ESTABLISHING BREEDING PRIORITIES AND DEVELOPING CULTIVARS FOR ORGANIC VEGETABLE GROWERS IN THE NORTHEAST

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ABSTRACT

The goal of the work outlined in this thesis was to employ the techniques of plant breeding while engaging farmers in dialogue about priorities for the organic vegetable production community. This thesis details an effort to hear from Northeastern farmers about the traits that matter to them in the crop varieties they grow, and describes breeding projects to develop new varieties of bell pepper and winter squash for organic vegetable farmers in the northern US. Chapter One reviews research related to breeding for organic production and briefly introduces the Northern Organic Vegetable Improvement Collaborative (NOVIC), a partnership of public plant breeding programs developing new vegetable varieties suited to organic management. Chapter Two describes work done in 2015 to hear from organic vegetable growers in the Northeast in order to establish breeding, research and education priorities to strengthen organic production in the region. The third and fourth chapters detail the goals, process, and results to date of specific breeding projects under NOVIC.

BIOGRAPHICAL SKETCH

Rachel Hultengren is from Seattle, Washington, where she studied Biology and Spanish at the University of Washington. As an undergraduate, she volunteered at the UW student farm, and after receiving her bachelor's degrees in 2010, Rachel spent a year as an intern on an organic vegetable farm in Washington State. Later, she worked as a consultant to the Agricultural Development Initiative at the Bill & Melinda Gates Foundation; it was during her time there that she met scientists working to address the needs of smallholder farmers through plant breeding, and decided to pursue a degree in the field herself. During her time at Cornell, Rachel was an active member of Synapsis (the Plant Breeding & Genetics graduate student club); she served as co-president of the graduate student club 2015-2016. She loves semicolons unapologetically.

DEDICATION

This thesis is dedicated, with my enduring gratitude, to Dr. Elizabeth Wheat, for fostering my curiosity about how food is and can be produced, and for urging me to pursue opportunities beyond my initial expectations. Thank you for being a shining example of loving kindness and of never letting go of the passion that propels you forward.

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LIST OF ABBREVIATIONS

CWT	Hundredweight
GMO	Genetically Modified Organism
IPM	Integrated Pest Management
NE	Northeast
NOFA	Northeast Organic Farmer Association
NOP	National Organic Program
NOVIC	Northern Organic Vegetable Improvement Collaborative
OMRI	Organic Materials Review Institute
OSA	Organic Seed Alliance
OTA	Organic Trade Association
PPB	Participatory Plant Breeding
QTL	Quantitative Trait Loci
R&D	Research and Development
URL	Uniform Resource Locator
USD	U.S. Dollars
USDA	United States Department of Agriculture

CHAPTER ONE

BREEDING FOR ORGANIC VEGETABLE PRODUCTION

Organic agriculture: an introduction

The organic label has been federally regulated in the United States since 2002. In October of that year, the National Organic Program (NOP) began its official oversight of organic agriculture by implementing the USDA-NOP standards, which codified the efforts of farmers and food-focused organizations across the country to promote sustainably-produced food (USDA, 2012). The standards define organic agriculture in both philosophical terms (the "what" and "why") and practical terms (the "how"). Title 7, Part 205.2 of the Code of Federal Regulations states that organic agriculture is "a production system that is managed… to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biological diversity" (Coleman, 2012). The standards go on to enumerate the practices and materials that are, and are not, allowed on a certified organic farm. Broadly, these standards outline methods of managing soil fertility, as well as disease, pest and weed pressures, and the sourcing of materials that can be used on a certified farm. By regarding a farm as a functioning ecosystem and valuing its overall health, the organic philosophy requires that growers address challenges in an integrated and holistic fashion; the NOP standards are the legal framework for enforcing that philosophy. In this thesis, the word 'organic' will refer to management systems in accordance with the NOP standards.

Increasing demand for organic products

In the 15 years since the establishment and initial enforcement of the NOP standards, demand for certified organic products has grown rapidly; the organic food industry has seen steady growth over the past 15 years, with no indication of levelling off in the near future. The USDA Economic Research Service reported that in 2012, organic products in the United States accounted for $28.4B USD (roughly 4% of total food sales), and that 43% of those sales were produce (USDA ERS, 2017). A survey done by the Organic Trade Association (OTA) showed that just one year later, that number was $35.1B USD, almost 5% of total food sales (OTA, 2014). The most recent OTA State of the Industry report, released in 2016, estimated that 2015 sales were at $43.3B (OTA, 2016). This increased demand is not merely a passive response to the availability of organic products in the marketplace; rather, American consumers are intentionally seeking out such products. In 2014, a Gallup survey focusing on food consumption trends concluded that just under half of all Americans "actively try to include organic foods in their diet" (Riffkin, 2014); other studies indicate that consumers purchase organic products for a variety of reasons, including perceived food safety and health benefits, aesthetic appeal and environmental impact (Lee and Yun 2015; Gwira Baumblatt et al. 2017). It is clear from the 2014 Gallup survey that younger age groups are driving more of the demand than older consumers (Riffkin, 2014). If those young consumers continue to preferentially purchase organically labelled foods as they age, and if the next generations of young people also demand organic products, the demand is likely to continue to increase.

As demand has grown for organically certified products, supply has increased (Greene et al., 2017). In 2015, over 13,000 crop and livestock production operations were USDA certified organic, and 3.2M acres of cropland were under organic cultivation. Though these numbers are growing, the supply of organic products is still insufficient to satisfy the demand (ibid).

The demand for organically produced food items is likely to continue to grow, and it may be a challenge for production to keep up while staying true to the core tenants of the NOP standard. To achieve this, either more farms need to be established or certified, or existing farms need to increase their production capacity. The conditions that are unique to organic management - and which constrain production - need to be understood and addressed in order to improve the efficiency of organically certified farms.

Benefits and limitations unique to organic agriculture

The impacts of organic production are not only economic. Indeed, the NOP standard's very existence is a recognition of the ecological benefits that result from managing food production systems in a way that imitates natural systems. It is important to recognize that all agricultural production has an impact on the natural world; at best, organic management minimizes the detrimental effects of cultivation on the surrounding landscape. These purported benefits exist in several areas, including the maintenance of biodiversity, the regulation of nutrient and water cycles, the maintenance of soil health, and the reduction of agriculture's dependency on fossil fuels.

Global biodiversity of plant and animal species is threatened by the reduction of appropriate habitat, and the expansion of cultivated land contributes to that threat. According to Hole et al. (2005), several organic management strategies help to support on-farm biodiversity: the cultivation of a diversity of crops, the reduced use of pesticides, and the "sympathetic management of non-cropped habitats". Their meta-analysis, comprising 76 studies that compared biodiversity around organic and conventional farms, concluded that the trends in these studies support the claim that organic farms have higher levels of biodiversity of non-cultivated plants and animals living in and around the production space than their conventional counterparts. The authors note that for this reason, organic farming can be an important component of conservation efforts. They acknowledge that the specific effect depends on the location of the farms, the crops grown, and other management choices unregulated by US or international organic standards.

Organic management practices also offer the potential to mitigate the negative impacts of agriculture on human health (Horrigan et al., 2002). Fertilizer run-off from farm land contributes to water pollution on a massive scale; the use of cover cropping to add organic matter to the soil also improves soil retention, thus mitigating run-off. Exposure to some pesticides has been shown to increase rates of certain types of cancer and immune disorders in humans (ibid); the use of integrated pest management (IPM) strategies offers a means by which off-target pesticide impacts can be reduced.

Finally, agriculture's reliance on fossil fuels may potentially be lower under organic management due to the exclusion of synthetic fertilizers, which depend on high energy input to create bioavailable forms of nitrogen. It has been demonstrated that for grain crops, the energy requirements (in million kilocalories hectare $^{-1}$ year $^{-1}$) under well-managed organic production can be lower than under conventional production (Pimentel et al., 2005); while the energy requirements of organic versus conventional management for vegetable production have not been studied as extensively, it is reasonable to conclude that in instances where nitrogen demand is high, and soil nitrogen is managed through the use of animal manure or leguminous cover crops, reliance on fossil fuels may be relatively diminished. This may have multiple benefits, including reduced CO_2 emissions from the burning of fossil fuels, and reduced ecological damage due to fossil fuel extraction practices. It is important to note that many of these benefits are conceived relative to conventional management practices, and may only be meaningful on a per unit area basis (farm level), not per unit output (standardized by the amount of crop produced) (Seufert and Ramankutty, 2017). Conversion of wild areas to cultivated land has large negative impacts; if more land is needed to produce the same amount of food, the net result of organic production may not be positive.

As organic agriculture gains popularity, researchers have begun investigating how feasibly the world's population might be adequately fed by organically managed farms. The question of, "Can organic feed the world?", to which varied conclusions have been offered, has been investigated by both proponents and skeptics of organic agriculture. In 2012, Seufert et al. found that the yield gap between organic and conventional agriculture was highly context specific. Their meta-analysis of 66 studies showed that organic agriculture yields were 75% of conventional yields on average, but that there was significant variation across the studies, depending on the type of crops included, and the acro-ecology of the study site. The authors acknowledged that the yield gap is reduced when the organic system is managed according to best practices, highlighting the importance of farmer knowledge and capacity in what is a complex system. Finally, Seufert and her colleagues note that while the focus of this study was on the yield of crops grown under the two systems, there are other metrics by which to evaluate the potential benefits of organic agriculture, including the environmental impact, impact on human health and economic considerations of the farmer.

Another meta-analysis of conventional versus organic yields also released in 2012 (de Ponti et al.) came to similar conclusions about the relative yield gap between the management systems (with organic farms yielding ~80% of comparable conventional farms) and also cautioned that the difference varied dramatically based on context. These authors went further than Seufert et al. (2012), asserting that comparisons between conventional and organic systems are only reasonable when both are managed according to best practices. It is important to note that "best practices" include the use of crop varieties well suited to the system under which they were managed, and as it is unlikely that the cultivars chosen in these studies were particularly adapted to low input agriculture, comparisons of current yields are not necessarily fair. De Ponti and his colleagues remind readers that conventional agriculture relies on exhaustible external inputs, such as phosphorous and the fossil fuels consumed in the Haber-Bosch process. In the future, we may be forced to move away from current conventional practices, regardless of the yield gap; with this in mind, it is critical to examine the ways in which organic agriculture can be made more productive. Lastly, the authors suggest that the discrepancy between the amount of time and resources devoted to researching and optimizing each system likely contributes to the relatively lower yields of organic farms. To support organic agriculture, the United States needs to invest in research focused on providing solutions to the unique challenges organic growers face, including the development of new crop varieties with traits that organic farmers need to succeed.

