties, and distributing seeds (Morris and Bellon, 2004). In addition, the distinction is usually made between "formal-led PPB," in which control of the project rests with scientists housed at public research institutions, and "farmer-led PPB," in which scientists play a more supportive role in the farmer's project (Sperling et al., 2001: 440). The selection environment can vary, with centralized PPB projects occurring on formal research stations while decentralized PPB projects take place in farmers' fields. Goals of PPB projects range from developing improved varieties, often for marginalized areas, to maintaining biodiversity, empowering disadvantaged groups (especially women), and/or reducing breeding costs and breeding timeframes (Sperling et al., 2001). After years of experimentation with the methodology, users can now follow step-by-step guides to creating a PPB program, such as Ceccarelli's (2012) comprehensive *Plant Breeding with Farmers: A Technical Manual*. Finally, there is no shortage of case studies documenting successful PPB projects in developing countries, and a growing number of examples from developed countries as well (see Ashby, 2009 for a review).

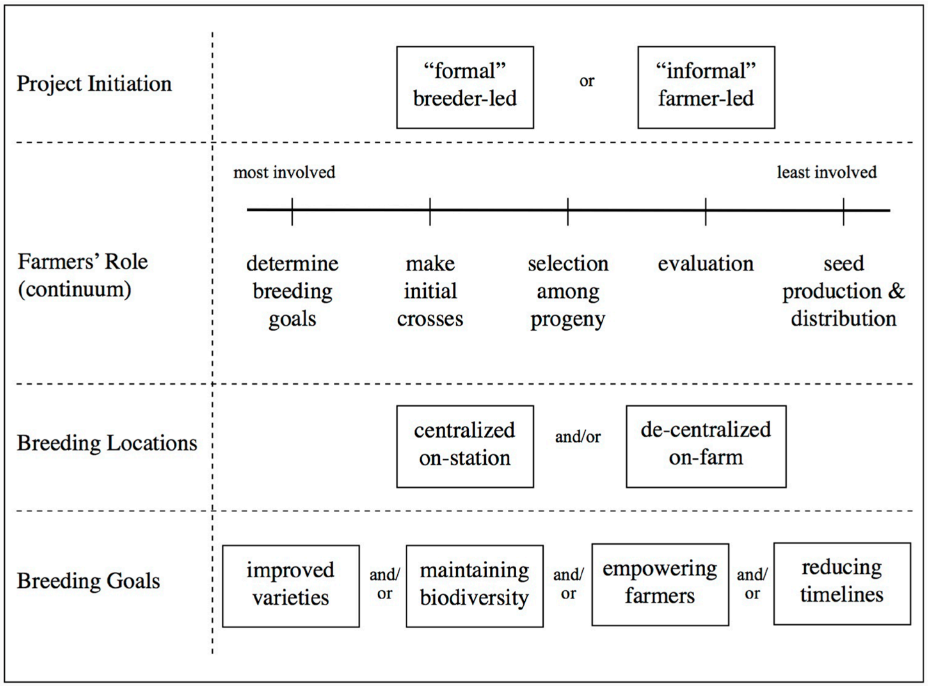

Figure 1

Various components of participatory plant breeding (PPB).

The components of participatory plant breeding projects can vary depending on the unique set of participants involved and the resources available to them. Each project will look slightly different depending on who initiates the project, the farmers' level of involvement with the breeding process, the breeding locations, and the overall goals of the project.

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Participatory plant breeding and organic agriculture

