Journal of Agriculture, Food Systems, and Community Development
ISSN: 2152-0801 online
https://foodsystemsjournal.org

Special Section:
Fostering Socially and Ecologically Resilient Food and Farm Systems Through Research Networks

SPECIAL SECTION SPONSORED BY:

Participatory breeding in organic systems: Experiences from maize case studies in the United States

Christopher Mujjabi,[a] Martin O. Bohn,[b] *
Michelle M. Wander,[c] and Carmen M. Ugarte [d] *
University of Illinois at Urbana-Champaign

Submitted August 27, 2023 / Revised November 21, 2023, and January 8, 2024 / Accepted January 8, 2024 / Published online March 6, 2024

Citation: Mujjabi, C., Bohn, M. O., Wander, M. M., & Ugarte, C. M. (2024). Participatory breeding in organic systems: Experiences from maize case studies in the United States. *Journal of Agriculture, Food Systems, and Community Development*, *13*(2), 23–36. https://doi.org/10.5304/jafscd.2024.132.008

Abstract
Participatory breeding and crop selection can satisfy the needs of underserved groups of farmers (e.g., organic producers, farmers producing specialty grain for niche markets) neglected by the modern global seed industry. Participatory research methods that value local knowledge and facilitate the active involvement of producers, researchers, and other actors involved in the agri-food system are tactics that can help us achieve sustainable agriculture. Interest in the use of participatory methods to increase the value of U.S. land-grant universities to society has grown rapidly during the last decade.

[a] Christopher Mujjabi, Graduate Research Assistant-Maize Breeding and Genetics, Department of Crop Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

[b] * *Corresponding author:* Martin O. Bohn, Associate Professor-Maize Breeding and Genetics, Department of Crop Sciences, University of Illinois at Urbana-Champaign; 1102 S. Goodwin Ave. MC-046; Urbana, IL 61801 USA; mbohn@illinois.edu

[c] Michelle M. Wander, Professor-Soil Fertility/Ecology, Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

[d] * *Corresponding author:* Carmen M. Ugarte, Assistant Professor-Soil Ecology, Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign; 1102 S. Goodwin Ave. MC-047; Urbana, IL 61801 USA; cugarte@illinois.edu

Author Note
Portions of this manuscript were included in Christopher Mujjabi's master's of science thesis (Mujjabi, 2022)

Funding Disclosure
Financial support for this work was provided by the USDA National Institute for Food and Agriculture (USDA-NIFA) through award No: 2017-51300-27115.

Development of the JAFSCD special section in which this article appears, "Fostering Socially and Ecologically Resilient Food and Farm Systems Through Research Networks," was sponsored by INFAS and eOrganic and supported in part by the U.S. Department of Agriculture, National Institute of Food and Agriculture, through the Organic Agriculture Research and Education Initiative, Grant # 2017-51300-27115.

Interest includes re-engagement in the development of maize hybrids that perform well in a diverse range of heterogeneous growing environments and that are better suited for sustainability-minded producers, buyers, and consumers. Systems-based breeding aimed at protecting the environment and providing food, fiber, and energy while considering equity issues, has been proposed as a way to overcome the shortcomings of privatized approaches. In this article, we consider recent projects that use collaborative methods for hybrid maize breeding, cultivar testing, and genetic research to develop, identify, and deliver traits associated with crop performance, quality, and sustainability. Three case studies consider the efforts focused on developing non-GMO varieties for organic and specialty markets. We find that, unlike many successful efforts focused on the improvement of other crops, there are few promising models for participatory breeding of hybrid maize. Even though many projects have sought to involve stakeholders with a variety of methods, all have struggled to meaningfully engage farmers in maize hybrid improvement. Still, our reflection of case studies calls for systems-based breeding and suggests a path forward. This route would seek to address the needs, perspectives, and values of a broader range of actors participating in the food system by leveraging technologies and infrastructure in service of the public. Land-grant universities are well positioned to play a crucial role in coordinating efforts, facilitating partnerships, and supporting breeding programs that satisfy societal wants that include health, equity, and care.

Keywords
participatory research methods, hybrid maize, participatory breeding, organic systems, land-grant universities

Introduction

Participatory plant breeding (PPB) is an inclusive and decentralized approach to cultivar development in which farmers, breeders, and other stakeholders in the value chain collaborate to advance sustainable agriculture and promote the adoption of technology by underserved groups (Colley et al., 2022). This approach assumes that the likelihood of generating useful outcomes is increased when all participants in the value chain play an active role in decision-making (Swanson et al., 1998). Participatory efforts focused on crop breeding emerged in the 1980s as a response to the limitations of centralized research programs that developed following the Green Revolution and that failed to address the needs of resource-poor farmers in countries of the Global South (Ashby, 2009). The concentration of breeding efforts within a few private companies might result in the neglect of small markets and farmers who employ alternative production methods that are suited to their growing environments, resource availability, and philosophies of management (Endres et al., 2022). Centralized breeding models develop and evaluate germplasm using controlled experiments at research stations where breeders select materials that excel under conditions favorable for high-yielding cultivars. In the later stages of a breeding program, promising varieties are tested in numerous locations in the targeted growing environments. To accurately identify elite varieties and subsequently maximize genetic gain, breeders strive to create on-station conditions that closely resemble the target environment (Dawson et al., 2008). Accordingly, the centralized breeding model is most effective in industrialized production systems that are managed in regions with optimal fertility inputs, and that use seed and herbicide treatments to reduce disease and weed pressure (Murphy et al., 2007). This approach is less successful in organic farms where management practices and on-farm environments typically vary more widely (Seufert & Ramankutty, 2017).

