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Participatory Breeding of Wheat for Organic Production

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Abstract

To improve food systems, plant breeding programs must (1) identify needs in crop improvement, (2) select better genotypes, and (3) achieve field adoption of superior varieties. A participatory wheat breeding program in the Northeast United States began to identify, select, and adopt superior genotypes for organic production. Clients of the breeding program prioritized selection, including weed competitiveness, Fusarium head blight resistance, straw production, lodging resistance, artisanal bread quality, and taste. Three years of variety trialing identified superior genotypes of wheat, spelt, emmer, and einkorn for organic management, artisanal baking, and sensory quality. After crossing superior genotypes and increasing early generation seed, eleven organic farmers are selecting segregating biparental populations for priority traits. Evaluation of gains from on-farm selection can guide future efforts in breeding for underserved seed markets.

Introduction

Plant breeding programs rely on three stages to improve food systems. Participatory plant breeding (PPB) methods facilitate the (1) identification of needs in crop improvement, (2) selection of better genotypes, and (3) farmer adoption of superior genotypes. While it is often described as one method, PPB encompasses a broad array of projects that incorporate varying degrees of participation and decentralization (Ceccarelli 2015). Participation defines the involvement of "clients" in the breeding process (Witcombe et al. 2005), while decentralization describes the use of many selection sites scattered over broad environmental gradients.

First, client participation can accurately assess problems that need to be solved through breeding. Surveys, transect walks, focus group discussions and other basic tools of social science can assess the needs of clients (Pretty and Vodouhê 1997; Soleri and Cleveland 2009; OSA 2012). Across many crop species and environments, clients valued different traits than plant breeders (Ashby 2009). Participation allows flexibility in the selection program, so that if needs change during the lengthy process of plant breeding, clients can help reorient the objectives to ensure relevant end products.

Second, decentralization and participation ensure that selection gains are relevant to farmers' fields. Plant breeders make selections in environments that differ from the array of farms that will eventually grow developed varieties (i.e. the target environment). If genotypic performance between selection and target environments is inconsistent, as a result of genotype by environmental interactions (GxE), gains made in a breeding program will be inefficient or irrelevant for farmers' fields (Ceccarelli 2015). Decentralization moves selection closer to the target environment. By reducing genotype by environmental interactions

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between the selection and target environment, decentralization can increase the gains made by a breeding program. When GxE was significant in breeding programs, lines selected under PPB have performed better for client priority traits than materials selected under formal plant breeding methods (Joshi et al. 2007; Ceccarelli et al. 2001; Goldringer 2014; Kirk et al. 2015).

Third, participation facilitates one of the most difficult stages of plant breeding: variety adoption. PPB varieties are more likely to be adopted because participants have ensured that developed material is relevant to their needs (Ashby 2009). In addition to adopting more varieties, farmers involved in PPB projects also adopt varieties earlier (Ashby 2009; Ortiz-Perez et al. 2006; Mustafa, Grando, and Ceccarelli 2006). Because selection takes place over multiple years in the target environment, farmers may be able to adopt varieties without waiting for additional multi-environment trials. Reduced trialing of advanced lines also saves considerable cost for PPB programs (Mangione et al. 2006).

PPB programs can increase gains while reducing cost when (1) client needs are not well understood by plant breeding programs, (2) large GxE exists between selection and target environments, and/or (3) there is a history of low variety adoption, In the case of wheat for organic systems, all three stages of the breeding process support the use of PPB. First, organic farmers in Minnesota defined different priorities for agronomic and quality traits from conventional breeding programs (Kandel et al. 2008). Second, wheat genotypes demonstrated significant GxE interactions between organic and conventional management systems (Kirk, Fox, and Entz 2012; Hoagland 2009; and Murphy et al. 2007). When grown under organic conditions, wheat populations selected under organic management produced higher yield and protein content than genotypes selected under conventional environments (Kirk, Fox, and Entz 2012; Reid et al. 2011; Murphy et al. 2007; Brancourt-Hulmel et al. 2005). These results indicate that the estimated 95% of plant breeding environments that are not organic are failing to produce optimal genotypes for organic systems (Lammerts van Bueren et al. 2011). Third, there is widespread mistrust of modern varieties among clients of wheat breeding, including farmers, bakers, and consumers (Davis 2011; Kissing Kucek et al. 2015). Consequently, participatory plant breeding is a great fit for rebuilding client trust of improved varieties. Finally, PPB has shown a high benefit to cost ratio (Mangione et al. 2006). As only 2% of farms in the Northeast are organic, a small fraction of those grow wheat, and many farmers save their own seed, there is very little market incentive to breed organic wheat varieties. PPB can provide a high benefit to cost ratio for minimal investments in the breeding project.