The success of PPB in producing improved varieties for marginalized farmers around the world has stimulated proposals to use this methodology for breeding adapted varieties for organic farming systems in developed countries (Murphy et al., 2005; Dawson et al., 2008; Wolfe et al., 2008; Dawson et al., 2011; Humphries et al., 2015). Similar to the situation of farmers in many developing countries, organic farmers often encounter heterogeneous environmental conditions, and lack suitable crop varieties due to minimal market influence with the larger conventional seed industry (Chiffoleau and Desclaux, 2006). In addition, a diversity of management practices are employed within organic farming systems, potentially further stratifying variety performance between farms (Wolfe et al., 2008). According to Atlin et al. (2001: 472), PPB programs are most effective when either "the targeted region has specific local requirements or when the cropping system differs greatly from that normally targeted by conventional programs." Both of these criteria apply to organic farming. With a strong focus on direct customer sales through farmers markets and Community Supported Agriculture (CSA), organic growers often have different quality requirements than their conventional counterparts (Dimitri and Greene, 2002). Growing conditions on organic farms also can be vastly different than those found on high-input, conventional farms and breeding stations (Drinkwater et al., 1995; Bengtsson et al., 2005). Organic on-farm PPB projects are becoming increasingly common, such as durum and bread wheat projects in France (Chiffoleau and Desclaux, 2006; Dawson et al., 2011), vegetable breeding projects in the Northeastern United States (Mazourek et al., 2009; Mendum and Glenna, 2010), and a broccoli breeding project in Oregon (Myers et al., 2012), to name just a few. In addition, the majority of these organic PPB projects involve breeders from the public sector.

Dawson et al. (2008) provide a comprehensive literature review of the selection theory used to justify PPB for low-input systems in developing countries as well as low-external-input systems such as organic in developed countries. Much of the theoretical and experimental evidence can be attributed to the work of Salvatore Ceccarelli, who has been using PPB to successfully develop barley varieties since the 1990s at the CGIAR center in Syria, ICARDA (Ceccarelli, 2014). In essence, selection schemes are most effective when the genetic correlation coefficient between the selection environment and the target environment are high, and the heritability of the traits under selection is also high. Centralized non-participatory breeding programs tend to increase heritability by reducing environmental variance through replicated trials repeated over multiple years and locations, and reducing the error variance by minimizing field heterogeneity through chemical fertilizers and pesticides. Yet these conditions differ greatly from those found on low-input and low-external-input farms, meaning that the correlation between the selection environment and the target environment is low. As a result, varieties respond differently in the different environments, an example of an effect known as genotype by environment (G x E) interactions. Centralized non-participatory breeding programs often attempt to minimize the effect of G x E by selecting varieties that are widely adapted through multiple environment testing. PPB allows for direct selection in the environment of intended use, actually exploiting G x E by intentionally choosing varieties that are best adapted to a specific location or production system.

In addition to the biological arguments for using PPB, practitioners also stress the value of PPB as democratizing the plant breeding process. To this point, Kloppenburg (1991: 535) states that "it is one thing to argue that the technical knowledge of resource poor farmers should be taken seriously precisely because they are resource poor and therefore not in a position to take advantage of the technologies that science has to offer. It is quite another thing to argue that farmers who do have the material and intellectual resources to make use of science-based technologies possess – in addition – knowledge that should be used to alter the way science develops and deploys these very technologies." Thus, despite the improved varieties that can arise when farmer knowledge is incorporated into the breeding process, PPB is often met with resistance from institutions because it opposes the traditional structure of public agricultural research. Of course, offering new research models is precisely part of PPB's value, beyond applying it to develop useful new varieties. All plant breeding methodologies must engage the farmer at some point. Yet this typically occurs at the very end stage of the breeding process, when a variety is released and will either find acceptance or rejection in a farmer's field. PPB fundamentally changes the role of plant breeders through active farmer participation in the entire breeding process. No longer is a breeder developing new varieties *for* farmers, but he/she is developing varieties *with* farmers. The power dynamic shifts considerably with the recognition that both breeder and farmer have equally valuable, yet critically different, perspectives to contribute to the process. Coming from the social science traditions of science and technology studies and actor-network theory, Chiffoleau and Desclaux (2006: 121) state that "PPB can be interpreted as an innovative socio-technical network" that encourages human and biological diversity by empowering otherwise silent actors. Mendum (2009: 7) goes even further by suggesting that "applying participatory plant breeding methods to a U.S. context could be understood as a radical act of democratization." The history of the organic movement, summarized below, shows that these cultural implications of PPB justify its use for US organic agriculture as strongly as its biological relevance.