The objectives of PPB include developing crop varieties that meet farmers' needs (e.g., possess desirable food or feed grain characteristics, compatible with their management practices and farming conditions) while promoting crop genetic diversity by developing germplasm suitable for different micro-environments and empowering farmers to understand and participate actively in the breeding process (Thro & Spillane, 2000). The PPB model is assumed to be most effective for enhancing crops intended for small, localized niche markets. The production for these markets often features highly variable, sometimes marginal soil environments that can amplify genotype-by-environment interactions (Morris & Bellon, 2004). Plant breeders commonly use participatory methods in countries where farming systems are typically managed with low inputs, the growing environments are heterogeneous, crop and soil management are less mechanized and more diverse, and the adoption of modern crop varieties may be low to negligible (Walker, 2006). Involving farmers in the direct selection of varieties well adapted to these diverse and often marginal target environments might also reveal the crop traits that are important to participants. This approach to breeding should also be well suited to alternative agriculture systems in the Global North, where diversity and complexity of management practices are considered to be the main challenges for crop improvement (Bhargava & Srivastava, 2019; Dawson et al., 2008). This approach may work well for organic corn grain production operations in the U.S. Midwest, where farmers use a wider range of agronomic management practices than their counterparts who use conventional practices (Ugarte et al., 2018).

At present, the majority of the organic maize acreage in the U.S. is planted with certified organic seeds and less than one-third with conventionally produced untreated non-GMO seeds (Endres et al., 2022). The U.S. Department of Agriculture's National Organic Program allows the use of untreated non-GMO seeds when comparable organically produced are unavailable. Both sources of hybrid seed rely primarily on parental inbred lines developed and tested in fields using conventional management practices (e.g., high inorganic nitrogen [N], herbicides, seed treatments) that are not representative of organic farming systems. Furthermore, the privatization and concentration of the conventional maize seed industry, the associated capture of elite genetics by this industry (IPES-Food, 2017), and the relatively high labor needs leading to the greater costs of organic seed production are thought to be major barriers to hybrid improvement and seed production for the organic maize sector (Endres et al., 2022). Loss of maize genetic diversity grown in farmer fields is most prominent in markets like the U.S., where hybrids replaced maize landraces and open-pollinated varieties (OPVs) by 1950. Seed collections like the USDA Agricultural Research Service (USDA ARS) North Central Regional Plant Introduction Station in Ames, Iowa, retain a significant portion of these genetic materials for public use, whereas commercial hybrids and their inbred line components are developed and owned by the private sector by utilizing federal plant variety protection and patent laws. The hybrid breeding and seed production pipeline has matured into a formalized seed system that is now global and promotes the use of modern technologies, including genetically modified maize cultivars, the application of genome editing and doubled haploids to speed up the breeding process, as well as inputs that are easier to produce and control (Brush, 2004, p. 277; Khoury et al., 2022; Robinson, 2018). This continued consolidation of the seed sector, in which the top ten breeding companies and seed suppliers hold 65.4% of the global market share (Howard, 2009), restricts the selection of genetically diverse corn hybrids. This limited choice may hinder the success of organic and other alternative farmers who require a more diverse catalogue of hybrids that can perform well across a wider spectrum of environmental conditions and management practices.

Collaborative networks that re-engage public-sector scientists with independent breeders and other participants in the agri-food system might accelerate the development of regionally adapted cultivars. This approach would not only contribute to genetic diversity and crop performance but also help involve farmers from diverse backgrounds and with varied philosophies of management (Adam, 2005; Luby et al., 2018). Ashby (2009) identified five levels of participation (conventional, consultative, collaborative, collegial interactions, and farmer experimentation) used by collaborative networks based on how decision-making is shared and whether new knowledge is co-produced by breeders and farmers. The conventional participation category suggests there is no organized communication between breeders and farmers regarding the establishment of breeding objectives or selection of suitable germplasm. Researchers using consultative participation do solicit farmers' opinions and preferences via one-way communication, but these views may or may not influence decision-making or objective-setting. Collaborative participation refers to the implementation of structured methods that encourage mutual communication between breeders and farmers, ensuring joint authority in decision-making. Collegial participation arises when a group of farmers, in structured communication with breeders, makes breeding decisions autonomously, not always considering the breeders' input. Finally, in farmer experimentation, breeding decisions are collectively made by farmers without any structured input from breeders (Ashby, 2009). While other nomenclatures could be used and adapted, versions of all of these classes exist in participatory research; however, a detailed review is beyond the scope of this article.

Most efforts identified as PPB (or participatory variety selection or testing) vary based on the degree and timing of farmers' participation in the breeding work, that is, creating genetically diverse breeding populations, as well as selecting and testing new cultivars (Ashby, 2009; Walker, 2006). In PPB programs, local knowledge is recognized, and farmers' engagement is high as they actively select parental germplasm based on their traits of preference, make crosses to generate segregating breeding populations, and select genotypes with desirable traits from a range of materials to test in farmers' fields and under a particular range of growing conditions (Joshi & Witcombe, 1998; Walker, 2006). The extent of farmer participation in this breeding process varies based on the desired cultivar type (e.g., line cultivars, open-pollinated varieties, or hybrids). Breeding inbred varieties of wheat, barley, oats, and soybean, or the more genetically diverse open-pollinated varieties in maize, is less complex and requires fewer inputs than the process to develop hybrid cultivars. Other projects outside the U.S. that pertain to PPB for maize typically apply mass selection protocols (Mendes-Moreira et al., 2017). These are technically less demanding than the breeding methods used in hybrid cultivar development. However, selection response from mass selection (i.e., selecting ears from an open-pollinated variety post-harvest) is slow in outcrossing species like maize, aimed at improving key quantitative traits such as grain yield, nutritional grain composition, and tolerance to abiotic and biotic stresses. Progeny testing approaches using recurrent selection methods improve the selection response, but they require more time, resources, and training. In general, the improvement is incremental from one selection cycle to the next. Developing hybrid cultivars necessitates maintaining and enhancing different heterotic groups simultaneously and using a reciprocal recurrent selection approach for the targeted exploitation of heterosis. This usually falls beyond farmers' areas of interest or expertise, which probably prevents networks working with hybrid maize from succeeding beyond niche markets. Coordinating networks for the organic sector or other communities neglected by the commercial seed industry poses a significant challenge for conventional breeding programs focused on developing hybrids that succeed in multiple environments (Ceccarelli & Grando, 2020). Re-entry of the public sector into maize breeding may provide a way to offset the greater costs and complexity of hybrid development, as proposed by Gerpacio (2003).