Objectives

1. *Assess needs in wheat breeding for organic systems through client interviews,*
2. *Identify parents best suited to meeting client needs,*
3. *Select segregating populations on-farm according to farmer priority traits.*

Methods

Assess Needs in Organic Wheat Breeding

Regional researchers and extension personnel nominated eleven organic farmers to participate in the breeding project through purposive sampling. Farms represented the diversity of sizes, production systems, and climates of the Northeast (Figure 1). After learning about the project objectives, all eleven farmers agreed to participate. A researcher interviewed each farmer and conducted a farm transect walk (Table 1). Answers were recorded and coded for common and divergent answers among farms.

Identify Parents for Selection

To identify the best varieties to use as parents in the breeding program, researchers evaluated diverse lines of wheat at three organically-managed sites in the Northeast from 2012 to 2015 (Figure 1). Lines included 38 winter wheat, 24 spring wheat, 7 winter spelt, 6 spring spelt, 15 emmer, and 3 einkorn varieties. All lines were replicated three times and plot sizes varied from 3.8 to 8.8 square meters, depending on location. Data collected on each line included plant height, visual assessment of lodging and disease, days to heading, yield, and test weight. A subset of winter and spring wheat varieties were also screened for sourdough baking quality by regional artisanal bakers and for sensory quality by a trained taste panel.

Select Segregating Populations

Individuals at Cornell University, University of Vermont, Washington State University, and Butterworks Farm crossed selected parental varieties and increased seed to the F3 generation. Bulked F3 biparental families of winter wheat, einkorn, and spelt were planted on five participating farms. On the remaining six participating farms, researchers planted F4 biparental families of spring wheat. Each farm established five biparental families in two replicates, along with one check variety. Winter and spring on-farm selection plots varied in size from 4.1 to 8.8 square meters and were surrounded by a border row of wheat or barley. Eight hundred headrows of F2:F3 individuals were also planted at an organically-managed research station in Freeville, NY and a low-input Fusarium head blight (FHB) nursery in Ithaca, NY.

Throughout the season, farmers evaluated individual plants for priority criteria. The farmer visually separated the field into four quadrants and selected the plants best meeting the criterion in each quadrant. At the end of the season, farmers selected the best 10% of individual plants or spikes in each biparental family plot. The same number of spikes was also selected at random from each plot. Each year, farmers also attend a field day to determine selection criteria and select populations on a regional farm (Freeville and Ithaca, NY; Orono, ME; Westfield, VT). After two seasons of selection and self-fertilization, farmer collaborators will decide how to distribute the 97% homozygous F6 lines harvested from each plot.

Results and Discussion

Assess Needs in Organic Wheat Breeding

Eleven participants farmed a mean of 629 acres (range 7-1500). The average number of wheat acres per farm, 41 (range 1-200), sharply contrasts with the nationwide average of 332 (2012 Ag Census). Experienced farmers were sought for their ability to identify superior lines of wheat for their farm. Although farming experience averaged 23 years per farmer (range 3-40), experience farming wheat was nearly half that, at 12 years (range 3-40). Farms exhibited high temporal and spatial diversity. Over a mean rotation length of 5.5 years (range 2-8), 17 crops were grown per farm (range 5 to more than 30). 72% (8 of 11) participants also raised livestock on their farm. Consequently, wheat straw was an important product for all spring wheat farmers. Markets for wheat were focused on local, direct-to-market sales. Ten of 11 farmers milled their own flour or were partners with a local miller.

Figure 2 shows the barriers that prevent farmers from meeting their objectives in growing wheat. As wheat genetics influence 70% of the barriers described by farmers, a breeding program is capable of breaking down barriers and improving organic wheat production and marketing. Figure 3 depicts the relative importance of wheat traits to farmers. Most farmers valued several traits in common, although many farmers emphasized traits that were uniquely important to their operation. Important traits for winter spelt and einkorn included high production of spring tillers and ease of dehulling, respectively. The traits identified by farmers highlight the importance of incorporating client input when designing the breeding program. One priority trait, artisanal baking quality and flavor, is not generally incorporated in wheat breeding programs. The highly-rated traits of weed competitive ability, straw quantity/tall height, and performance under low nitrogen conditions are inversely correlated with breeding targets commonly used by wheat breeding programs. Wheat breeders often select for dwarf and semi-dwarf varieties, performance under optimal nitrogen inputs, and plants that "play nice" in dense monoculture rather than vigorously competing with weeds (Lemerle et al. 2001). The priority traits of protein and yield, which demonstrate large GxE between conventional and organic environments, underscore the need to make selections under organically-managed environments.