The organic farming movement in the United States

The roots of organic agriculture in the US can be traced to Franklin Hiram (F.H.) King, a University of Wisconsin-Madison agricultural physicist and USDA chief of the Division of Soil Management. Disenchanted with the increasing dependence of US farmers on mineral fertilizers, King wrote *Farmers of Forty Centuries* (1911), in which he emphasized the value of maintaining biologically rich soils based on his observations of indigenous agricultural societies in China, Korea, and Japan. While King's writing did not find much resonance in the US at the time, it did strongly influence Sir Albert Howard, an agricultural scientist from England. Howard spent 26 years directing agricultural research centers in India and developed a successful composting technique called the Indore Process. Like King, Howard greatly respected the peasant farmers with whom he worked, viewing them as the greatest teachers (Conford, 2001). Upon his return to England in 1931, Howard gained the support of like-minded farmers, scientists, and writers by promulgating his theories of returning organic waste materials from plants and animals back to the soil in order to support the growth of vigorous plants, animals, and humans. Many organic farming practices that focus on maintaining soil structure are derived from Howard's theories, and as such he is often regarded as the founder of the organic movement (Conford, 1988; Heckman, 2006; Youngberg and DeMuth, 2013).

In the US, the Dust Bowl of the 1930s served as a dramatic indication that a change in agricultural production techniques might be necessary, especially in regards to soil management. In the USDA's 1938 Yearbook of Agriculture, titled *Soils and Men,* Secretary of Agriculture Henry A. Wallace writes, "The social lesson of soil waste is that no man has the right to destroy soil even if he owns it…The soil requires a duty of man which we have been slow to recognize" (USDA, 1938: foreword). Yet it was the efforts of J.I. Rodale, an accountant and publisher from New York, who came across Howard's works in the 1940s and set in motion the US organic movement (Fromartz, 2006). Rodale became an ardent supporter of Howard's theories about soil health and nutrient cycling, and dedicated the rest of his life to promoting what by then had become known as organic farming (credit for the term "organic" is given to Lord Northbourne in 1940) (Scofield, 1986). In 1942, Rodale published his first edition of *Organic Farming and Gardening*, a magazine that continues to this day under the name *Organic Gardening*. Rodale also became a staunch critic of the use of pesticides in food production, citing not only their danger to human health, but the likelihood of accelerating the evolution of pest resistances as well (Conford, 2001). Rodale spread his ideas through the publication of numerous books and magazines, and established a research farm in Pennsylvania that manages long term farming system trials comparing conventional and organic production techniques. In so doing, Rodale inspired an entire generation of new organic farmers in the US (Conford, 2001).

With increased access to inexpensive and effective fertilizers and pesticides after World War II, conventional farmers and agricultural scientists were more than a little reluctant to embrace the labor-intensive, low-external-input systems of organic agriculture (Kelly, 1992). Some researchers at land grant universities (LGU) were openly hostile to the movement, including another University of Wisconsin-Madison soil scientist, Emil Truog, who thought that the avoidance of chemical fertilizers by organic farmers was "just pure bunkum" (1946: 317–318) and later referred to the organic movement as a "cult" (1963: 12). According to Youngberg and DeMuth (2013: 5), many agricultural scientists had grown up on farms similar to the mixed crop-livestock operations espoused by organic advocates, and their memories of long days of laborious work "collided with what they saw as little more than the romantic symbolism of organic farming." The authors go on to suggest that the researchers who held positions of authority at LGUs and within the USDA likely achieved their professional success by conducting "their own peer-reviewed research on the very same technologies now being criticized by (what appeared to be) non credentialed and overly zealous organic farmers" (Youngberg and DeMuth, 2013: 6).