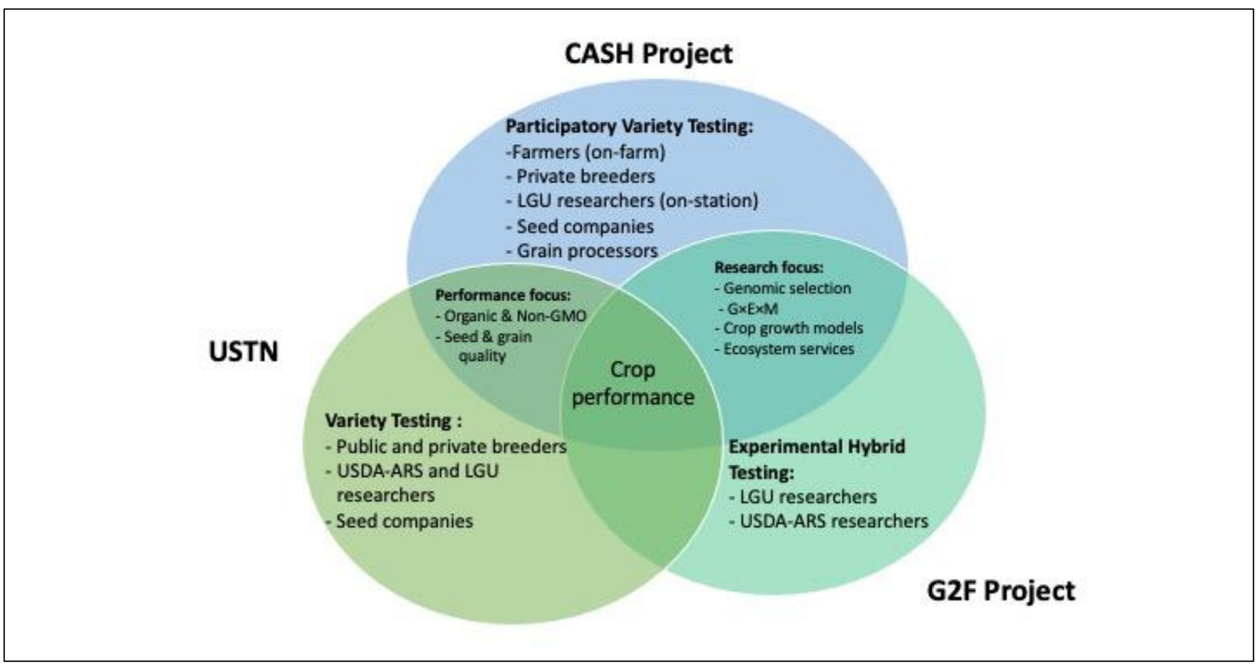
Prior to the 1960s, plant breeding in the U.S. was managed largely by public breeders at 1862 land-grant universities (1862 LGUs) that have traditionally received a greater proportion of resources compared to non-1862 institutions. As the demand for maize produced in more environmentally friendly and equitable agroecosystems grows, recognizing and integrating the needs identified by researchers serving across all LGUs, minority-serving institutions, and federal institutions (such as the USDA ARS and USDA Economic Research Service [USDA ERS]) become crucial (Brzozowski et al., 2022). Ganning et al. (2012) highlighted the potential of LGUs to serve as "regional resources for a new era of agricultural development" (p. 493) particularly through community-university partnerships that emphasize inclusive and sustainable agricultural practices. The recent trends toward the development of a more resilient food system that use sustainable production practices has brought renewed focus to the leadership that can be generated from within LGUs (Brzozowski et al., 2022; Lyon et al., 2021; Shelton & Tracy, 2016). We recognize that disparities among LGUs exist, but the adoption of inclusive approaches can rejuvenate public research and development, begin to address historic structural inequities (Partridge, 2023) and be integral in shaping resilient, equitable, and sustainable food systems.

Despite our optimism about publicly supported research networks, we note that few scholarly inquiries have considered when and why project outcomes from participatory efforts focused on knowledge co-creation and system change often fall short of goals (Turnhout et al., 2020). A recent systematic review identified the recognition of contextual diversity of participants, preemptive and intentional engagement of knowledge-holders, formation of shared understanding of project goals, and empowerment of actors, as the core components of collaborative research networks (Zurba et al., 2022). The recent review by Colley et al. (2021) of participatory plant breeding methods in the U.S. reported only one example of maize breeding using participatory methods. That effort did include researchers at an LGU (the University of Wisconsin) and was focused on sweet corn. While the number of participants was limited, the project was motivated by farmer interest. Despite this, the sustained engagement of farmers in the breeding process was challenging due to the long-term commitment required for recurrent selection and reliance on winter nurseries. While sweet corn seed production and sales might be less centralized and serve a broader spectrum of markets, these barriers to participation are equally or even more pertinent to farmers interested in enhancing field maize seed. In this reflective essay, we introduce three case-study projects that use collaborative networks for hybrid maize breeding and cultivar development in the U.S. with the goal of identifying strategies for systems-based breeding that meet the broad organic goals of health, wellness, and care, and contribute to sustainability by protecting the environment and providing food, fiber, and energy (Chable et al., 2020; Lammerts van Bueren et al., 2018).

Projects Using Participatory Methods in the U.S.

In this work, we considered case studies (Figure 1) that were started within the last 10 years in the U.S. to address the needs of farmers neglected by the dominant hybrid model for commercial maize cultivar development and seed production. To our knowledge, these are the only collaborative projects in the grain sector dedicated to field maize. The projects are arranged in descending order based on the level of farmer involvement and their potential to satisfy the systems-based breeding objectives listed in Table 1. Reflection and analysis were based on reports available in the literature, presen-

Figure 1. Key Characteristics, Goals, and Outputs of Three Projects Working to Develop Maize Seed that Satisfy the Needs of Organic or Non-GMO Markets



tations at relevant conferences (including the Organic Seed Growers Conference and the American Seed Trade Association), and project reports available online. Our team was actively involved in the Corn and Soil Health (CASH) project; therefore, more information is available for this specific case study.