Identify Parents for Selection

Parental selection is key to developing the best genotypes (Virk et al. 2005). After testing varieties across a gradient of Northeastern environments, top-performing lines were identified for many farmer-priority traits. Variety performance results from field to table are available online at Cornell Small Grains Cultivar Testing. As early generation selection for artisanal baking quality and flavor is particularly difficult, the project incorporated parental varieties with good baking and sensory quality. Selection of parents took place after one year of variety trials. Subsequent years of agronomic trails revealed top-performing varieties that were not included as parents in the selection scheme, in addition to selected parents that did not consistently perform in the Northeast. Consequently, the authors recommend waiting until multiple years of variety trials are complete before selecting parents. Similar to participatory wheat breeding work in Canada (Kirk et al. 2015), farmers expressed interest in selecting parents for crossing. A participatory variety trialing component could help gather farmer knowledge on top-performing parents before beginning on-farm selection, similar to the methods used by Virk et al. (2005).

Select Segregating Populations

The most important trait among farmers, particularly for spring wheat, was weed competitive ability. A literature review identified wide first and second leaves and overall ground cover at the third to fifth leaf stage as easily-phenotyped traits that are correlated with weed competitive ability. For the six farmers who ranked weed competitive ability as a priority trait, plots were space-planted so individual plants could be identified, and best individuals were flagged in each plot.

The second most important trait for farmers was FHB tolerance. Selecting for disease resistance is most effective on controlled research station conditions in which plants are inoculated with the disease (Kornegay, Beltran, and Ashby 1996). F3 populations are being screened for FHB infection and severity at Ithaca, NY. Populations with the best FHB index scores will advance to the F4 selection stage.

Farmers' third highest ranked trait was protein. For farmers who selected protein as a priority trait, the 50% of selected spikes with highest protein will be passed to the next generation using a single seed non-destructive NIR machine. Seed size will be simultaneously measured to avoid selecting the smallest seeds, which would reduce early season vigor and weed competition. Height and lodging were also highly valued traits listed by farmers, particularly for spring wheat. Farmers who desired tall plants selected for that trait. As height is pleiotropic with early vigor (Worthington and Reberg-Horton 2013), selected genotypes with tall height should also be more competitive with weeds. For lodging, a literature review revealed that stem diameter was the most correlated and easily measureable phenotype for lodging. After farmers selected plants of interest in a plot, each stem was measured with a pair of calipers. The largest 50% of stems were selected for the next generation.

Conclusions

Involving organic farmers in the breeding process demonstrated needs that are distinct from conventional wheat breeding programs. A decentralized model has tailored selection to the unique environment and priority traits of each participating farm. Evaluations in 2015 and 2016 will measure gains from selection by comparing weed biomass, protein, plant height, lodging, seed size, and yield of farmer-selected populations to randomly-collected populations and check varieties.

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Appendix

Table 1. Semi-structured interview questions.

1. What crops and/or livestock do you farm? What is your typical rotation?
2. How many acres do you farm? How many acres are in wheat? Is some or all of your land certified organic?
3. For how many years have you been farming? For how many years have you grown wheat?
4. What products do you market, and where do you market them?
5. What are your short and long term goals for your farm?
6. Why are you interested in wheat on your farm? What do you hope to achieve by growing these crops?
7. What barriers do you see to meeting your objectives in growing organic wheat?
8. Describe your ideal wheat. What specific characteristics do you seek in this ideal wheat? Please rank them in order of importance to you.