Public opinion on the current course of conventional agriculture began to change, despite Secretary of Agriculture Earl Butz's quip in 1971 that a switch to organic farming would require a decision about which 50 million Americans must starve (Treadwell et al., 2003). Rachel Carson's *Silent Spring* (1962) highlighted the potential harmful effects of unregulated pesticide use to humans, wildlife, and the environment. This increasing environmental awareness, coupled with Cesar Chavez's United Farm Workers Union revealing the dangerous conditions endured by migrant farm workers, inspired some urban dwellers to disengage from the industrial agriculture model by returning back to the land. But as veteran organic policy advocate Michael Sligh points out, the organic farming movement did not rest solely on the backs of environmentalists and social justice advocates who were abandoning the city life to try their hand at harvesting their own food. The growing influence of corporate agribusiness created an economic structure in which farm size needed to increase in order for farmers to stay competitive, thus forcing many out of business (Sligh, 2002). As Sligh states, "part of what drove family farmers into organic farming was that conventional agriculture drove them out" (Fromartz, 2006: 235).

Facing an absolute dearth of public research into effective organic farming systems, the growing number of organic farmers relied heavily on resources within their own community to discover and share effective production systems. According to the State of Organic Seed report (2011: 6), "it is no exaggeration to say that in the early decades of the organic movement there was a strong distrust of [the] Land Grant University system." Grassroots organizations such as the Maine Organic Farmers and Gardeners Association (MOFGA) and Natural Organic Farmers Association (later renamed the Northeast Organic Farming Association or NOFA) in Vermont were founded in 1971, with 35 grower support groups active in 28 states by the end of the decade (USDA, 1980). Organic farmers would congregate at annual regional gatherings, such MOFGA's Common Ground Fair, which began in 1977. In addition to Rodale's *Organic Farming and Gardening,* publications such as *Acres, U.S.A.* and *Mother Earth News* also began in the early 1970s and served an important function in disseminating useful information to organic farmers.

The USDA was also fielding an increasing number of requests for information regarding organic agriculture, and in 1980 released its *Report and Recommendations on Organic Farming* (1980). This report, the first of its kind undertaken by the USDA, was commissioned by Secretary of Agriculture Robert Bergland in part to determine the extent to which "organic systems might help to address the environmental, structural and financial problems that were now plaguing American agriculture" (Youngberg and DeMuth, 2013: 7). The report's findings suggested that the agronomic and environmental benefits of organic farming justified increased research and support from the agricultural research community (Youngberg and DeMuth, 2013). Yet a backlash from conventional agriculture led to a rejection of the report by the incoming Reagan administration, who quickly eliminated the USDA's newly established Organic Farming Coordinator position (Youngberg and DeMuth, 2013).

In 1988, after multiple failed legislative attempts by Senator Leahy of Vermont and Representative Weaver of Oregon to implement the recommendations of the 1980 report, funds were directed to the USDA to establish a competitive grants program for Low Input Sustainable Agriculture (LISA), which later became known as Sustainable Agriculture Research and Education (SARE). A notable aspect of this funding stream, still important for organic research today, is inclusion of farmers and non-governmental organizations in the award process, indicating their continued influence and involvement in shaping the organic movement (Treadwell et al., 2003). Conspicuously absent from this program, however, is the term "organic," which policy makers believed was still too contentious. Yet the market for organic food continued to grow, and many organic advocates believed that a national certification standard would be beneficial for organic farmers and consumers. The Organic Foods Production Act was included in the 1990 Farm Bill with the purpose of defining the production standards for organic agriculture. After 12 years of intense deliberation, the NOP, housed within the USDA's Agricultural Marketing Service and advised by a 15-member group of organic representatives called the National Organic Standards Board (NOSB), established its Final Rule on organic agriculture in the United States in 2002.

The organic industry now has an official description of production practices defined by the USDA and has grown at an unprecedented rate, generating over $43 billion dollars in sales in 2015 (Organic Trade Association, 2016). Attitudes within academia have changed as well. A recent commentary in the journal *Science* states that "even in advanced economies, human well-being depends on looking after the soil. An intact, self-restoring soil ecosystem is essential, especially in times of climate stress" (Scholes and Scholes, 2013: 565). While the article does not refer specifically to organic agriculture, this clearly is at the heart of the organic philosophy. True to its roots, organic farmers continue to have differing opinions about the speed with which the movement has grown and the decisions that have been made along the way, as well as the direction in which to chart its future course. Yet certainly the prevalence of organic food on most supermarket shelves today would not have been possible without the century-long struggle of farmers, consumers, scientists, and policy advocates committed to promoting the organic movement.