The Corn and Soil Health Project (CASH)

The CASH effort evaluated experimental maize hybrids using a participatory selection model for organic systems. Beginning in 2018, a group of researchers at the University of Illinois worked with a diverse group of stakeholders in the food industry to foster transdisciplinary research that evaluated maize hybrids for their agronomic potential and prospects to make contributions to a broader range of ecosystem services. Efforts included a participatory on-farm testing network and a participatory educational network. The goal of the on-farm testing network was to gather information regarding the various strategies that culti-

Table 1. Projects Using Participatory Variety Testing Methods for Grain Maize in the United States

	Corn and Soil Health (CASH)	United States Testing Network (USTN)	Genome to Field Project (G2F)
Project duration	2017–2022	2009–2019	2013–present
Levels of participation	Collaborative with a participatory variety testing model	Consultative with farmers and with a variety testing model	Collaborative between scientists and using a variety testing model
Participating actors	Farmers, seed retailers, food processors, public and private breeders, soil scientists, agricultural economists	Public and private plant breeders, nonprofit project managers	Crop scientists, engineers, and computational scientists
Lead institutions	University of Illinois	Practical Farmers of Iowa	University of Wisconsin
Testing sites	All certified organic fields. 43 field plots across three states in organically managed land (WI, IL, and IN)	Mostly conventional management and a few certified organic fields. 53 field plots (10 certified organic) across 6 states (NE, IA, WI, OH, NY, MD)	180,000 field plots at LGUs/USDA-ARS managed experimental stations using conventional production practices and across 16 states (CO, NE, TX, MN, IA, MO, WI, IL, IN, MI, OH, GA, NY, DE, NC, SC)
Weather and management information	Weather data collected from regional weather stations, rotation details including crop sequence, rate and type of fertility amendments, frequency and intensity of tillage	None collected (or shared publicly)	Weather data collected from stations installed at each field plot, previous crop, pre-plant tillage and in-season tillage methods, irrigation information
Agronomic traits	Stand count, plant height, ear height, test weight, kernel weight, moisture content, grain yield	Stand count, root lodge, stalk lodge, green snap, plant height, ear height, pollen date, silk date, test weight, moisture content, grain yield	Stand count, root lodging, stalk lodging, days to silking/anthesis, plant height, grain moisture, test weight, grain yield
Ecosystem services traits	Organic seed; soil traits related to soil fertility; soil biological activity; nutrient cycling, and soil organic carbon; plant beneficial microbes, functional genomics of rhizosphere microbiome	Non-GMO traits may serve as proxy of ecosystem services	Soil traits related to soil fertility; genomic sequencing for all inbreds
Grain quality traits	Grain protein, starch, and oil content, aminoacid content, antioxidant content	N/A	N/A

vars use to cope with diverse environments and how crop cultivars respond to specific farming practices as well as biotic (e.g., pests, diseases, competition against weeds) and abiotic (e.g., cold, hot, dry, wet growing conditions, nutrient deficiency) stresses (Table 1). Between 2018 and 2021, the researchers worked with 24 farmer collaborators to assess maize hybrids in 15 fields in Illinois, 10 in Indiana, and 18 in Wisconsin. Gaining a deeper understanding of the cultivars' potential to respond to inputs and stresses is the first step to efficiently improving crop productivity in complex organic farming systems. For this, researchers maintained regular communication with the participating farmers and developed, with farmer input, a detailed manual that identified goals and methods for on-farm phenotypic evaluation of hybrids. Student researchers collected supplementary data to assess additional project objectives. The team of researchers met with participating farmers each year to adapt a standard planting plan to accommodate farmers' equipment and interests, as well as to identify a field that fit the rotation characteristics and that would be planted into maize. The winter before planting, researchers shared information on a selected set of hybrids available for testing based on known agronomic traits. Farmers generally selected cultivars based on their market outlets, with farmers in Wisconsin choosing maize with greater lysine and methionine contents suited for the dairy and poultry feed industry, and collaborators in Illinois and Indiana favoring food-grade cultivars with high carbohydrate contents suited for cereal and bread-making.

During in-person interviews and subsequent discussions, farmers provided details about their organic farming practices used at least three years before the testing period to satisfy the requirements for organic certification. A summury of documented management practices is in Table 1. The range of management used by participating farmers was representative of the diverse practices used in organic grain production systems in the region. For the purposes of our work, each field location was treated as a single replicate. Detailed site and soils information was collected and used to prepare yearly, personalized reports that were shared with farmers during one-on-one and group meetings. Their feedback informed activities in subsequent years. Reports included information about the yield performance of each tested hybrid in comparison with the average of all testing sites, as well as information about soil quality and related soil health contributions to ecosystem services like nutrient cycling and climate mitigation achieved by increasing soil organic matter reserves. This two-way exchange let farmers and researchers from the University of Illinois share their opinions about the hybrids and details about on-farm realities like stand establishment and management that might have influenced results. Overall, this effort evaluated germplasm developed by three breeding programs under a wide range of selective pressures introduced by an even wider range of management practices and environmental conditions.

While participating farmers were eager to share their views, time constraints limited their ability and interest in participating in plot maintenance or phenotypic evaluations. Similar experiences have been observed in participatory breeding efforts in the Global South (van Etten et al., 2019) and echo findings of Colley et al. (2021) suggesting that farmers may not want to participate directly in the breeding process. After two years of testing, we reduced our expectations for field engagement and asked farmers only to help plant, cultivate for weed control, and, in a few cases, harvest the trial when equipment was available. The shift in responsibilities transformed the network from collaborative to consultative, heightening the researchers' workload and control over data. This kind of modification of roles is common during the implementation phase of participatory research projects as members seek to build capacity (Cargo & Mercer, 2008). This change added logistical hurdles for a small team of students and research assistants that needed to visit farm fields distributed throughout the region at specific crop growth stages. Additionally, turnover in network facilitation personnel added to the challenges faced by students scheduling these visits, but also added value by increasing their interactions with and understanding of farmer cooperators. Farmers who were in the testing network also engaged through an educational network that linked them and other interested farmers with food processors and grain buyers (including restaurant owners), as well as crop breeders and agronomists to explore opportunities for producing maize with value-added traits. Some members of the participatory educational network were farmers who hoped to have greater control over their seed or market aspirations that were incompatible with the hybrids we offered for testing. Farmers who produce for niche markets generally save their seed and prefer to use OPVs. This group may be much more willing to regain the skills, e.g., conducting on-farm selection and seed processing, needed to translate phenotypic characteristics into meaningful indicators of yield, quality, insect resistance, and aesthetics. Other participants included farmers who normally produce white maize for the food industry and were worried about cross pollination with yellow dent maize from our trials. These are cases when farmers chose to opt out of the on-farm testing network but remained involved and interested in project results.