Keeping all this in mind, it is important to study the unique challenges that organic growers face as they comply with the NOP standards. As Lammerts van Bueren et al. note (2011), the transition from conventional to organic management entails more than a simple cessation of synthetic fertilizer and pesticide application: organic growers actively manage soil fertility, along with pest, disease and weed pressure in a manner distinct from that of conventional growers. While conventional growers are able to rely on fast-acting solutions to the problems that arise during the growing season, organic growers depend on longer-term processes (e.g. building soil fertility and biodiversity of beneficial organisms) to mitigate losses. While organic agriculture is often considered ‘low-input’, there are organic farmers that incorporate materials that are that are approved for organic systems and listed by the Organic Materials Review Institute (OMRI) to complement their management system; a focus on the level of external inputs to distinguish between certified-organic and conventional agriculture is therefore less useful and less illustrative of the differences between the two systems than a focus on the nature of the input. In organic management, growers take preventative measures to improve the system's self-regulating capacity, whereas under conventional management, growers can employ curative measures to address the challenges that do arise. Put more succinctly, organic agriculture can be characterized as proactive, as opposed to the predominantly reactive nature of conventional management.

The reason for this difference is that many of the tools used in conventional agriculture to control pest and pathogen populations are excluded by the NOP standards; given this, organic growers require unique strategies to address these challenges. Organic growers employ numerous strategies to manage soil fertility in the absence of synthetic fertilizers, including the use of cover cropping, crop rotation, and manure or compost application; the planning and successful implementation of these long-term strategies requires meticulous attention and foresight. These strategies differ in the short-term from conventional strategies as well, as the bio-availability of important plant nutrients depends on the source. Synthetic fertilizers are designed to provide precise and steady amounts throughout the growing season; manure-based fertility is less precise and can be difficult to manage (Messmer et al., 2012).

Conventional agriculture relies heavily on synthetic pesticides to mitigate damage by reducing or eliminating pest populations. Some of these (e.g. neonicotinoids) have been under scrutiny in recent years for their potential impact on pollinating insects (Rundlöf et al. 2015). In an organic production system, plant pathogens and pests are managed in an integrated fashion. The health of crops is supported through appropriate soil management with the expectation that a healthy plant will better fend for itself (Lammerts van Bueren et al., 2002). There are lowefficacy broad-spectrum OMRI listed pesticides; growers can also employ practices that limit pest damage, such as row cover (Adams et al., 1990) or trap cropping (Cavanagh et al., 2009). These cultural techniques require additional resources and planning, and must be put in place at exactly the right time to be effective against the specific insect pest. In the case of fungal pathogens, the widespread use of fungicidal seed treatments has led to a significant reduction in the incidence of some diseases under conventional systems, but because seed treatments are excluded by the NOP standards, they are therefore unavailable to organic growers. Crop rotation provides a break in disease and pest cycles, which can have major landscape-scale epidemiological effects for plant diseases. However, crop rotation requires that fields be taken out of production periodically, which reduces farm-level yields. These limitations make clear the need for crop varieties that excel under the conditions specific to organic management.

Organic growers need the tools and information that will allow them to manage their farms efficiently while adhering to the principles set out in the standards. Crop varieties that are adapted to organic systems environments are a powerful resource to improve the yield - and therefore the environmental benefits per unit output- of organic agriculture. In the absence of varieties that excel in their site-specific conditions, organic growers will be forced to use seed not suited to their needs (Hubbard and Zystro, 2016), to the detriment of their production.

Breeding for organic production systems

The development and production of varieties that will excel under organic management is critical to improve the productivity and efficiency of organic farms. The question, then, becomes one of *how* these varieties will be developed. It cannot be taken for granted that varieties that are bred and evaluated under conventional management will be suited to organic systems; thus, it is important that material intended for organic production systems be evaluated and selected under organic conditions. This was demonstrated by Murphy et al. (2007) in their study of wheat varieties under conventional and organic management. By looking at changes in yield rank under the two production systems, the authors conclude that varieties that produced more under organic management would not have been selected in a breeding program in which lines were trialed under conventional management. Further, they argue that yield under conventional management is not well correlated with yield under organic management. For complex traits with low heritability (like yield), indirect selection on conventionally managed yield may result in varieties inappropriate for organic systems; direct selection is particularly important given that organic environments are generally lower-yielding (Ceccarelli, 1989).

The final expression of a given trait of interest in a crop plant is the result of its genotype, the environment under which it grows, and the interaction between these two factors. For a farmer to reach a theoretically maximal season yield on their farm, they would need access to the varieties that did best on their individual farm; it is not enough for a cultivar to be generally good across varied environments if a grower's field and management practices represent a different context. As noted in de Leon (2016), "plant productivity is a direct consequence of how well adapted the genotype of an individual is to the surrounding environment." In other words, adaptation is environment specific.

Many traits come together to ultimately give rise to yield, and the stability of yield across environments is a question that plant breeders consider in their work. In Finlay and Wilkinson's 1963 analysis, adaptation of a given cultivar is calculated relative to other genotypes in the trial. Generally-adapted (also known as "broadly-adapted") varieties perform above average in all the test environments. This, naturally, has implications for the conclusions of a trial, as they will be dependent upon the germplasm included in the study. Stability, on the other hand, is selfreferential (though it, too, depends on the ordering of environments by quality, which is defined by the set of entries grown); stability refers to how well a cultivar performs relative to itself across various environments.

These concepts are illustrative in explaining how plant breeding efforts intended to support conventional agriculture may not inherently serve the needs of organic growers. If breeders prioritize material that does well under ideal conditions (conventional and managed with best practices), but poorly under low-yielding environments, the result may be a cultivar that will not perform well in an organic system. If material is not adequately tested under organic conditions, the breeder will not know whether it is appropriate for that context, even if it is otherwise well adapted to varied conventional environments (Finlay and Wilkinson, 1963). For organic farmers to have access to varieties that work for them, material intended for organic management needs to be tested and selected under such conditions (Wolfe et al., 2008). Highly stable varieties that are shown to yield sufficiently under low-yielding conditions and/or less stable varieties specifically adapted to an organic environment will serve organic farmers. Those that excel in these environments potentially offer greater productivity gains for organic growers; if performance under conventional management is not a criterion for selection, a breeder focused on organic adaptation may find material with greater yield potential.

Efforts to improve the productivity of organic systems, therefore, must include breeding crops with traits that allow those varieties to excel under organic agriculture. In Lammerts van Bueren et al. (2011), the authors suggest a list of such traits and describe the needs of organic growers in relation to each. Some traits that are important to organic farming are also a priority in conventional management; it is critical that these traits (e.g. disease resistance) be robust under organic management. Other traits are of particular importance to organic growers and not those growing conventionally. Nutrient use efficiency, for example, is a complex trait mediated in part by relationships with bacteria and fungi in the soil, which may have a yield cost in high-input systems where nitrogen and phosphorous are not limiting. In some cases, a non-organic solution has all but eliminated the risk of a disease; of course, conventional wheat growers would benefit from more effective genetic resistance to common bunt, but with modern seed treatments being as effective as they are, genetic resistance will not be as high of a breeding priority for conventional systems as it should be for organic systems, where seed treatments are an excluded material. A similar case can be made for insect resistance: neonicotinoids are extremely effective in controlling striped cucumber beetles, but are unavailable to organic growers. The authors conclude: "without special breeding efforts for the organic sector, there is a great risk that in future [sic] the needs of organic farmers will not be met."

Plant breeders play an important role in the success of a farm, and by extension, the robustness of a region's food system. In order to assure that their work is useful to organic farmers, plant breeders must understand the context of the growers they aim to support and prioritize traits (both agronomic and quality) that will bring the best new cultivar to those growers in their breeding program. To do this, breeders need to hear from growers about the constraints to production that can be addressed through breeding, and about the characteristics their customers look for in the food they purchase.

Breeding for organic markets and regional priorities

While there are some farming practices universal to organically managed agriculture anywhere in the United States – those dictated by the NOP standards – there are others that differ between farms and locations, such as the particular practices involved in IPM strategies (e.g. the inclusion of OMRI-listed pesticide sprays or use of row cover), or the primary source of soil nitrogen (e.g. composted animal manure or leguminous cover crops). The variation in these practices suggests that there is not one organic production system for which to breed, but many.

There are several possible strategies for developing organically-adapted varieties that will excel under organic conditions. One proposed strategy is to define an organic crop ideotype, as suggested by Lammerts van Bueren et al. (2002). In this approach, the traits contributing to optimal yield (and acceptable ranges for those traits) are defined to build a model for a given crop (Donald, 1968). A crop ideotype depends on a defined environment in which the breeder hopes the crop will achieve optimal yield.

However, while there are traits that, broadly, would benefit organic growers, there is no single universal method of farming a given crop under the NOP standards, and therefore no single suite of narrowly defined characters that can be expected to provide maximum yields on all organic farms. Lammerts van Bueren et al. acknowledge that the farmer is a meaningful part of the site-specific conditions of a farm (2002); the farmer's management decisions play a significant role in the environment a crop experiences. The ideal variety, therefore, will depend on exactly how the organic standards are culturally upheld.

Of possibly even greater importance are unique regional conditions; a variety well-suited to a given farm will be also adapted to the light quality and temperature regime of the region, as well as the specific pathogens and pests present. Donald (1968) suggested that farmers could tailor their production system to create the ideal environment for the ideotypic variety they would grow; it would likely be far more difficult for an organic grower to alter their system to fit a specific variety, as many management decisions are made in response to site-specific conditions.

Another approach in seed crops is to pursue evolutionary breeding (Murphy et al., 2005). In this scheme, a diverse set of parent lines are grown under organic management, seeds are harvested in bulk, and individual genotypes with high fitness (i.e. yield in grain number and weight in grains) increase in representation in the population through natural selection. Other selection schemes can also be pursued under organic management to identify genotypes that yield well under those conditions.

Not only do farmers in a particular region of the country face distinct climatic conditions and biotic stresses, but the qualities prioritized for a given market may be different from those important in other value chains. Supporting the farmers of a region requires that both the production culture and consumer preferences be understood.

For example, many small scale organic growers market their produce through channels distinct from those used by large-scale conventional farms. Although the majority of organic products are sold in supermarkets (USDA ERS, 2017), the growth in demand for these products has been accompanied by a growth in the number of farmers markets operating in the U.S. At present, there are over 8600 farmers' markets registered in the USDA's farmers market directory (USDA AMS, 2017). These spaces facilitate direct sales from growers to consumers, which is of particular importance to growers who do not produce enough to supply their product to wholesale distributors; direct sale also provides the possibility of improved profit margins for small-scale certified or transitioning growers (Griffin and Frongillo, 2003). While farmers markets are not generally limited to organic products or producers, there is a high demand for these products at farmers' markets across the country (Kremen et al., 2003). To support organic growers, plant breeders must understand which traits are most important to consumers of the markets in which those growers primarily sell. Chapter Two of this thesis outlines efforts to engage growers, seed company representatives and public researchers in identifying the needs specific to organic vegetable growers here in the Northeastern U.S.

Role of public research & development

The NOP standards require that growers use organically grown seed for their production. If there is a variety for which no organically grown seed is available, and no organically grown equivalent can be reasonably substituted, growers are allowed to purchase untreated seed of the variety they want to grow (Coleman, 2012). This exemption creates a Catch-22 situation, in which seed companies are not incentivized to offer organically certified seeds because their market is not effectively demanding them.