Steeped in this history of self-reliance, organic farmers are eager to participate in the breeding of improved cultivars when faced with the prospect of limited varieties adapted for their systems. Having been compelled to develop effective on-farm systems without the assistance of public research from LGUs for so many years, organic farmers, rather than agricultural researchers, tend to be the experts in organic production. Most public plant breeders, on the other hand, have been trained in conventional agriculture systems and may have little knowledge of the varietal needs of organic farmers. PPB works as a breeding method for organic varieties in part because organic farmers share their knowledge with breeders regarding the biotic and abiotic pressures particular to their farming systems, as well as the nuances of their consumer markets. In exchange, the farmers have the opportunity to learn aspects of the science and art of plant breeding.

With this newly gained skill, organic farmers can further adapt the varieties that they are growing on their farms, even after the specific PPB collaboration has ended. This aspect of continual improvement helps to explain the prevalence of organic PPB projects that focus on developing open-pollinated (OP) varieties (Dillon and Hubbard, 2011). Cross-pollinating OP varieties contain more genetic variability, compared to hybrids, allowing for on-going adaptations in response to environmental and human selection. In addition, seed from self-pollinating and cross-pollinating OP varieties can be saved from one year to the next, which allows the farmers (rather than the seed companies) to control the seed. This independence from external inputs has long been a value of organic farmers, as the history of the movement demonstrates. Other practical explanations also exist for the emphasis on OP varieties in PPB, including the large amount of land, labor, and capital required for hybrid development and seed production (Duvick, 2009). Yet, especially as seed ownership has become an increasingly contentious issue, many organic farmers agree with the sentiment that "everyone should be able to breed vegetables on their own and save their own seeds at all times" (Mendum, 2009: 153).

New collaborations between organic farmers and public plant breeders

In addition to the enthusiasm of organic farmers, public plant breeders are beginning to recognize the opportunity to develop improved varieties for organic farmers. In this context, the public sector includes breeders that are funded by federal and/or state appropriations, and may be based at federal research facilities, LGUs, or state agricultural experiment stations. Unfortunately, public plant breeding in the US is in crisis. Beginning with Frey's report (1996), a series of publications have documented the decline of public breeding programs, public breeding faculty positions, and government financial support over the past 20 years (Fuglie and Walker, 2001; Heisey et al., 2001; Guner and Wehner, 2003; Sligh, 2003; Gepts and Hancock, 2006; Hancock and Stuber, 2008; Carter et al., 2014). These ongoing budget cuts at the federal and state levels are part of a larger trend of stagnating public funds for agricultural research that has been occurring since the 1970s (Alston et al., 2010).

Public breeding programs are in decline at the same time that the private seed industry has grown at a staggering rate. With the advent of biotechnology in the 1990s, private seed companies began investing heavily in research and development, surpassing the amount spent in all other agricultural input sectors (Fuglie et al., 2011). By 2010, expenditures in seed and biotechnology research alone accounted for 45% of total private agricultural input investment (Fuglie et al., 2011). This emphasis on research and development has been profitable for the private seed industry, with the value of the global seed market estimated at $47 billion in 2012 (McNabb, 2013).