As the project team refined and clarified its goals, it acknowledged pluralism in wants and disparities in power that affect the efficacy of participatory efforts (Turnhout et al., 2020). We conducted a participatory maize-based case study by coupling educational efforts with on-farm comparisons of maize varieties using an iterative process that included a series of focus groups, workshops, and consultations to understand the perceptions of seed quality and to better tailor the activities of the network to suit their needs. Some farmers expressed doubts about the value of participatory data collection and sharing and expressed concerns about the amount of time it would take to identify locally adapted varieties. And while there was a consensus that widening breeding objectives to improve societal well-being was needed, farmers did not see themselves as central actors in this venture (Endres et al., 2022). Most farmers interested in modern hybrids expressed little interest in regaining the breeding and selection skills that were required in the 1930s, when farmers in the Midwest actively partnered with LGUs to improve corn varieties (Fitzgerald, 1993). We envision that instead of 'de-skilling' farmers and making them reliant on experts to understand grain performance, as suggested by Fitzgerald (1993), participatory breeding could empower them while liberating them from the painstaking work of breeding. Farmers and breeders engaged in the network identified privatized testing networks as a tactic that could lower transaction costs enough to provide real value.

U.S. Testing Network (USTN)

Between 2009 and 2020, the USTN served as a prime example of a privatized network. It rigorously tested maize seed for organic and non-GMO markets in the U.S. This effort facilitated exchanges among public and private breeders, farmers, and independent seed companies (Carlson, 2012).The members of the USTN were breeding companies, public breeders at the USDA ARS and LGUs, farmers, and seed producers (Figure 1). The effort was consultative and was coordinated by the Practical Farmers of Iowa, a nonprofit organization founded in 1985 to facilitate effective cooperation between farmers, extension services, and university researchers. Based on participants' interests collected during annual meetings, the USTN efforts broadened to test hybrids chosen for specific maize quality traits. These traits encompassed characteristics such as high lysine and methionine content; both amino acids are sought after by the poultry feed industry. Other traits included specialty grain colors required by the food industry. By 2018, the USTN provided an infrastructure of 53 testing sites, 12 of which were organically managed and distributed across 10 states (Table 1).

This network allowed for simultaneous testing across a wide range of growing environments that encompassed early, medium, and late relative maturity zones. The USTN gathered more agronomic trait data than the CASH project and shared averaged hybrid performance results across experimental sites publicly via the USTN Practical Farmers of Iowa website. Information about the experimental design and management practices used at the various testing sites were only available to USTN members (Table 1; Goldstein et al., 2012). This fact, and the absence of individual plot, site, or environmental data, as well as the methods used to engage farmers in data collection, prevent any comprehensive analysis of site-specific interactions between crop genetics, environments, and farm management. Despite their focus on value-added maize varieties, no data related to environmental outcomes or other ecosystem services were gathered. Reduced demand for the services provided by the USTN has been attributed to the relatively small number of maize breeders who devote their efforts to breeding for organic and non-GMO markets. This, and reduced levels of funding available for maintaining this type of infrastructure, ultimately contributed to the USTN's closure (Wilbeck & Carlson, 2018). Despite USTN's perceived compatibility with goals for hybrid development for stewardship-minded markets, and the fact it was organized in partnership with the farmers themselves, it failed to grow into the kind of diffuse seed system made up by small companies that Ceccarelli and Grando (2020) argue is needed for PPB to thrive. Failure to meaningfully engage farmers or other key stakeholders in the USTN network may explain why it was discontinued despite its compatibility with many breeders' preferences that seek farmer engagement through variety testing during the latter stages of the breeding process and across a wide range of environmental conditions (Ceccarelli & Grando, 2020). Although this approach of participatory variety selection or testing is considered easier to organize, requires fewer resources, and more rapidly identifies mature varieties suitable for seed production and distribution to farmers (Joshi & Witcombe, 1998), it is less participatory than PPB. Farmers have restricted ownership and influence over the materials they assess, and often lack the resources, both in terms of time and labor, to actively participate.

The Genome to Fields (G2F) Initiative

The third case study considers the Genome to Fields (G2F) collaborative network. Even though it does not currently include farmers' direct input into the effort., it does involve other important stakeholders, including plant breeders, geneticists, agronomists, and the regional and national maize growers associations that represent farmers across the U.S. Corn Belt. The research objectives of the G2F are more fundamental than those of CASH or USTN. The G2F aims to understand the functions of all genes in the maize genome across a broader range of environments, ultimately benefiting growers, consumers, and society (G2F Initiatives, 2017). It may provide a way for society to derive added value from the public funds used to sequence the maize genome. Initiated in 2013 with support from the Iowa Corn Growers Association (IowaCorn), the G2F represents collaborations in diverse environments and a wide variety of conventional management practices. Since 2014, more than 30 collaborators from academia and federal organizations across 15 states, from Texas to New York and Minnesota to Georgia, have planted thousands of yield trial plots, phenotyped hundreds of experimental hybrids based on agronomic traits, logged weather data for all fields, and provided soil and management data summarized in Table 1 (AlKhalifah et al., 2018). All these data, including the genetic information from all tested maize cultivars, is publicly available (G2F Initiative, 2017). This public-private collaboration supports initiatives funded by research-driven grants. The research projects under the ubrella of the G2F aim to deepen our understanding of plant-soil interactions, plant-soil-microbiome dynamics, and disease resistance. Additionally, they focus on pioneering engineering approaches to phenotyping, including the use of unmanned aerial vehicles (drones) and nitrogen sensors. All collaborators, stakeholders, and interested groups meet annually to report results, discuss research agendas, and consider new phenotyping (G2F Initiative, n.d.).