This market failure is exacerbated by the fact that organic growers represent a small percentage of the customer base of seed companies. Despite growth in demand for organic products, organic vegetable producers still represent a small market for large seed companies; the lack of a ‘profitable’ market for organically suited varieties has led to a lack of research and development for such varieties, resulting in a paucity of organically-certified seed and organically-adapted varieties (Hubbard and Zystro, 2016). The current degree of consolidation of the seed industry in the United States is unprecedented (Howard, 2015), likely exacerbating this market failure; as large companies merge, organic growers become an even smaller piece of their market share, and are more likely to suffer from product line discontinuation, particularly of untreated seeds. This points to an urgency for US organic production to be supported by public institutions (e.g. the land-grant universities), as one of the roles of the public sector is to invest in areas of market failure in which social returns are high but profits are uncertain and/or insufficient to attract private investment (Griliches, 1958). In addition to supporting organic growers in the absence of meaningful private investment, public research and development

(R&D efforts may encourage future private investments in the area. While private players focus on profit in markets with reliable returns, the outputs of public R&D investments in areas requiring high starting costs or long term support (such as organic plant breeding) can provide private R&D with commercial opportunities (Fuglie and Walker, 2001).

Northern Organic Vegetable Improvement Collaborative (NOVIC)

The roles of the public and private industry are distinct in agricultural research & development, with public entities (e.g. universities) able to focus efforts on areas where high development costs and low immediate returns have discouraged private investment (Fuglie and Walker, 2001). Organic agriculture presents an example of one such area. Despite increasing demand, the involvement of the private seed sector has historically been relatively low, resulting in a lack of appropriate varieties and organically-certified seed. This need, which constitutes a significant barrier to the growth and success of organic agriculture (Hubbard and Zystro, 2016), provides an opportunity for public plant breeders to contribute their expertise and efforts. In the Seufert et al. meta-analysis (2012), the yield gap between organic and conventional systems was highest for vegetables, suggesting a high potential impact for focused efforts to improve productivity in vegetables. The Northern Organic Vegetable Improvement Collaborative (NOVIC), a collaboration among Cornell University, University of Wisconsin-Madison, Oregon State University and the Organic Seed Alliance, is a project aimed at addressing this need by focusing on developing regionally appropriate varieties for organic vegetable growers in the U.S.

Under the second phase of NOVIC (2014-2018), plant breeders at these institutions are trialing varieties of five crops (tomato, sweet corn, bell pepper, cabbage and winter squash) under organic management, and developing new cultivars suited to organic production in these crops. Each institution leads one or more of the breeding projects, and shares germplasm ready for trialing with the others. At each institution, commercially available varieties of these crops are grown alongside the material under development in replicated trials, and evaluated for agronomic and quality traits.

In addition to the replicated trials at the research stations, the varieties were grown on farms in New York, Wisconsin, Oregon and Washington State, in order to understand how well they perform for market production. Interviews with growers and qualitative data from those trials helped to inform breeding decisions and evaluate material under development.

By trialing across the northern U.S., we can generate information about these currently commercially available varieties so that farmers can see what works well for them and for their neighbors. By breeding under organic conditions, we can develop new varieties better suited to organic agriculture in our region. The NOVIC network allows us to then test whether those new varieties are also appropriate across the northern U.S.

The participatory aspect of NOVIC is an important component of the work. Participatory plant breeding (PPB) is a model in which farmers are partners in the cultivar development process, instead of the passive recipients of the outputs of research.

In the early 20th century, rural sociologists studied the process by which farmers were adopting agricultural technologies, such as equipment and hybrid maize seed. In his book *Diffusion of Innovations*, E. Rogers proposed the ‘innovation-decision process’, a theoretical framework that explained the steps taken to consider and evaluate a new idea (Rogers, 2003). In this model, a person first learns about an innovation (the “knowledge” step), then forms an opinion toward the new tool or behavior (“persuasion”). At some point they conclude that the innovation will benefit them (“decision”), or that it isn’t suited to their needs. If they choose to adopt, they put the innovation into use ("implementation") and evaluate the results ("confirmation").

In the case of a new crop variety, the Diffusion of Innovations theory gives a simplistic picture in which the breeder delivers a fully-formed product to the farmer, whose only action is to adopt or reject it. Outside the scope of the model are critical questions: If the variety isn't adopted by the farmers that the breeder was working for, why? If it doesn't provide something new and needed in an appropriate way, why was it prioritized by the breeding program? Not only does the top-down approach of the theory offer no opportunity for feedback from farmers to be incorporated into the breeding process, but it also fails to acknowledge why that feedback is critical, or how it might be best obtained and acted upon.

The PPB model acknowledges that growers bring knowledge and skills that complement the scientific expertise that the breeder offers.

To consider how a farmer might be involved in the process of plant breeding, it's important to understand that cultivar development is a multi-step process with the following stages: priority setting, experimental design, development of experimental material, selection, variety evaluation, and the release of new cultivars (Vernooy, 2003). 'Participatory plant breeding' has been defined in various ways; some definitions propose farmer involvement in specific stages of the breeding process, while others are more broad. In this thesis, we'll consider PPB as the participation of target farmers, to any degree, at any stage of cultivar development.

The outcomes of PPB depend on the approach; many reviews go into detail about the greater gains possible when selection of material takes place in farmers' fields. Drawing on quantitative genetics theory, Atlin et al. (2001) and Ceccarelli (1989) argue that direct selection (within the target environment) is more effective in making progress than indirect selection (where selection takes place outside of the target environment). Another commonly-cited goal is that of increased adoption (Ceccarelli, 2015). If farmers are engaged in the final stages of evaluation and trialing a new cultivar, that cultivar may be effectively adopted even before formal release. This assurance of adoption increases the efficiency of the breeding process.

Successes documented in the literature come primarily from the developing world, where diverse local conditions often vary from the environment of the research station, and where the model has been adopted most widely. Across crops and locations, PPB has been shown to increase rates of adoption through producing more desirable varieties for smallholder, resource-poor farmers (Vernooy, 2003; Ashby, 2009).

Shelton and Tracy (2016) review the history of participatory plant breeding and organic agriculture, drawing parallels between low-input agriculture in developing countries and organic agriculture in the developed world to explain the utility of PPB for organic growers (namely, that formal breeding efforts have failed to adequately equip them with appropriate varieties). The authors assert that, in addition to the prospect of improved cultivars, the decentralization of power that lies at the core of participatory plant breeding resonates with the social values of the organic movement in the US.

In Sperling et al. (2001), the authors lay out a framework for considering the benefits and costs of PPB. The various possible models differ mainly in the roles and objectives of the actors involved. Without a clear understanding of these different approaches, they argue, defining and measuring success is not possible; choosing the right approach depends on the project’s ultimate goals, and defines the outcomes that can reasonably be expected. The authors enumerate a list of broad potential goals, and specific indicators that could point to success in each category.

Many of these ‘possible indicators’ could apply to the work outlined in this thesis. We did not set out with these goals stated explicitly, and therefore did not measure outcomes, but we can speak to the impacts we theorize could result from the work; though it may be difficult to fully quantify these impacts, future efforts will hopefully illuminate the extent to which outcomes were realized. This thesis include a brief description of expectations and assumptions related to the participation of organic farmers in the work described herein, using the framework provided in Sperling et al. (2001).

The NOVIC grower trials comprised two related activities: trialing commercially available varieties to evaluate their appropriateness for northern organic vegetable growers, and providing feedback on material still under development. (Another participatory aspect of NOVIC, not discussed in this thesis, has been annual plant-breeding workshops in which the co-principal investigators train farmers in basic selection concepts and techniques.) These activities may result in various outcomes under the goal of “capacity building and knowledge generation” by strengthening the relationships between formal research organizations and growers, thereby improving the two-way flow of information about available varieties (to farmers from researchers) and about the value of breeding lines through the lens of farmers’ own priorities (from farmers to researchers). The on-farm trials provide NOVIC breeders the opportunity to evaluate their material in the target environment; through selection has not generally taken place on-farm, the information about how well lines perform in farmer trials can be useful in making breeding decisions. Measurement and evaluation activities at the end of NOVIC II would help to make clear the benefits that farmers perceive to have received from their participation. Shelton and Tracy (2016) suggest that historic distrust of the land-grant universities explains, in part, the appeal of farmer-led participatory plant breeding to U.S. organic growers. It would be enlightening to investigate whether farmers that participate in NOVIC indicate a more positive regard for their local research partner.

Because the Mazourek breeding program has experience and expertise in pepper and squash breeding, Cornell University has led the breeding work in these crops. The goals of these projects, developed through conversations with organic growers and echoed in the results of the organic vegetable breeding needs survey (see Chapter Two of this thesis), are high-quality, disease-resistant bush delicata squash, and early maturing, blocky bell peppers. The third and fourth chapters of this thesis go into greater detail of this work.

Conclusion

Breeding for organic agriculture is a need that has gained growing attention and interest in recent years. An expanding body of research makes compelling the need to breed specifically for organic management, and more work is needed to provide organic growers with cultivars that are appropriate to their production and market.

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CHAPTER TWO
BREEDING, RESEARCH, AND EDUCATION NEEDS ASSESSMENT FOR ORGANIC VEGETABLE GROWERS IN THE NORTHEAST

Introduction

The goal of this work is to develop a vision for future organic vegetable breeding and the research and outreach necessary to support the continued growth of Northeast organic vegetable production. The objectives include determining:

1) target traits in major vegetable crops that are priorities for breeding and new cultivar introduction for this region,

2) major production issues that transcend growers' differences in scale of production and marketing focus, and

3) gaps in educational outreach of existing research and successful production techniques.

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Context: Ten years of organic seed dialogue in the NE

Such a steering event was long overdue in our region. The only organic breeding survey was conducted ten years ago by the Northeast Organic Farming Association of New York (NOFA-NY) of its statewide membership. In 2005, as part of the USDA-funded "Breeding in and for Organic Farms" (NESARE LNE04-204), organic breeding variety roundtables were held in Maine, New York, Vermont and Pennsylvania to assess the breeding, variety, and specific trait needs of organic farms. Small groups of organic farmers, breeders, and seed companies were brought together to share their organic vegetable breeding needs, varietal trait preferences, and other needs related to availability of organic vegetable seed. The roundtables were held to specifically guide breeding as part of the NESARE-funded grant, but this information has also been used extensively to direct additional breeding as part of the USDA-OREI-funded "Organic Seed Partnership" (Award No. 2004-51300-02229), "NOVIC-Northern Organic Vegetable Improvement Cooperative" (Award No. 2009-51300-05585), and "Addressing Critical Pest Management Challenges in Organic Cucurbit Production" (Award No. 2012-51300-20006). The Organic Seed Partnership and its predecessor, the Public Seed Initiative (Agreement No. 2001-52101-11347), were formative events, based in the Northeast, which influenced national models for work in regional seed systems. Some of the first organic public breeding for organic vegetable growers arose from these efforts. Given the sustained importance of this agricultural sector in our region, the great changes it has undergone and progress it has made within the past decade, and our reliance on up-to-date established priorities to guide future work, it was imperative that we update the Northeast organic vegetable community's needs and priorities.

The Organic Seed Alliance (OSA) surveyed growers throughout the US in 2011 and brought together organic stakeholders as part of their "State of Organic Seed Symposium"

(Dillon and Hubbard, 2011). This was part of an ongoing project to monitor the status of organic seed systems in the United States. The key finding was that "Organic seed systems are improving but require increased attention and resources."