This growth is particularly remarkable given that recouping full research investments through seed sales is inherently difficult. As a living biological organism, planting a seed does not use it up. Instead, the seed will naturally reproduce itself, and at an exponential rate (one corn seed kernel will produce an ear with upwards of 300 kernels). With no assurance that a farmer will purchase new seed each year, private seed companies are likely to underinvest in research and product development – a classic case of market failure. Intellectual property rights (IPR) provide one remedy for this situation; and both biological and legal forms of IPR have been used to spur the growth of the seed sector. These include development of hybrid cultivars beginning in the 1920s, passage of the Plant Patent Act (PPA) of 1930 and the expanded Plant Variety Protection Act (PVPA) of 1970, the 1980 U.S. Supreme Court decision in *Diamond v. Chakrabarty* which ruled that living things are patentable subject matter, and finally the 2001 decision in *J.E.M. Ag Supply, Inc. v. Pioneer Hi-Bred International* to allow the granting of utility patents for plants in conjunction with PPA and PVPA. These events have increasingly limited the ability of farmers and industry competitors to save, replant, and sell seeds (see Kloppenburg, 2004 for a thorough history and analysis of the commodification of seed).

In addition, Fuglie and Toole (2014) suggest that the advances in recombinant DNA that led to GE varieties further incentivized significant private investment. This technology, in conjunction with strengthened IPR, allows seed companies to apply for utility patents on a new variety, the specific GE traits it contains, as well as the processes by which the traits are integrated. A single GE variety can incorporate as many as 40 different technologies, as in the now-famous case of GoldenRice^{TM}, with an accompanying licensing fee for each patent (Kryder et al., 2000). Monsanto, the industry leader, earned $11.7 billion in 2009 through seed sales and licensing of its GE traits to hundreds of firms, including its main competitors (The Economist, 2009). High licensing fees are ultimately passed on to the farmer, with seed costs that increased by approximately 50% (adjusted for inflation) for corn and soybeans between 2001 and 2010 (Fernandez-Cornejo et al., 2014).

Farmers now have fewer and fewer options in the marketplace as the private industry continues to consolidate at an alarming rate. Since 1996, at least 200 independent seed companies have been lost through mergers, acquisitions, and closures (Hubbard, 2009). By 2011, six firms (Monsanto, DuPont, Syngenta, Bayer, Dow and BASF) controlled an estimated 60% of the global proprietary seed market (Howard, 2015). At the time of this publication in 2016, federal anti-trust regulators are considering the approval of ChemChina's purchase of Syngenta, a joint merger between DuPont and Dow, and Bayer's acquisition of Monsanto. As the monopolistic power of the private industry grows, the varietal needs of farmers based outside of major production areas, once served by small regional seed companies, goes unmet.

The economic strength of the private seed industry begs the question of the role of public plant breeders in developing finished cultivars. According to the classic model of research policy espoused by President Franklin Roosevelt's science advisor Vanevar Bush (1960), upstream basic scientific investigations leads to downstream technological advancements, and allows for separate yet complementary roles for public and private research. For example, a public breeder might screen exotic germplasm for a particular disease resistance, and then transfer the resulting improved material to a private breeder for introgression into a commercially viable finished variety. Critics have argued that this concept of a linear flow between basic science and applied technology is not nearly so distinct, and that assessing whether or not public and private sector research investments complement or compete with one another depends on the particular industry in question (Fuglie and Toole, 2014). In the case of the private seed sector, research investments are directed towards a few high value conventional crops such as corn, soybeans, and cotton (King et al., 2012). Even with strengthened IPR, minimal private money is spent on developing finished varieties of crops with lower economic returns, such as some small grains, perennial forages, and some vegetables. These crops may generate less revenue because the seed is readily saved and replanted by farmers, the crop is not easily transformed with genetic engineering, the value of the seed crop is minimal, or an unfavorable ratio exists between the cost of seed production and the market value of the seed. Maintaining a resilient agricultural system requires a diversity of crop varieties and public plant breeders are well suited to address this public good by developing improved cultivars of underutilized species.