The addition of intentional mechanisms for including the participation of underserved and aspirational growers into the G2F could help reforge ties that were lost during the past half century. At present the advisory board of the G2F consists of academics from LGUs and the USDA ARS and a representative from the Iowa Corn Growers Association. While grower participation may not provide a formal tie to research, it certainly can and does influence the public research agenda. The G2F's current structure echoes the 1960s, when plant breeding was largely under the purview of public breeders at 1862 LGUs and USDA ARS. By strengthening partnerships among G2F members, including geneticists, agronomists, plant pathologists, food scientists, and statisticians, and bridging collaborations with LGUs, federal entities like USDA ARS and USDA ERS, and producers, the network is poised to cater to diverse stakeholder needs, from processors to consumers to citizens. This synergy holds the promise of pinpointing and promoting innovative maize hybrid traits. The greatest impact might result from the true regionalization and engagement of smaller and more distributed seed-producing efforts that meet the needs of regional markets and that contribute to harnessing genetic diversity. This vision is in line with recent proposals for more equitable public breeding programs led by LGUs and that amplify the needs and values of an ever-growing group of diverse stakeholders (Brzozowski et al., 2022). The growing demand for sustainable food systems has garnered significant attention from crop breeding programs at 1862 LGUs, as highlighted by Shelton and Tracy (2016). Looking ahead, we anticipate and advocate for these efforts to increasingly attract and integrate minority-serving institutions, enhancing the diversity and impact of these initiatives.

To improve the value of the G2F to farmers and markets interested in value-added traits that do more than signal intent, the range of farming systems and traits measured must be expanded. While only the CASH project sought to measure traits associated with social and environmental outcomes, the USTN relied on market-associated traits, such as non-GMO seed and high amino acid content, that might be useful proxies for desired environmental or health outcomes (Endres et al., 2022). The vast array of genetic data gathered by the G2F initiative can help the public and others to achieve social goals. This is equally relevant to breeders and others, whether they are interested in using classical or advanced breeding methods or developing a product for organic, non-GMO, regenerative, or standard markets. Projects and partnerships interested in pursuing opportunities can readily leverage G2F resources and protocols while working on securing competitive grants.

Synthesis and Conclusions

Given the limited amount of funds available to support publicly funded research and the significantly greater investment realized through the private sector, how do we serve farmers who want to have greater control over their seed and to use varieties with broad adaptation that could ensure yield stability even under extreme weather conditions? How do we overcome barriers to farmer participation in active breeding and selection during the growing season? According to Montenegro de Wit and Iles (2016), breeding strategies and technologies used to cultivate seeds that promote entrepreneurial approaches and business models gain credibility due to active involvement of the public and agroecologists in general.

While all three efforts described in this work focused on crop performance, which served as the primary objective, only the CASH project included active stakeholder participation. Both the G2F and USTN projects allowed testing of varieties and experimental hybrids across a wide geographical area. Different project priorities resulted in key differences in organizational structures and methods for stakeholder engagement. The CASH project's participatory variety testing model needed to better consider farmers' time and availability to ensure that demands for this effort did not represent a conflict with other farm operations during the growing season, as noted in other projects (such as Healy & Dawson, 2019). Only the CASH efforts asked farmers to evaluate the work undertaken by breeders and researchers and provide feedback. Farmers who remained engaged in the participatory educational network presumably found enough value to share their time and opinions. Determining how to sustain ongoing engagement that does not overburden participants is essential, as is providing them with a legitimate voice in decision-making.

The involvement of all institutions in the U.S. LGU system is essential to revitalizing public and private collaborations. LGUs have the capacity to direct the efficient use of resources like genomic sequence information generated in the G2F project while adopting some of the methodologies laid out in CASH to cater to the needs of diverse production systems. For instance, LGUs can coordinate the use of molecular methods compatible with the regulations in the National Organic Program and PPB methodologies to accelerate the entire breeding process (Ceccarelli et al., 2007). Efforts to integrate and build capacity and infrastructure at minority-serving institutions are crucial. These can steer major breeding efforts to address the needs and values of historically underserved producers. This can be further amplified if LGUs coordinate public-private partnerships in support of diverse and equitable breeding programs through grant funding. While funds obtained through competitive programs are typically available for durations shorter than regular breeding cycles, LGUs can provide leadership to ensure the continuity of funding. Models that establish partnerships for germplasm improvement and dissemination can engage and support small seed companies that produce seeds tailored to specific environments (López Noriega et al., 2013; USDA, 2022).

Acknowledgments

We would like to acknowledge Dr. Walter Goldstein for his efforts with farmer engagement in Wisconsin. We would also like to acknowledge Dr. Alice Formiga, leader of the eOrganic Community of Practice, for her contributions in the workshop we hosted at the Organic Seed Alliance conference and for facilitating access to the eOrganic insfrastructure needed for networking and engagement.

References

Adam, K. L. (2005). *Seed production and variety development for organic systems*. ATTRA. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=94700c8b5c06e992468997ac1677b234aef9f173

AlKhalifah, N., Campbell, D. A., Falcon, C. M., Gardiner, J. M., Miller, N. D., Romay, M. C., Walls, R., Walton, R., Yeh, C.-T., Bohn, M., Bubert, J., Buckler, E. S., Ciampitti, I., Flint-Garcia, S., Gore, M. A., Graham, C., Hirsch, C., Holland, J. B., Hooker, D., … Lawrence-Dill, C. J. (2018). Maize genomes to fields: 2014 and 2015 field season genotype, phenotype, environment, and inbred ear image datasets. *BMC Research Notes*, *11*, Article 452. https://doi.org/10.1186/s13104-018-3508-1

Ashby, J. A. (2009). The impact of participatory plant breeding. In S. Ceccarelli, E. P. Guimarães, & E. Weltzien (Eds.), *Plant breeding and farmer participation* (pp. 649–671). Food and Agriculture Organization of the United Nations (FAO). https://www.fao.org/3/i1070e/i1070e.pdf#page=662

Bhargava, A., & Srivastava, S. (2019). Advantages and cost of participatory plant breeding. In *Participatory plant breeding: Concept and applications* (pp. 87–107). Springer Singapore. https://doi.org/10.1007/978-981-13-7119-6_4

Brush, S. B. (2004). *Farmers' bounty: Locating crop diversity in the contemporary world* [Online ed.]. Yale Scholarship Online. https://doi.org/10.12987/yale/9780300100495.001.0001

Brzozowski, L., Hanson, S., Jannink, J.-L., Meints, B., Moore, V., Tufan, H., &Villwock, S. (2022). Towards equitable public sector plant breeding in the United States. *Crop Science*, *62*(6), 2076–2090. https://doi.org/10.1002/csc2.20800

Cargo, M., & Mercer, S. L. (2008). The value and challenges of participatory research: Strengthening its practice. *Annual Review of Public Health*, *29*(1), 325–350. https://doi.org/10.1146/annurev.publhealth.29.091307.083824

Carlson, S. (2012, January 19–21). Breeding more options in the corn seed marketplace. In *Strengthening community seed systems. Proceedings of the 6th Organic Seed Growers Conference* (pp. 13-14), Port Townsend, Washington, USA. Organic Seed Alliance.