Organic growers have specific requirements that are not adequately addressed by conventional agricultural research or cultivar development. They depend on plow-down cover crops, slow release fertilizers, animal manures, and compost for soil and plant fertility. Pests and diseases are managed as a part of a whole-farm systems approach with only a very few allowable organic pesticides with limited effectiveness. With fewer inputs, organic growers rely more on the vegetable varieties they grow to themselves provide superior pest resistance and high nutrient uptake. Organic farmers thus need varieties that are specifically bred and selected to excel in organic farming systems. This breeding and availability of varieties that perform well for organic farms is one important component in the profitability and success of organic vegetable production. For this breeding work to be effective, the current needs of organic vegetable growers must be known.

Ten years ago, growers provided us with long lists of varieties that they could no longer access which they had depended on to provide communities with robust harvests of marketable crops within specific regions. Replacement varieties had reduced yield and lacked qualities their consumers desired because they were developed to serve markets and priorities of other regions of the U.S. Growers shared production challenges and specific unmet variety needs that could be addressed through improved crop genetics. Since then, the organic market has continued to grow, with a twelve percent growth from 2014 to 2015 (Greene, 2016). With a growing number of organic farmers and a huge diversity in their scale, marketing, and even production techniques, we needed to better determine common needs of organic vegetable growers so that future breeding, research, and outreach can have the largest impact with limited funding. The information from roundtables and surveys ten years ago no longer necessarily represented the needs of current organic growers. Furthermore, from ten years of breeding in organic systems, we better understood the questions we need to ask growers to better determine their specific needs.

Regionally, there has been increased private sector interest and growth in organic seed production with two new companies growing and selling organic seed starting up in the last ten years in New York State alone. The regional seed companies dedicated to organic seed production in Maine and Vermont continue to grow. This expansion has brought a renewed interest in how to best continue to support this market and the food security, economic, and sustainability contributions of this diversified agriculture in the Northeast. This current work supports the renaissance and revitalization of the seed company by determining the gaps that still exist, and providing public research efforts with priorities to which they can align in service of the goal of sustainable agriculture in the Northeast.

Although the target audience of this work is organic vegetable growers, solutions for organic growers can also help conventional growers to implement more sustainable practices. Reduced pesticide use and lower input practices is a cornerstone of sustainability in agriculture and are embraced by an increasing number of growers. Organic growers rely more on the traits in their vegetable varieties and on cultural practices to overcome production challenges than on chemical pesticides and herbicides. This restriction prioritizes the development of robust genetics and novel approaches. Conventional growers can then utilize the cultural techniques and new resistant varieties developed for organic growers. There are many challenges, like downy mildew in cucurbits, where solutions developed from research in organic systems have widespread relevance in all production systems (Holdsworth et al., 2014).

Organic growers in the Northeast are testing new approaches in sustainability and serving major population centers with fresh regional produce. Organic growers have reduced reliance on fossil fuel-derived inputs on their farms. Organic growers have already found alternatives to the neonicotinoid insecticides that are implicated in the loss of honeybee pollinators. Their crops are delivered in short supply chains as fresh, nutritious crops to metropolitan and rural areas that add layers to the existing food system, contributing to resilience in food security and offsetting the vulnerabilities imposed by reliance on food sourced at long national or global distances which can be affected by weather events and international relations.

Although the results of past breeding roundtables have been very useful in helping to steer organic breeding projects, organic agriculture has undergone significant changes in the past ten years and information about the specific current production constraints and needs of growers was needed in order to inform all future organic breeding. This current work reevaluates emerging and continuing needs to assure that organic vegetable breeding and seed production are accurately and appropriately addressing the needs of farmers here in the Northeast.

Organic Vegetable Breeding Needs Survey

In the spring of 2015, we created and shared a needs assessment survey with vegetable farmers growing organically in the Northeast to identify future breeding priorities for organic vegetable production. We hope that this work will support organic vegetable production in the Northeast.

Using Cornell's in-house survey software (Qualtrics), we created the "Organic Vegetable Breeding Needs Assessment Survey". This public, anonymous survey was activated on February

9th, and closed on May 1st, 2015. The survey asked respondents to identify crop varieties that they consider critical to their production, target traits in major vegetable crops that they think should be priorities for breeding and new cultivar introduction for the Northeast, and the major biotic constraints with which they contend (see Appendix A). The survey had five sections. For most of the survey questions (except for rating questions), respondents were allowed to provide more than one response.

- **Section 1** asked respondents to provide basic demographic information about themselves and their production practices; this allows us to differentiate the responses of individuals whose farms have been certified organic (and must therefore comply with more stringent production standards), and those who use mixed practices.
- **Section 2** highlighted potential vulnerabilities in the organic seed supply. Respondents listed varieties of crops that they rely on disproportionately – that is, the varieties that would be a significant loss if the seed were no longer provided as organic or untreated seed – and elaborated on the qualities which make those varieties unique.
- **Section 3** asked respondents to identify any crop varieties that they have relied on in the past, but which are no longer available (having been discontinued by the seed company who previously sold them).
- **Section 4** provided respondents the opportunity to suggest improvements on existing crop varieties.
- **Section 5** asked growers to identify major pests affecting their production, to rate the importance of resistance to various biotic constraints, and to rate the importance of various quality traits. Growers were asked to rate the importance of resistance of various crops to biotic stresses. Ratings were from '1 – Resistance is a critical priority' to '5 –

This pest/disease is not a problem'. Growers were asked to rate the importance of various seed qualities. Ratings were from '1 – High priority – please focus on this in your breeding!' to '5 – Not important'.

To reach appropriate growers, we created a database of contacts using the 2014 USDA-NOP database of certified-organic growers (downloaded from http://apps.ams.usda.gov/nop/) to find contact information for growers in the Northeast (CT, ME, MA, NH, NJ, NY, PA, RI, VT) who produced vegetables. We then contacted certifying agencies to inquire whether they had more updated contact lists that they could share with us (Supplementary Table S1). We also contacted relevant grower-focused organizations to ask if they could share the survey in any upcoming communication with their members, or through their social media sites (Supplementary Table S1). The goal of this work was to identify breeding needs for organic production, so we also sought to integrate those who use techniques or approaches that directly overlap with the National Organic Program Standard, but who are not organically certified. In order to do this, we searched NOFA chapter lists of growers who had signed the NOFA-NY Farmer's Pledge™, the NOFA/Mass Sustainability Pledge, and the NOFA-CT Farmer's Pledge. We were then able to filter responses by asking respondents to identify whether some or all of their practices are aligned with the National Organic Program (NOP) standard.

On February 9th, we sent an email with a link to the survey to our contacts (n = 1,003), encouraging growers to share their thoughts with us and share the survey link with others who might be interested. We sent two reminder emails before the survey closed on May 1st.

The survey was completed by 210 participants; while 250 surveys were started online, only 210 provided information to at least one of the questions (see Figure 2.1 for state representation). Of these, 123 (59%) respondents identified their operations as 'Certified Organic', with the remainder of respondents growing according to NOP-standards (but not certified), according to the 'Naturally Grown' standard, or using a combination of conventional and NOP-compliant practices (Figure 2.2). The results discussed in this report exclude growers who reported cultivating vegetables on less than 1 full acre of land. (See Appendix B for complete survey responses.)

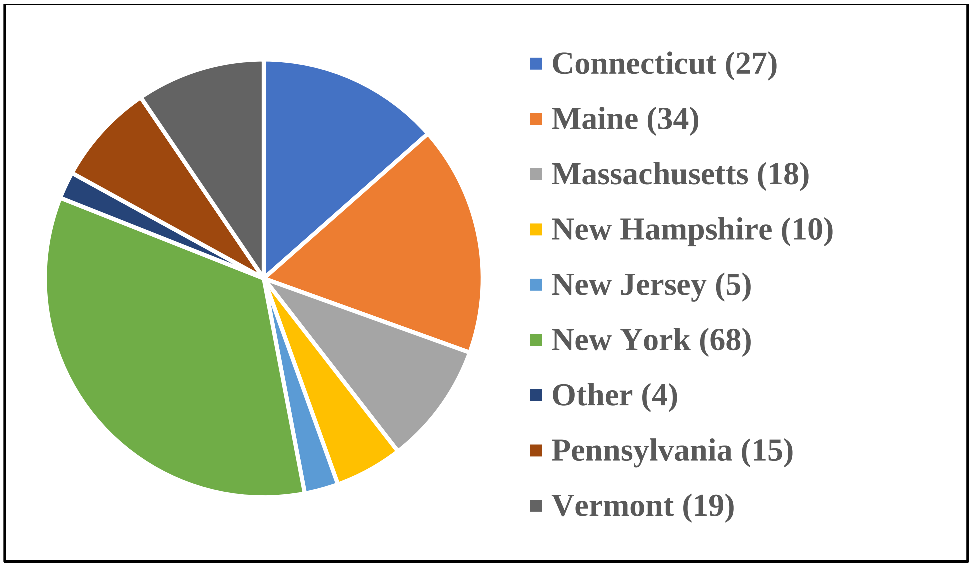


Figure 2.1 Survey respondents by state

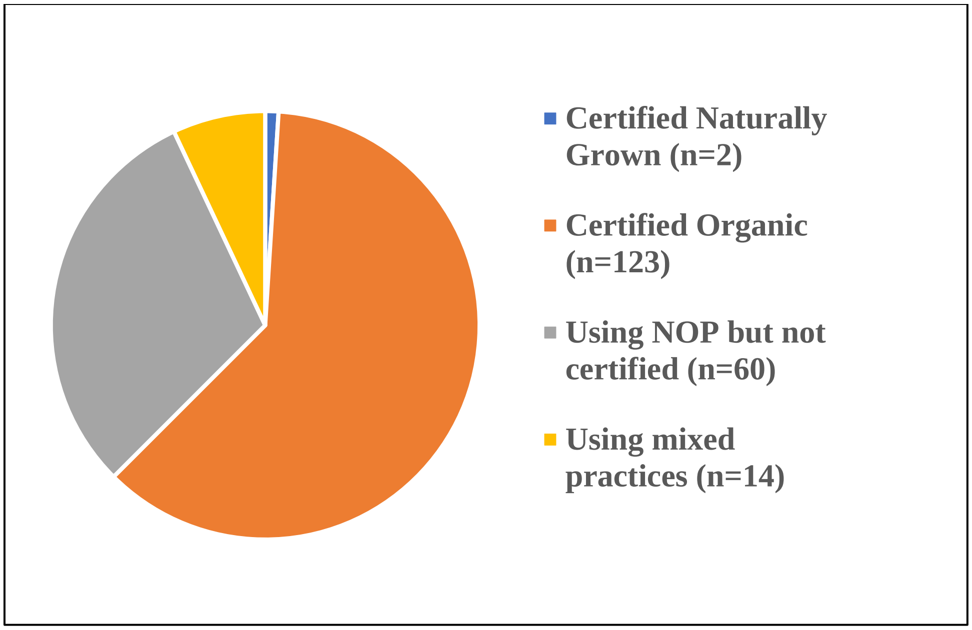


Figure 2.2 Type of management used by survey respondents

Highlights of survey results

Though the survey was explicitly focused on vegetable production, we received several non-vegetable responses (e.g. grain and perennial fruit crops) to some of the questions; while these responses are a reminder of the crop diversity grown on small organic produce farms, they have been removed from the figures below.