Griliches (1958: 430) suggests that "to establish a case for public investment one must show that, in an area where social returns are high, private returns, because of the nature of the invention or of the relevant institutions, are not high enough relative to other private alternatives." Breeding varieties for organic agriculture fits this description well, as the opportunity costs for a company catering to organic farmers are high in comparison to revenue generated by the conventional seed sector. Organic agriculture produces positive social outcomes by reducing some negative impacts of conventional farming practices. Numerous studies have shown that organic agriculture enhances plant and animal biodiversity, increases soil organic matter, and lowers soil nutrient runoff (Bengtsson et al., 2005; Gomiero et al., 2011; Nemecek et al., 2011; Tuomisto et al., 2012). Enabling more farmers to incorporate organic practices, however, requires developing new organic varieties of crops and vegetables. A private organic seed sector does exist, but it is not sufficient to meet this need. Most seed companies catering to organic farmers tend to identify and sell varieties that, even though conventionally bred, will perform adequately in organic production systems. Fewer companies are breeding new varieties specifically adapted for organics. As the executive summary of the 2011 State of Organic Seed Report states, "challenges and needs loom large for expanding organic seed systems" (Dillon and Hubbard, 2011).

This underinvestment is understandable, given that less than 1% of total farmland in the US is certified organic (USDA, 2013). The small market limits the organic seed industry's growth potential, and limits the ability of individual companies to make sizeable investments in developing improved varieties for organic farmers. Yet even as the organic industry grows, other self-imposed limitations will further prevent the level of growth observed in the conventional private seed industry. While the organic seed industry does utilize some IPR strategies to recover research investments, such as hybrid seeds and PVPA certificates, the use of utility patents on organic varieties is not common. Utility patents for GE varieties enables high profit margins through restrictive licensing, but the prohibition of GE varieties for organic certification eliminates this income stream for the organic seed sector.

Perhaps more significantly, the organic community tends to view all forms of IPR critically, as there is a strong sentiment that seed is a common resource that should be shared collectively, rather than individually owned. Pervasive use of IPR by a company catering to organic growers may result in fewer customer sales, as the quality of a product is not always as important as the philosophy behind it. For example, the majority of Fedco Seeds customers, a company that has been providing seeds to organic growers since 1978, voted to drop all Seminis vegetable varieties from the Fedco seed catalog when Seminis was acquired by Monsanto in 2005 (Trueman, 2009). While replacing the gaps left by the Seminis varieties was a challenge for the small seed company, Fedco sales doubled in the two years following their decision (Trueman, 2009). On the other hand, there is a willingness to experiment with new distribution models, as is demonstrated by the 2014 release of vegetable and crop varieties with an "Open Source Seed Pledge" that encourages growers to use the varieties in any way they like, as long as they do not protect the varieties (or their derivatives) with patents or restrictive licenses. Of the initial 27 varieties released by small seed companies and public breeders with this pledge, 22 of the varieties were certified organic.

Public plant breeders can play a crucial role in supporting the growth of the organic seed sector in the face of these private economic constraints. With funding from federal and state governments, public plant breeders are not bound by the profit incentives of the private sector. Instead, they are able to focus on issues of food security, sustainability, public service, and education (Tracy, 2004). Breeding for organic agriculture addresses these goals by supporting a more environmentally sustainable farming system that can produce food that is higher in antioxidants and lower in chemical residues (Baranksi et al., 2014). Public breeders have the flexibility to engage with organic farmers collaboratively, as equal partners in the breeding process, rather than as end consumers of their work. The new varieties that emerge from this breeding methodology help to increase the feasibility of farming more acres organically. The value of this work is rooted in its contribution to the public good, rather than its economic influence on a corporation's bottom line.

Breeding for organic agriculture has opened up new avenues of funding that public plant breeders can access to support PPB. An increasing amount of public grant programs are being earmarked for organic research as a result of tireless work of organic policy advocates. The State of Organic Seed Report, 2016 shows that federal and state agencies have contributed more than $28 million to organic plant breeding and other organic seed initiatives from 1996 - 2018, with the largest funding source coming from the USDA - National Institute of Food and Agriculture's (NIFA) Organic Agriculture Research and Extension Initiative (OREI)