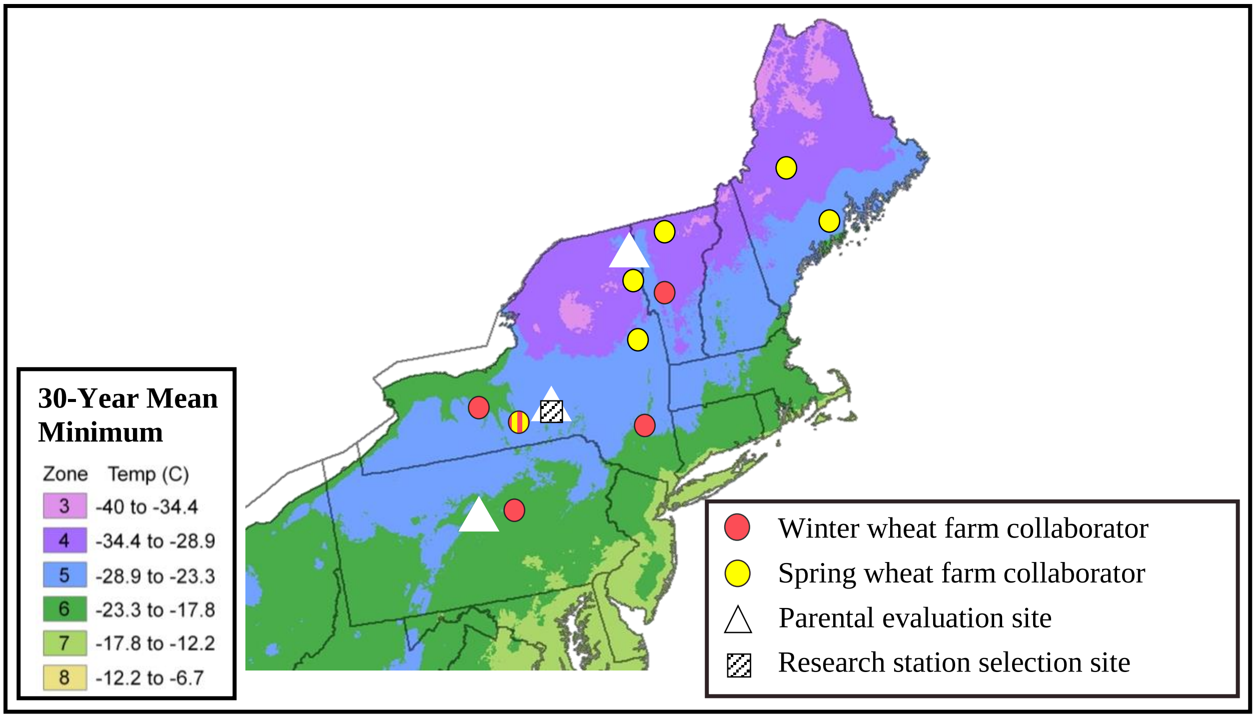

Figure 1. Location of farms participating in needs assessment and selection, variety trial sites for identification of parental lines, and regional research station selection site (map image modified from USDA).