Critical Varieties

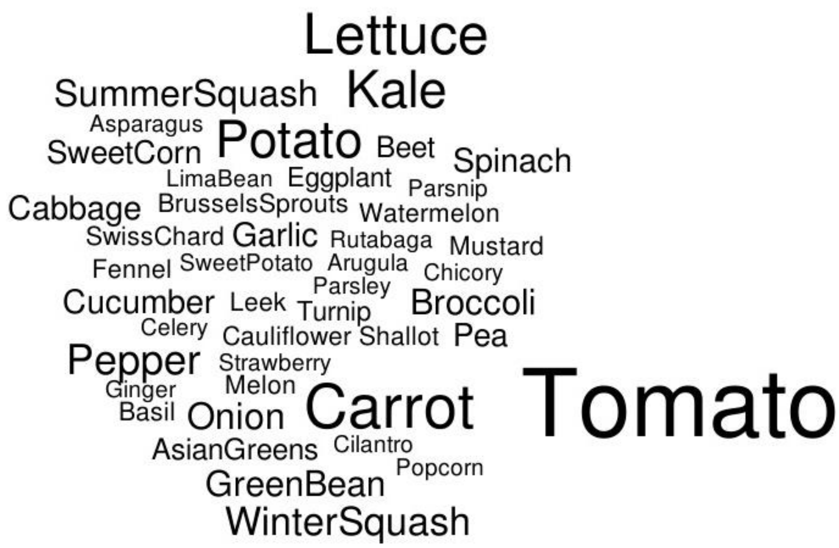
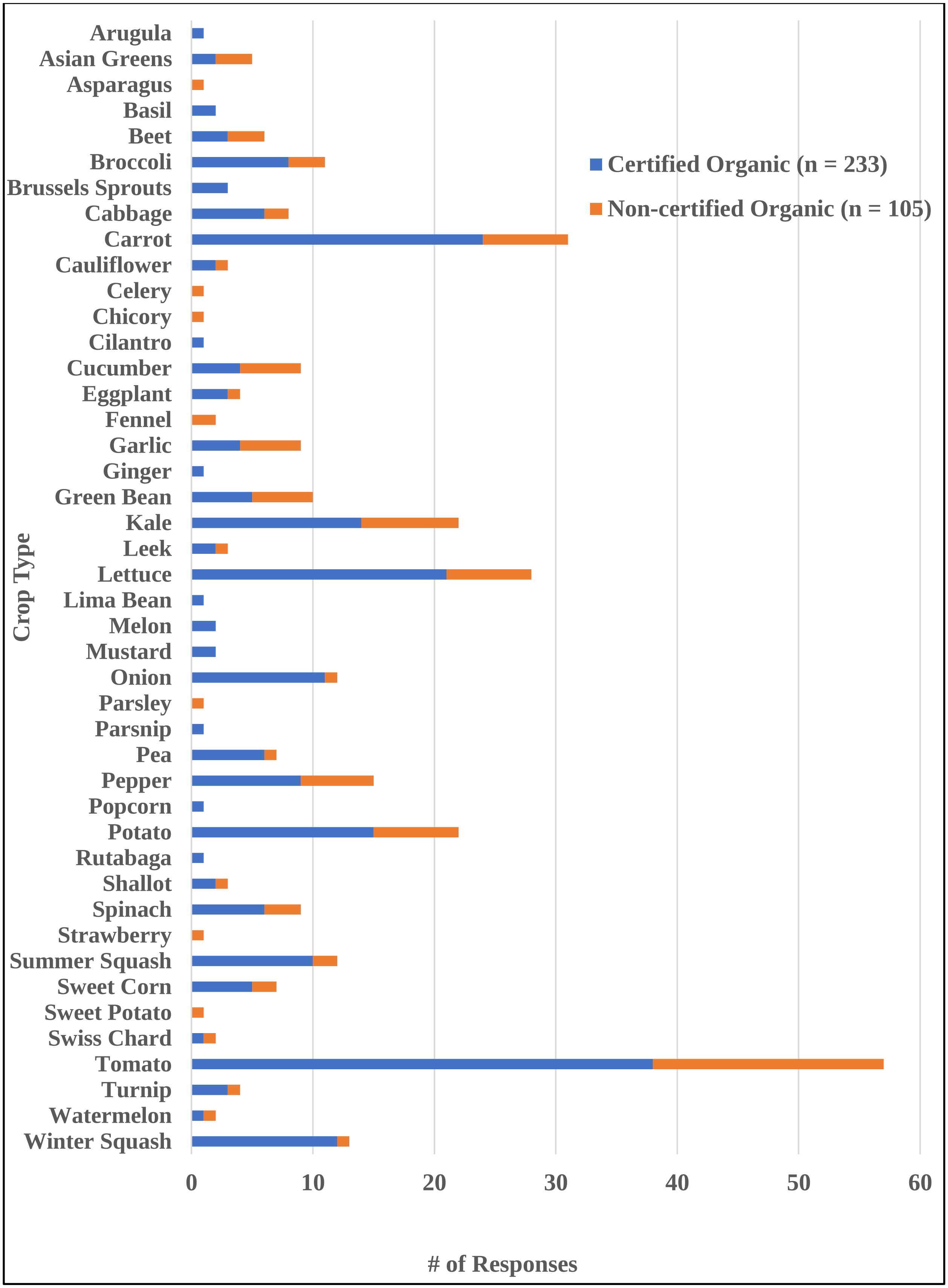


Figure 2.3 Crop type for critical varieties used in organic vegetable production in the Northeast. Size of words based on number of responses of that crop type received in needs assessment survey (higher count = larger words), not the number of distinct varieties mentioned within a crop.

We received 341 responses identifying critical crop varieties (233 of these identified by certified organic growers) (Figures 2.3 and 2.4). These are cultivars upon which growers rely on disproportionately, such that they would find themselves at tremendous loss if the seed were suddenly unavailable in an appropriate, useable form. Growers listed varieties of tomato as being critical to their production more than any other crop; as tomatoes are a high-demand vegetable, this was an unsurprising result.

Figure 2.4 Response counts for "Section II: Critical Crop Varieties" by crop type. Respondents identified cultivars upon which their production relied on heavily, indicating the crop type, cultivar name, and key attributes of the cultivar.


Arugula
Asian Greens
Asparagus
Basil
Beet
Broccoli
Brussels Sprouts
Cabbage
Carrot
Cauliflower
Celery
Chicory
Cilantro
Cucumber
Eggplant
Fennel
Garlic
Ginger
Green Bean
Kale
Leek
Lettuce
Lima Bean
Melon
Mustard
Onion
Parsley
Parsnip
Pea
Pepper
Popcorn
Potato
Rutabaga
Shallot
Spinach
Strawberry
Summer Squash
Sweet Corn
Sweet Potato
Swiss Chard
Tomato
Turnip
Watermelon
Winter Squash
Crop Type
Certified Organic (n = 233)
Non-certified Organic (n = 105)
0
10
20
30
40
50
60
# of Responses

Though the National Organic Program (NOP) standard requires that certified-organic growers use only organic seed when available, the exemption allows farmers to use non-organic, untreated seeds when an "equivalent organically produced variety is not commercially available". These survey responses make evident the fact that Northeast organic vegetable growers rely heavily upon varieties bred for conventional management. We conducted searches using PickaCarrot.com (a website with a feature to allow growers to locate sources of organically produced seed) to determine whether each variety was commercially available as organic seed. Many of the most heavily represented critical varieties are available only as conventionally produced, untreated seeds (Table 2.1).

Table 2.1 Most frequently listed varieties for "Section II: Critical Crop Varieties"

Crop Type	Most frequently listed critical variety (count/total)	Hybrid (F_1) / OP	Cultivar available as organically-certified seed
Beet	Red Ace (5/6)	F_1	Yes
Broccoli	Gypsy (5/11)	F_1	No
Cabbage	Storage #4 (4/8)	F_1	No
Carrot	Bolero (18/31)	F_1	No
Cucumber	Marketmore 76 (3/9)	OP	Yes
Green Bean	Provider (3/10)	OP	Yes
Kale	Winterbor (14/22)	F_1	Yes
Lettuce	Various	OP	Yes
Onion	Copra (3/12)	F_1	No
Pea	Sugar Snap (5/7)	OP	Yes
Pepper	Carmen (4/15)	F_1	Yes
Spinach	Tyee (3/9)	F_1	Yes
Summer Squash	Zephyr (3/12)	F_1	No
Sweet Corn	Luscious (2/7)	F_1	Yes
Tomato	Sungold (15/57)	F_1	No
Winter Squash	Delicata (5/13) *	OP	Yes

*Respondents primarily listed 'Delicata', which is a market class, not a specific variety, of winter squash.

Survey respondents rated the availability of variety as organically-certified seed as a high priority (Figure 2.5), and in their comments, growers noted that they lack appropriate organic options for these crops, and expressed interest in organically produced seed.

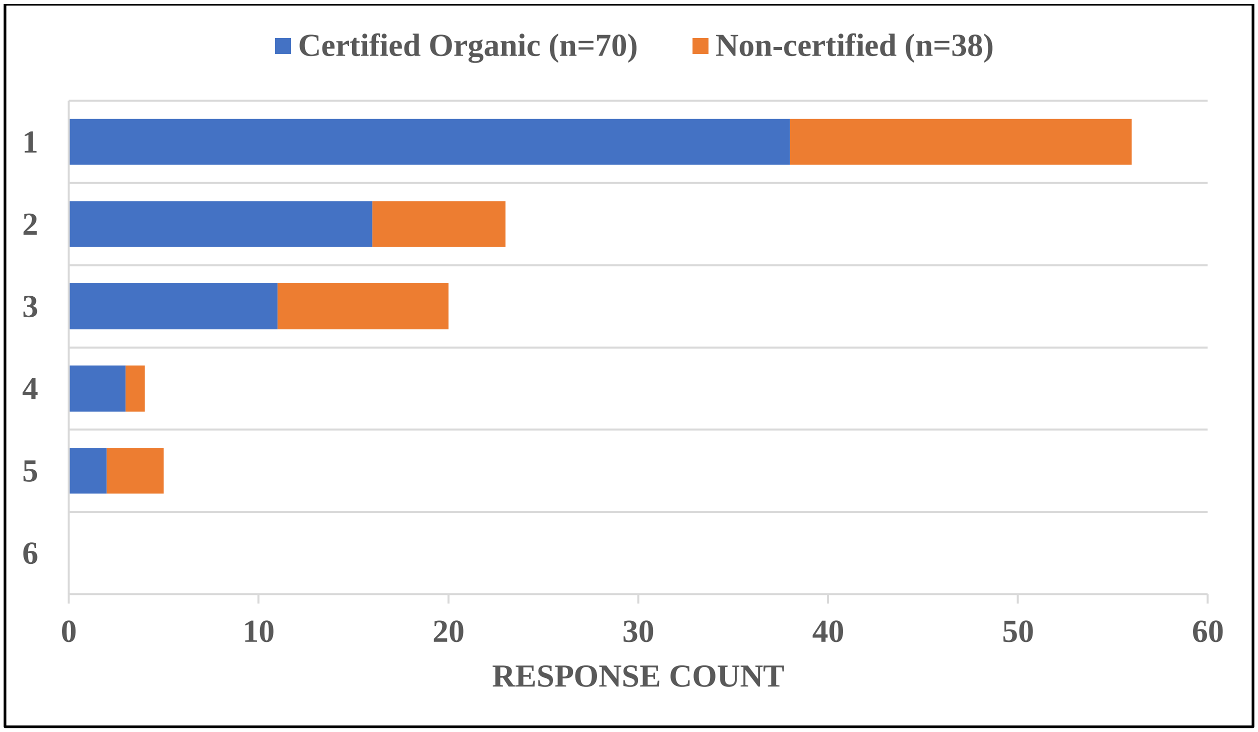


Figure 2.5 Response counts rating the importance of availability of a given cultivar as organically certified seed.
Key for Figure 2.5
1 - High priority - Please focus on this in your breeding!
3 - Somewhat important
5 - Not important
6 - Unsure

Below are examples of comments made in the survey (all sections of italicized text in this report are direct, unedited quotes from the 'additional comments' section of the survey).