Ceccarelli, S., Grando, S., & Baum, M. (2007). Participatory plant breeding in water-limited environments. *Experimental Agriculture*, *43*(4), 411–435. https://doi.org/10.1017/S0014479707005327

Ceccarelli, S., & Grando, S. (2020). From participatory to evolutionary plant breeding. In O. T. Westengen & T. Winge (Eds.), *Farmers and plant breeding: Current approaches and perspectives* (pp. 231–243). Routledge. https://doi.org/10.4324/9780429507335-15

Chable, V., Nuijten, E., Costanzo, A., Goldringer, I., Bocci, R., Oehen, B., Rey, F., Fasoula, D., Feher, J., Keskitalo, M., Koller, B., Omirou, M., Mendes-Moreira, P., van Frank, G., Naino Jika, A. K., Thomas, M., & Rossi, A. (2020). Embedding cultivated diversity in society for agro-ecological transition. *Sustainability*, *12*(3), Article 784. https://doi.org/10.3390/su12030784

Colley, M. R., Dawson, J. C., McCluskey, C., Myers, J. R., Tracy, W. F., & Lammerts van Bueren, E. T. (2021). Exploring the emergence of participatory plant breeding in countries of the Global North – A review. *The Journal of Agricultural Science*, *159*(5–6), 320–338. https://doi.org/10.1017/S0021859621000782

Colley, M. R., Tracy, W. F., Lammerts van Bueren, E. T., Diffley, M., & Almekinders, C. J. M. (2022). How the seed of participatory plant breeding found its way in the world through adaptive management. *Sustainability*, *14*(4), Article 2132. https://doi.org/10.3390/su14042132

Dawson, J. C., Murphy, K. M., & Jones, S. S. (2008). Decentralized selection and participatory approaches in plant breeding for low-input systems. *Euphytica*, *160*, 143–154. https://doi.org/10.1007/s10681-007-9533-0

Endres, A. B., Andrade Laborde, J. E., Bohn, M. O., Formiga, A. K., Goldstein, W. A., Marriott, E. E., Ugarte, C. M., & Wander, M. M. (2022). Influence of the seed loophole and bottleneck on quantity and quality of organic maize seed in the U.S. Midwest. *Frontiers in Agronomy*, *4*. https://doi.org/10.3389/fagro.2022.763974

Fitzgerald, D. (1993). Farmers deskilled: Hybrid corn and farmers' work. *Technology and Culture*, *34*(2), 324–343. https://doi.org/10.2307/3106539

Ganning, J. P., Flint, C. G., & Gasteyer, S. (2012). A case sudy from the post-New Deal state agricultural experiment station system: A life of mixed signals in Southern Illinois. *Agriculture and Human Values*, *29*, 493–506. https://doi.org/10.1007/s10460-012-9373-y

Genomes To Fields [G2F] Initiative. (n.d.). *Genomes To Fields (G2F) meetings*. https://www.genomes2fields.org/meetings/

G2F Initiative. (2017, May). *The Genomes To Fields (G2F) Initiative*. https://www.genomes2fields.org/about/

Gerpacio, R. V. (2003). The roles of public sector versus private sector in R&D and technology generation: The case of maize in Asia. *Agricultural Economics*, *29*(3), 319–330. https://doi.org/10.1111/j.1574-0862.2003.tb00168.x

Goldstein, W. A., Schmidt, W., Burger, H., Messmer, M., Pollak, L. M., Smith, M. E., Goodman, M. M., Kutka, F. J., & Pratt, R. C. (2012). Maize: Breeding and field testing for organic farmers. In E. T. Lammerts van Bueren & J. R. Myers (Eds.), *Organic crop breeding* (pp. 175–189). Wiley. https://doi.org/10.1002/9781119945932.ch10

Healy, G. K., & Dawson, J. C. (2019). Participatory plant breeding and social change in the Midwestern United States: Perspectives from the Seed to Kitchen Collaborative. *Agriculture and Human Values*, *36*, 879–889. https://doi.org/10.1007/s10460-019-09973-8

Howard, P. H. (2009). Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability*, *1*(4), 1266–1287. https://doi.org/10.3390/su1041266

IPES-Food. (2017). *Too big to feed: Exploring the impacts of mega-mergers, consolidation and concentration of power in the agri-food sector*. https://www.ipes-food.org/_img/upload/files/Concentration_FullReport.pdf

Joshi, A., & Witcombe, J. R. (1998). Farmer participatory approaches for varietal improvement. In J. Witcombe, J. Farrington, & D. S. Virk (Eds.), *Seeds of choice: Making the most of new varieties for small farmers* (pp. 171–190). Intermediate Technology Publications. https://assets.publishing.service.gov.uk/media/57a08da2ed915d3cfd001b30/RLPSRbookchap12.pdf

Khoury, C. K., Brush, S., Costich, D. E., Curry, H. A., Haan, S., Engels, J. M. M., Guarino, L., Hoban, S., Mercer, K. L., Miller, A. J., Nabhan, G. P., Perales, H. R., Richards, C., Riggins, C., & Thormann, I. (2022). Crop genetic erosion: Understanding and responding to loss of crop diversity. *New Phytologist*, *233*(1), 84–118. https://doi.org/10.1111/nph.17733