(Hubbard and Zystro, 2016). In addition, new funding streams from private foundations are increasing, such as the Seed Matters graduate student fellowships sponsored by the Clif Bar Family Foundation, as well as breeding grants from the Organic Farming Research Foundation (OFRF) and the Ceres Trust. Many of the government and non-profit requests for proposals specifically encourage projects that incorporate PPB and PVS (Hubbard and Zystro, 2016). Clif Bar & Company and Organic Valley, two organic food companies, have recently committed $1 million to establish the first endowed chair at a public university in the US to focus on plant breeding for organic crops. These grants alone are not enough to totally revive public breeding in the United States, as longer-term funding is still required to adequately support breeding projects that can take 7–10 years to reach fruition (Mendum and Glenna, 2010). In addition, breeding for organic systems can require increased research budgets in order to cover labor costs for weed management in breeding nurseries and trial locations. Yet by emphasizing the role that public breeders can play in promoting more sustainable agricultural models, this may help to leverage larger funding streams in the future.

Conclusion

Plant breeding impacts people and societies because it determines the course of our agricultural future. Without appropriate varieties that are relevant for their particular farming systems, farmers cannot be successful and consumers suffer from either price increases or lack of food availability, or both. PPB is a useful methodology that has enabled breeders and farmers in the developing world to create varieties adapted to the marginal conditions of many subsistence farms. PPB accomplishes this by taking advantage of G x E interaction, and selecting varieties directly in the environment of their intended use in order to achieve superior performance. Farmer participation is a crucial aspect of the methodology, as the farmer is best equipped to recognize the agronomic and quality traits that will enable the variety to be productive in his or her system.

As organic farming in the US has grown from outsider status to a more mainstream position in the agricultural sector, awareness of the need for organically adapted varieties has also grown. The quantitative genetic selection theory that supports PPB as a useful methodology for small-scale farmers in the developing world applies similarly to organic farmers in the US, whose growing conditions vary significantly from conventional production, where most crop and vegetable varieties are currently bred. In addition, farmers do not need formal training in quantitative genetic theory to actively contribute to PPB.

Organic agriculture and PPB share other important synergies as well. The history of the organic farming movement is one of farmer engagement in both the biological innovations necessary to cultivate a productive agroecological farming system and the political processes required to get official USDA recognition and support. Thus, farmer participation in breeding new varieties adapted for organic systems has strong cultural relevance within this community. Likewise, responding to the needs of farmers who are otherwise not being served by the conventional seed sector is a critical responsibility of public plant breeders. This partnership may have been highly unlikely in the early years of the organic movement but new attitudes of collaboration among organic farmers and public agricultural researchers, coupled with new funding streams, are much more prevalent today. Innovative models of sustainable farming are required as agriculture confronts the pressing issues of climate change, an increasing global population, shrinking land availability, and limited natural resources. Organic agriculture continues to be one of the best examples of a viable alternative, with PPB offering a robust method for developing the improved varieties required for future growth of this sector.

Abbreviations

CGIAR	Consultative Group of International Agricultural Research
CIAT	International Center for Tropical Agriculture
CIP	International Potato Center
CSA	Community supported agriculture
GE	Genetically engineered
G x E	Genotype by environment
ICARDA	International Center for Agricultural Research in the Dry Areas
IDRC	International Development Research Center
IPR	Intellectual property rights
IRRI	International Rice Research Institute
LGU	Land-grant university
LISA	Low Input Sustainable Agriculture
NIFA	National Institute of Food and Agriculture
NOP	National Organic Program
NOSB	National Organic Standards Board
OFRF	Organic Farming Research Foundation
OP	Open-pollinated

OREI	Organic Agriculture Research and Extension Initiative
PPA	Plant Patent Act
PPB	Participatory plant breeding
PRGA	Participatory research and gender analysis
PVPA	Plant Variety Protection Act
PVS	Participatory varietal selection
SARE	Sustainable Agriculture Research and Education
US	United States of America
USDA	United States Department of Agriculture

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Contributions

- Contributed to conception and design: ACS, WFT
- Contributed to literature review and analysis: ACS, WFT
- Drafted and/or revised the article: ACS
- Approved the submitted version for publication: ACS, WFT

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Competing interests

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