General *"The organic seed requirement is a real quandary-- so many of my favorite and most profitable varieties are not organic."*
Bolero carrots *"I would also like it as an organic option, not just untreated."*
Sungold tomato *"Main variety used for rainbow cherry mix. I keep looking for a good OG substitute."*
"This variety is my single biggest seller. I keep looking for an organic substitute, but have not found it yet."
"Chefs favorite. Cannot get similar in organic that is as good."

Hakurei turnip *"So delicious and tender. We've tried the other salad turnip varieties because we're so uncomfortable with our reliance on Hakurei turnips. But no other variety compares so far."*
Sugar Snap pea *"We love the taste and it has always been a dependable variety for us. Last year we had trouble getting it organically and were not pleased with the alternatives."*
Sunburst summer squash *"This variety seems to show resistance to cucumber beetles compared to green summer squash. Not available organically in organic, and other similar varieties do not produce as well."*

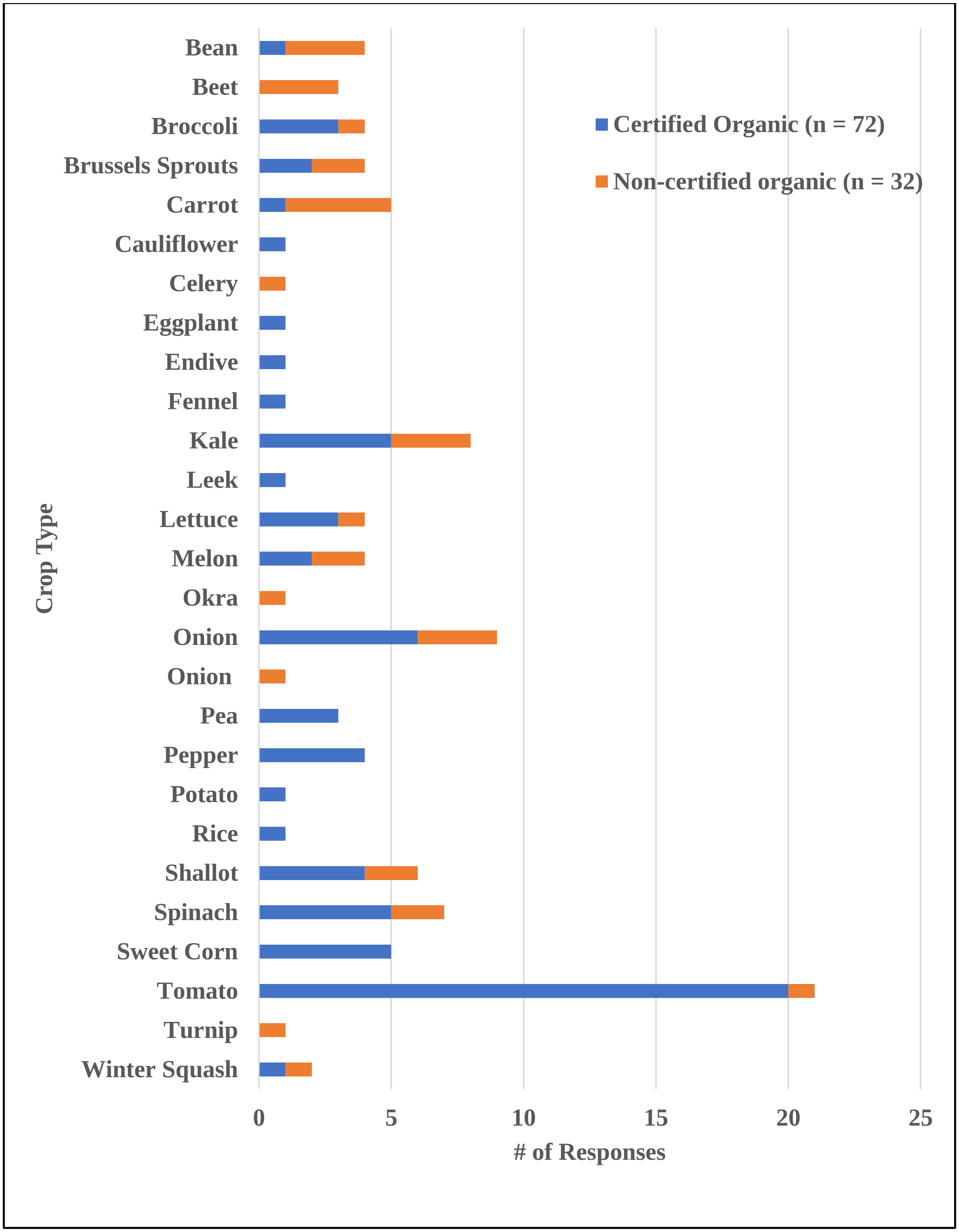
The inability of certified vegetable growers to obtain organic seed for their most important varieties is a handicap to organic production. Conventionally produced seeds are only allowed under the exemption so long as they are available untreated. If the seed companies offering these critical varieties choose to discontinue the lines as untreated seeds, organic vegetable production would suffer without adequate replacements.

Finding organic seed is a major issue. Most of the varieties that wholesale growers use are not available organically, and our certifier says we need 70%+ organic seed. Most of the organic varieties will not produce vegetables that our wholesale buyers will accept.

Lost varieties

Participants provided 106 responses to the question about 'lost' varieties (73 were identified by certified organic growers) (Figure 2.6). Using the Pick a Carrot search engine, it is clear that some of these varieties have not been discontinued permanently; instead, some that have been dropped from familiar catalogues are still offered by other seed companies. Diversifying the sources from which they obtain seeds can help growers to assure that they can continue to grow their critical varieties. However, expanding their seed search to include all possible sources requires a dedication of time and effort that producers likely do not have. Dependency on a single cultivar or a single source can create vulnerability; the organic vegetable seed production community can help mitigate this dependency by making it easier for growers to find the varieties they want to use, and by assuring that there are appropriate replacement varieties for those being discontinued.

Figure 2.6 Response counts for “Section III: Critical Crop Varieties that are no longer available” by crop type. Respondents identified cultivars which they were no longer able to purchase, indicating the crop type, cultivar name, key attributes of the cultivar, and the company from which they last purchased the seed.


Certified Organic (n = 72)
Non-certified organic (n = 32)
Crop Type
Bean
Beet
Broccoli
Brussels Sprouts
Carrot
Cauliflower
Celery
Eggplant
Endive
Fennel
Kale
Leek
Lettuce
Melon
Okra
Onion
Onion
Pea
Pepper
Potato
Rice
Shallot
Spinach
Sweet Corn
Tomato
Turnip
Winter Squash
0
5
10
15
20
25
# of Responses

Varieties to Improve

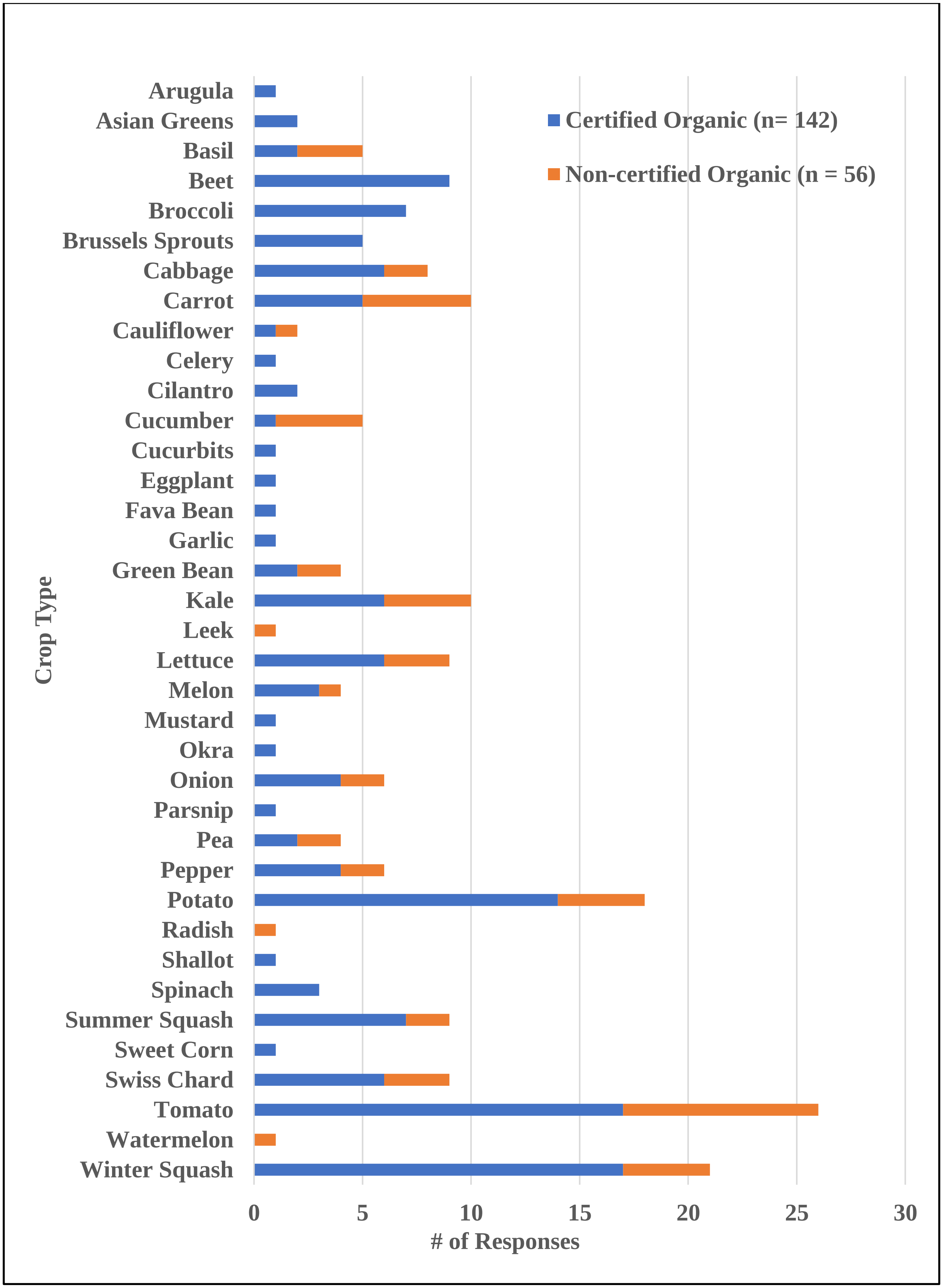
Participants suggested 198 improvements on existing crop varieties (142 were identified by certified organic growers) (Figure 2.7). Major themes in the responses included the need for improvement in storability, cold hardiness, and pest & disease resistance, and the importance of quality traits.