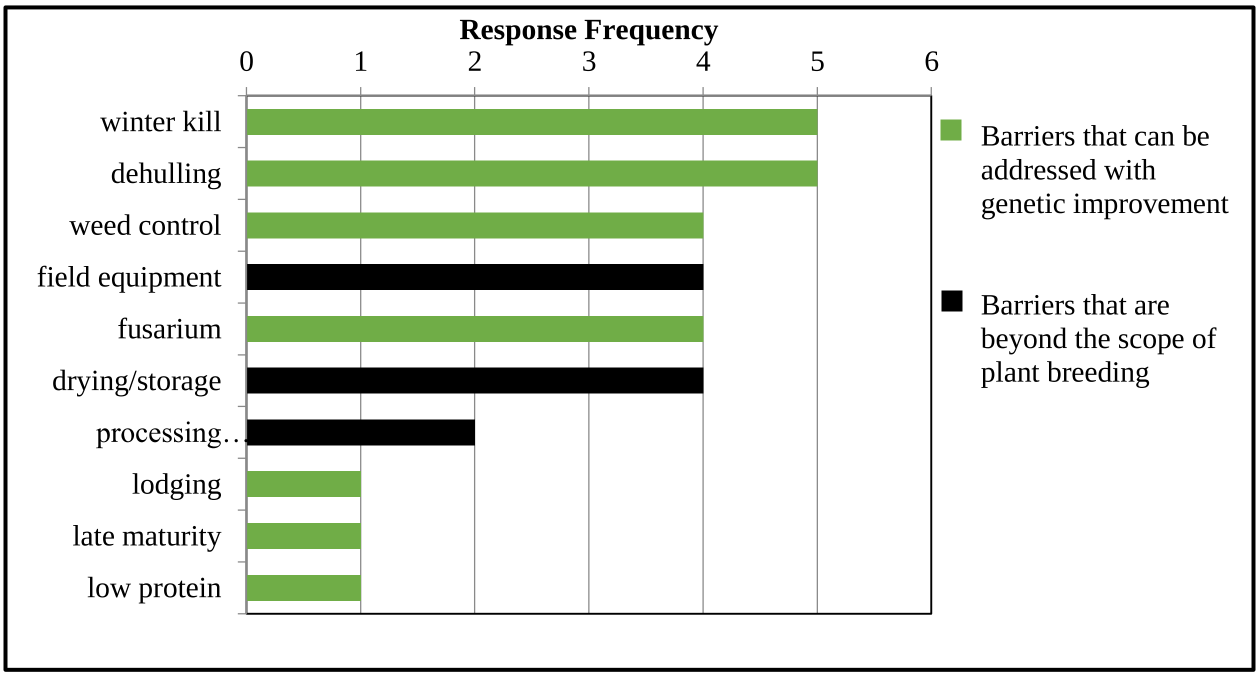

Figure 2. Barriers that prevent respondents from meeting their objectives in growing wheat. 70% of barriers can be addressed through genetic improvement. Participants described the winter kill barrier as primarily associated with wet soils and frost-heave.

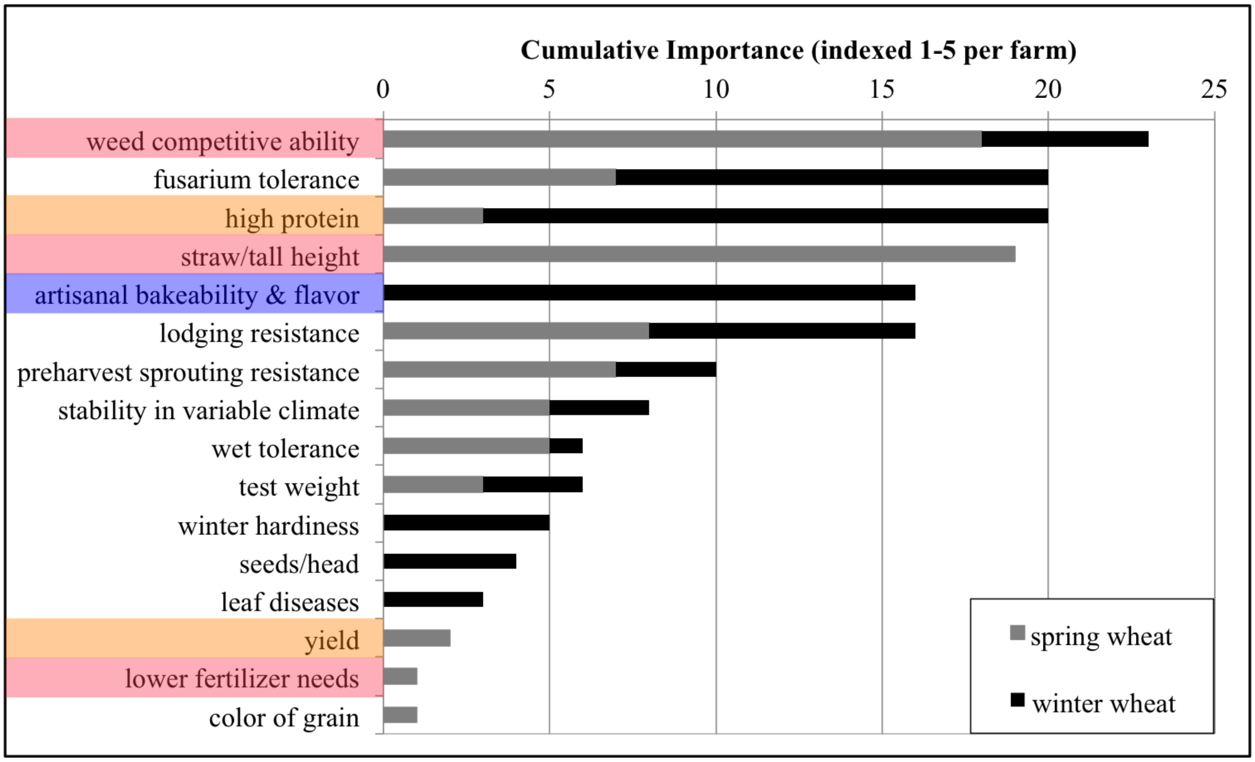

Figure 3. Farmer-identified priority traits for selection, weighted by rank of importance. Each farmer identified up to five traits and ranked them in order of importance. Traits highlighted in pink are negatively correlated with traits used in most conventional wheat breeding program. Traits highlighted in orange have evidence of high GxE between organic and conventional selection environments. Traits highlighted in purple are rarely screened in conventional wheat breeding programs.