Lammerts van Bueren, E. T., Struik, P. C., van Eekeren, N., & Nuijten, E. (2018). Towards resilience through systems-based plant breeding. A review. *Agronomy for Sustainable Development*, *38*, Article 42. https://doi.org/10.1007/s13593-018-0522-6

López Noriega, I., Halewood, M., Galluzzi, G., Vernooy, R., Bertacchini, E., Gauchan, D., & Welch, E. (2013). How policies affect the use of plant genetic resources: The experience of the CGIAR. *Resources*, *2*(3), 231–269. https://doi.org/10.3390/resources2030231

Luby, C., Endres, A. B., Wander, M., & Ugarte, C. (2018). *A primer on plant breeding and intellectual property rights in organic seed systems*. eOrganic. https://eorganic.org/node/27215

Lyon, A., Friedmann, H., & Wittman, H. (2021). Can public universities play a role in fostering seed sovereignty? *Elementa: Science of the Anthropocene*, *9*(1), Article 00089. https://doi.org/10.1525/elementa.2021.00089

Mendes-Moreira, P., Satovic, Z., Mendes-Moreira, J., Santos, J. P., Nina Santos, J. P., Pêgo, S., & Vaz Patto, M. C. (2017). Maize participatory breeding in Portugal: Comparison of farmer's and breeder's on-farm selection. *Plant Breeding*, *136*(6), 861–871. https://doi.org/10.1111/pbr.12551

Montenegro de Wit, M., & Iles, A. (2016). Toward thick legitimacy: Creating a web of legitimacy for agroecology. *Elementa: Science of the Anthropocene*, *4*, Article 000115. https://doi.org/10.12952/journal.elementa.000115

Morris, M. L., & Bellon, M. R. (2004). Participatory plant breeding research: Opportunities and challenges for the international crop improvement system. In *Euphytica*, *136*(1), 21–35. https://doi.org/10.1023/B:EUPH.0000019509.37769.b1

Mujjabi, C. (2022) The use of participatory breeding and testing networks in maize varietal development for organic systems [Masters's Thesis, University of Illinois at Urbana-Champaign]. https://www.ideals.illinois.edu/items/126726

Murphy, K. M., Campbell, K. G., Lyon, S. R., & Jones, S. S. (2007). Evidence of varietal adaptation to organic farming systems. *Field Crops Research*, *102*(3), 172–177. https://doi.org/10.1016/j.fcr.2007.03.011

Partridge, S. (2023, July 26). *The 2023 farm bill must address inequities in the land-grant university system*. Center for American Progress. https://www.americanprogress.org/article/the-2023-farm-bill-must-address-inequities-in-the-land-grant-university-system

Robinson, G. M. (2018). Globalization of agriculture. *Annual Review of Resource Economics*, *10*(1), 133–160. https://doi.org/10.1146/annurev-resource-100517-023303

Seufert, V., & Ramankutty, N. (2017). Many shades of gray—The context-dependent performance of organic agriculture. *Science Advances*, *3*(3), Article e1602638. https://doi.org/10.1126/sciadv.1602638

Shelton, A. C., & Tracy, W. F. (2016). Participatory plant breeding and organic agriculture: A synergistic model for organic variety development in the United States. *Elementa: Science of the Anthropocene*, *4*, Article 000143. https://doi.org/10.12952/journal.elementa.000143

Swanson, B. E., Bentz, R. P., & Sofranko, A. J. (1998). *Improving agricultural extension: A reference manual* (2nd ed.). FAO.

Thro, A. M., & Spillane, C. (2000). *Biotechnology-assisted participatory plant breeding: Complement or contradiction?* (Working Document No. 4 of the CGIAR System Wide Initiative on Farmer Participatory Research and Gender Analysis for Technology Development and Institutional Innovation). CGIAR. http://ciat-library.ciat.cgiar.org/Articulos_Ciat/Biotechnology_assisted_Participatory_Plant_Breeding_Complement_Contradiction.pdf

Turnhout, E., Metze, T., Wyborn, C., Klenk, N., & Louder, E. (2020). The politics of co-production: Participation, power, and transformation. *Current Opinion in Environmental Sustainability*, *42*, 15–21. https://doi.org/10.1016/J.COSUST.2019.11.009

Ugarte, C. M., Kwon, H., & Wander, M. M. (2018). Conservation management and ecosystem services in midwestern United States agricultural systems. *Journal of Soil and Water Conservation*, *73*(4), 422–433. https://doi.org/10.2489/jswc.73.4.422

U.S. Department of Agriculture. (2022, June 1). *USDA announces framework for shoring up the food supply chain and transforming the food system to be fairer, more competitive, more resilient* [Press Release No. 0116.22]. https://www.usda.gov/media/press-releases/2022/06/01/usda-announces-framework-shoring-food-supply-chain-and-transforming

van Etten, J., de Sousa, K., Aguilar, A., Barrios, M., Coto, A., Dell'Acqua, M., Fadda, C., Gebrehawaryat, Y., van de Gevel, J., Gupta, A., Kiros, A. Y., Madriz, B., Mathur, P., Mengistu, D. K., Mercado, L., Nurhisen Mohammed, J., Paliwal, A., Pè, M. E., Quirós, C. F., … Steinke, J. (2019). Crop variety management for climate adaptation supported by citizen science. *Proceedings of the National Academy of Sciences*, *116*(10), 4194–4199. https://doi.org/10.1073/pnas.1813720116

Walker, T. S. (2006). *Participatory varietal selection, participatory plant breeding, and varietal change*. World Bank. https://openknowledge.worldbank.org/handle/10986/9182

Wilbeck, C., & Carlson, S. (2018). *US Testing Network 2018 Annual Member Meeting*. Retrieved from Practical Farmers of Iowa website: https://practicalfarmers.b-cdn.net/wp-content/uploads/2019/04/USTN-2018-Member-Presentation.pdf

Zurba, M., Petriello, M. A., Madge, C., McCarney, P., Bishop, B., McBeth, S., Denniston, M., Bodwitch, H., & Bailey, M. (2022). Learning from knowledge co-production research and practice in the twenty-first century: Global lessons and what they mean for collaborative research in Nunatsiavut. *Sustainability Science*, *17*, 449–467. https://doi.org/10.1007/s11625-021-00996-x