The Northeast is a climatically unique region. The ability of a variety to reliably produce regardless of a given year's specific weather is particularly important here in the Northeast. Heat tolerance, cold hardiness and frost tolerance were highlighted as needs in survey responses for broccoli, cabbage, arugula, Swiss chard, onion, kale, leek and lettuce.

The suggested improvements (see Appendix B for respondents' full comments) highlight the role of high tunnel production for organic vegetables in the Northeast. Many of the traits prioritized at the 2015 working group meeting indicate that significant production already occurs in covered high tunnels and acknowledge the challenges unique to those growing conditions (see Table 2.3). The 2015 Vegetable PWT Research and Extension Priority Survey, conducted by Cornell Cooperative Extension's Vegetable Program Work Team, asked fresh market vegetable growers in New York State about their growing practices: 69% of the 187 respondents indicated that they use methods such as high tunnels and row cover for season extension (Zuefle et al. 2016). Northeast farmers rely on high tunnels to ameliorate temperature and damaging weather events (e.g. hail), thereby reducing their risk of crop failure and allowing production into times of the year when conditions would not otherwise be favorable. Priorities such as low light tolerance in arugula and spinach, and overwintering in lettuce would not be of great use to NE growers not already taking advantage of high tunnel production. While high tunnels allow greater control over growing conditions, they also bring challenges, such as the potential for increased disease and insect pest pressure. In a high tunnel, a crop can be in the ground for a longer season, allowing pests and pathogens to build up; additionally, air flow is reduced by the high tunnel itself, encouraging the establishment and growth of pathogens like gray mold on tomatoes, downy mildew on cucurbits, and white mold in beans. Breeding for tolerance to the unique conditions of high tunnels and resistance to pathogens with greater severity in high tunnels is clearly needed to support organic vegetable production in our region.

Storage is another critical component to extending the season and assuring steady income in winter months. As one grower noted, storable varieties are 'important to full year productive sales'. From the responses we received in the survey, storability was evidently a major factor in choosing important varieties of some crops (Figure 2.8). For example, some growers noted that they value Red Ace and Detroit Dark Red beets because these varieties store well after harvest. Storage and field-holding ability was also consistently mentioned as a reason for importance for cultivars of carrots, cabbage, garlic, kale, leek, onion, potato, and winter squash. Shelf life was noted as important for some varieties of tomato. Growers indicated that cultivars of cabbage, onion, pumpkin, potato, and winter squash (spaghetti squash, buttercup, butternut and delicata type squashes) would benefit from improved storability.

Figure 2.7 Response counts for “Section IV: New varieties that need to be developed” by crop type. Respondents identified cultivars that could be improved upon, indicating crop type, cultivar name, important current attributes, and suggested improvements.


Certified Organic (n= 142)
Non-certified Organic (n = 56)
Crop Type
Arugula
Asian Greens
Basil
Beet
Broccoli
Brussels Sprouts
Cabbage
Carrot
Cauliflower
Celery
Cilantro
Cucumber
Cucurbits
Eggplant
Fava Bean
Garlic
Green Bean
Kale
Leek
Lettuce
Melon
Mustard
Okra
Onion
Parsnip
Pea
Pepper
Potato
Radish
Shallot
Spinach
Summer Squash
Sweet Corn
Swiss Chard
Tomato
Watermelon
Winter Squash
0
5
10
15
20
25
30
# of Responses

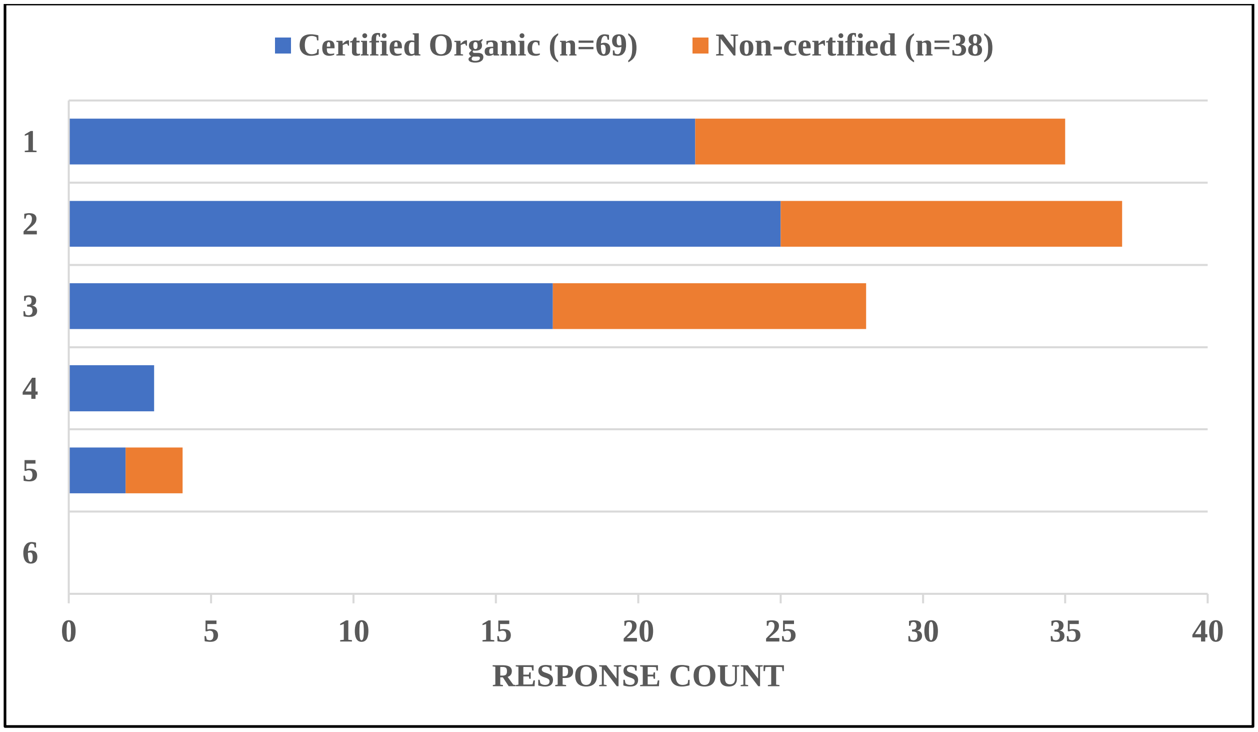


Figure 2.8 Response counts rating the importance of crop storability as a breeding priority.
Key for Figure 2.8
1 - High priority - Please focus on this in your breeding!
3 - Somewhat important
5 - Not important
6 - Unsure

Respondents value quality traits highly – the varieties they depend on are those that appeal to customers with notable appearance and flavor, and the improvements they suggest involve increasing production qualities. When asked to provide the best attributes of the varieties to improve, growers listed primarily quality-related words: sweet, flavor, look, marketability, taste, aroma, delicious, beautiful, color, distinctive, tender, appearance, texture, shape, popular, gorgeous, mild, smooth skin, creamy, attractive, crisp, vibrant, uniformity, consistent marketable shape and size, reliable performer. The vast majority of growers rated flavor as a high priority, indicating that breeding efforts should focus on maintaining or improving quality in addition to agronomic traits (Figure 2.9).

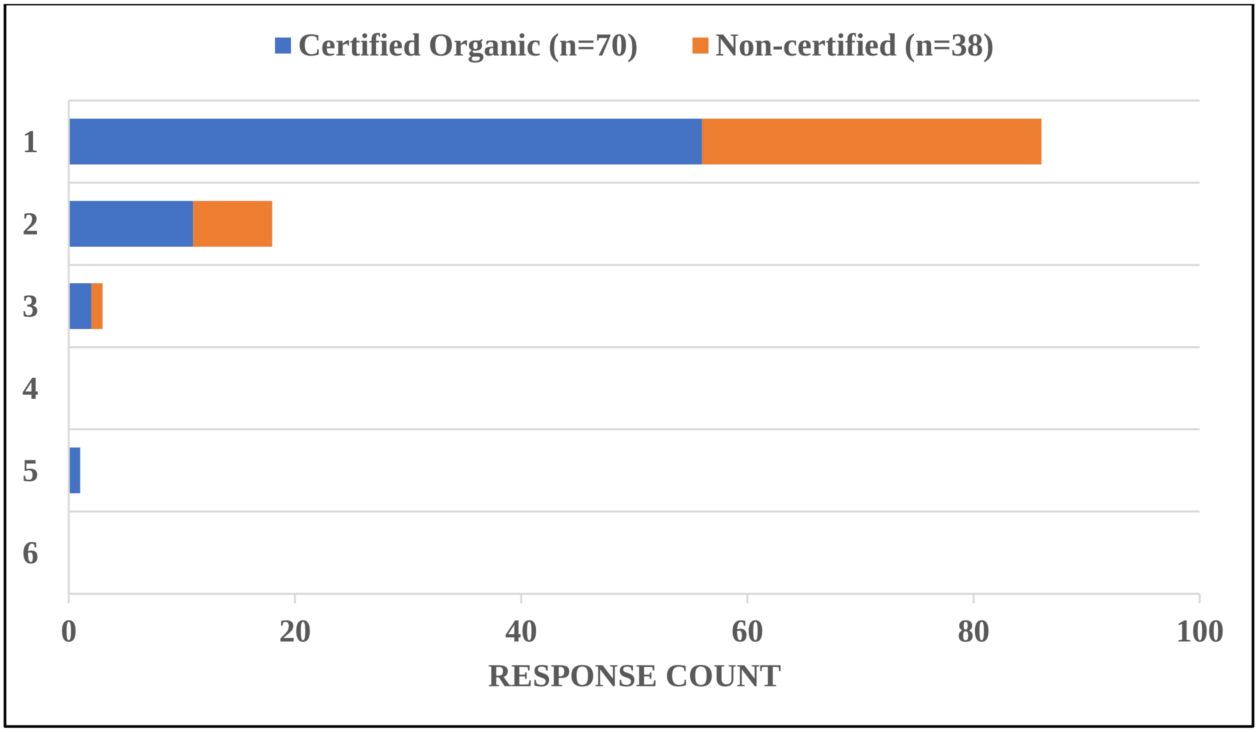


Figure 2.9 Response counts rating the importance of flavor as a breeding priority.
Key for Figure 2.9
1 - High priority - Please focus on this in your breeding!
3 - Somewhat important
5 - Not important
6 - Unsure

Pests & diseases

Growers were asked to identify pest problems that affect their crop production (by reducing yield, quality, and/or marketability) and are difficult to control (e.g. require spraying nearly every year, row covers, and/or other special treatment). While the question asked about pests specifically, respondents identified both pests and pathogens; we received 411 responses identifying pests and diseases constraining vegetable production (272 of these were identified by certified organic growers) (Figures 2.10, 2.11, and 2.12).

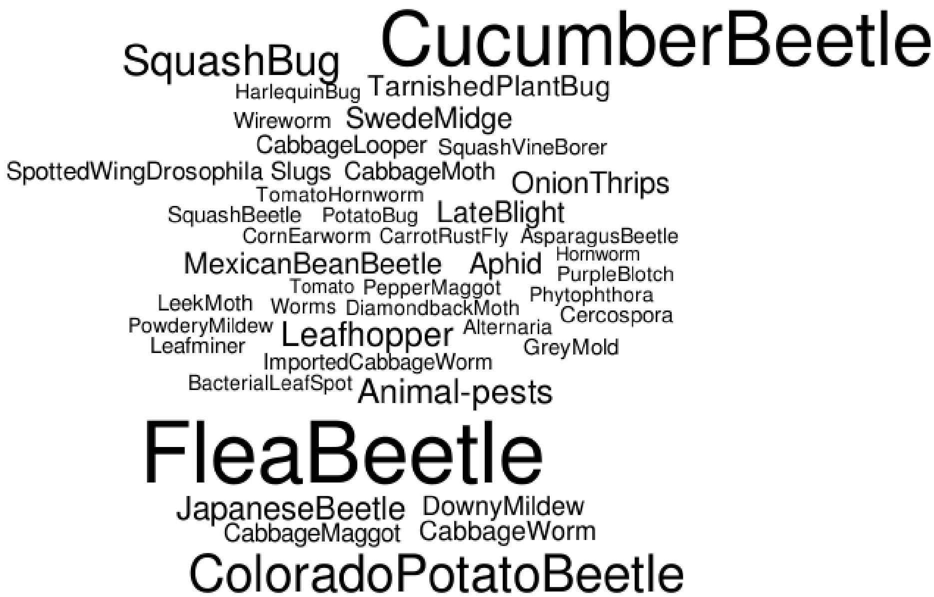


Figure 2.10 Word cloud of pest and diseases constraining organic vegetable production in the Northeast. Size of words based on number of responses received in needs assessment survey (higher count = larger words). (Excludes pests that received fewer than 2 responses.)

It is important to note that while this question asks about pests with significant impact, the responses suggest incidence more than severity; responses indicate the presence and importance of a pest without providing clear quantitative data on the amount or type of damage they inflict. The prominence of ‘flea beetle’, for example, points to flea beetles being a common problem for organic growers, but not, necessarily, an urgent one.

Some of the pests that respondents identified are continuing needs. For these pests with broad host ranges, there may be quantitative variation that breeders may exploit, however it is unlikely that breeding alone will mitigate their impact, as the germplasm sources of resistance are often still unknown. These constraints will need to be addressed through other efforts. In the case of cucumber beetles, the ability of conventional growers to apply effective pesticides has moved interest away from striped cucumber beetles. For organic growers without such options, the current work of the Mazourek lab to identify and incorporate sources of resistance into appropriate cultivars is an example of focused research efforts being fruitful in this area.

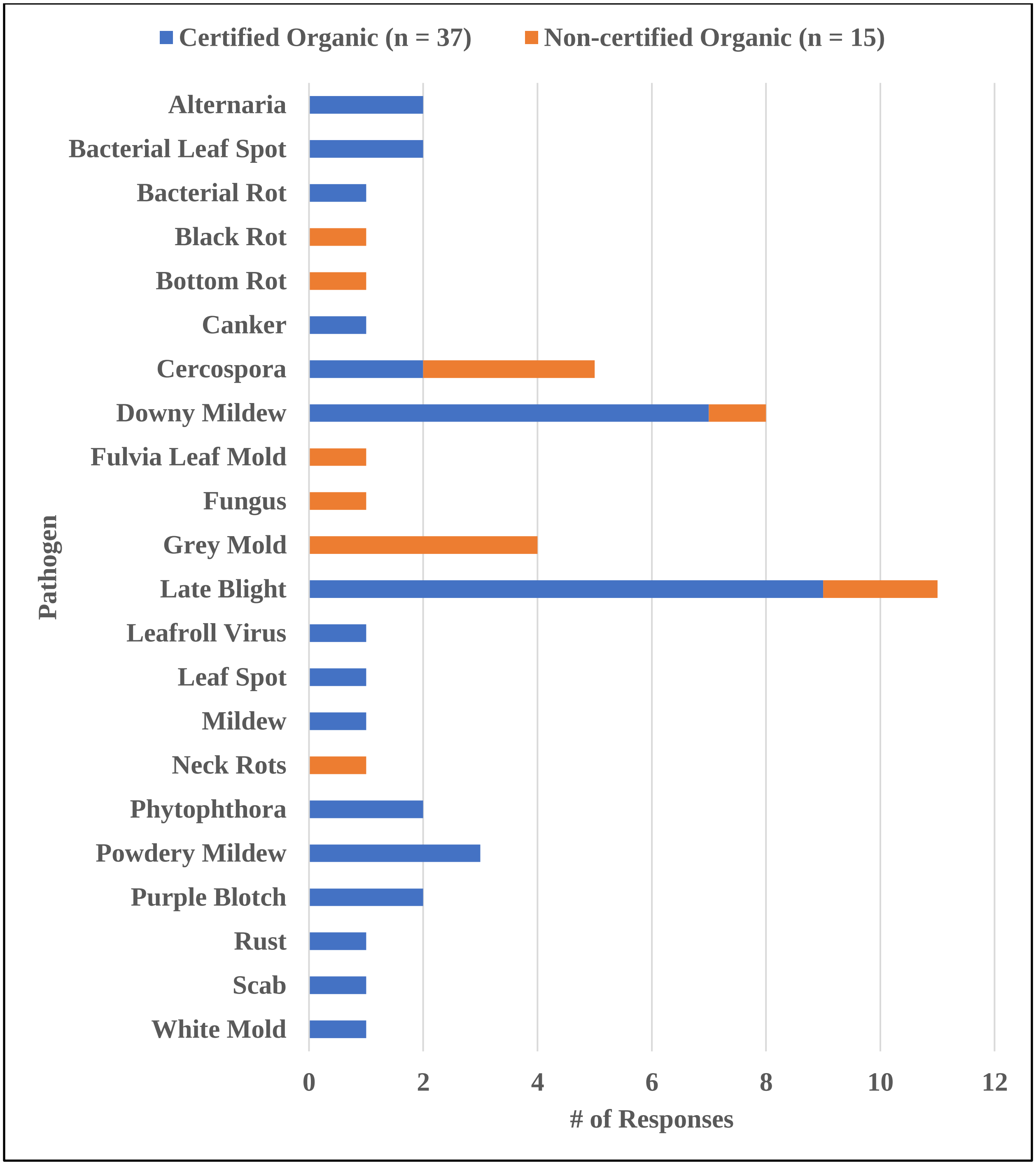
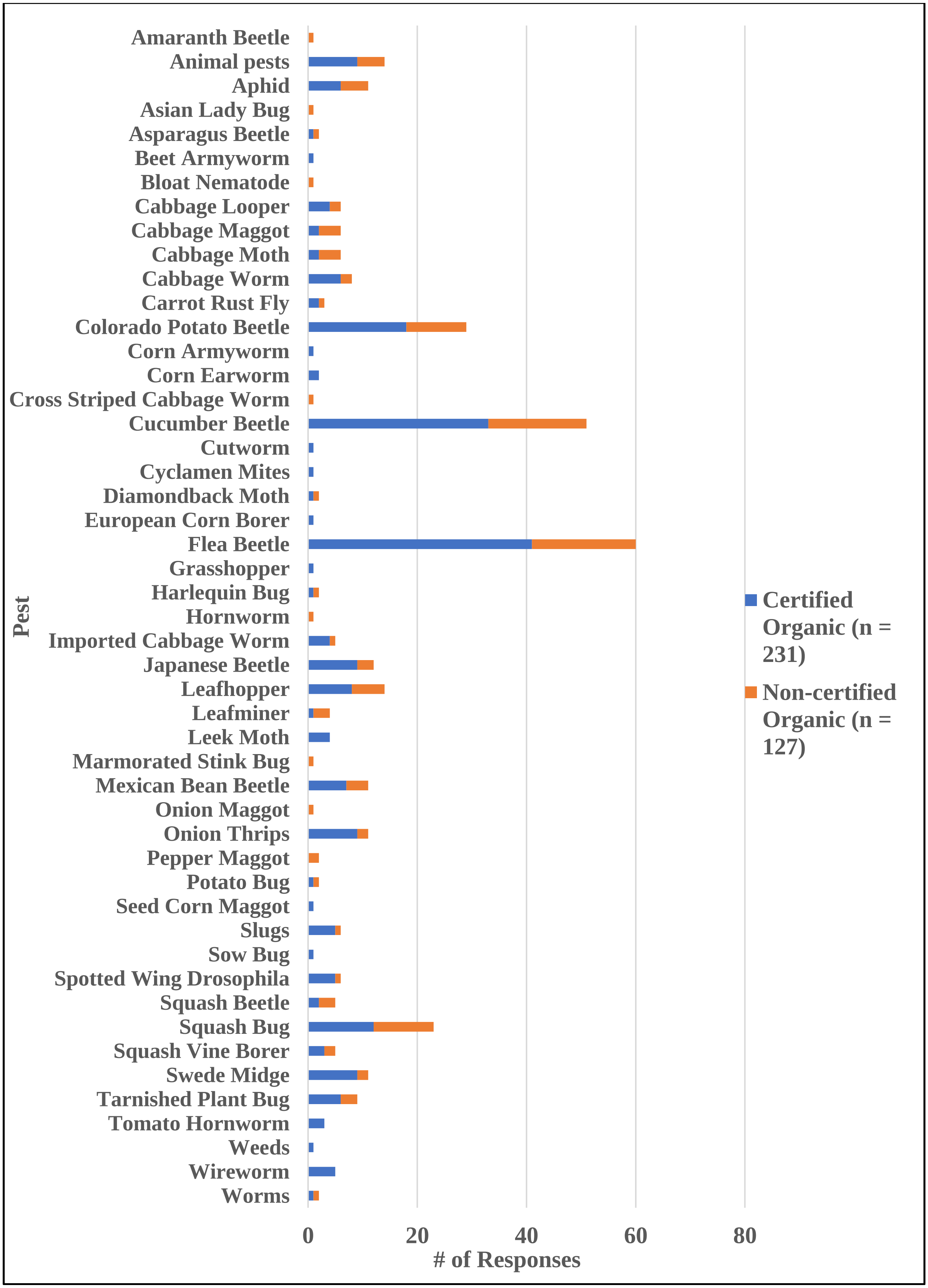


Figure 2.11 Survey response counts for “Section V: Production Challenges” identifying production constraints (infectious pathogens) to organic vegetable production in the Northeast.

Figure 2.12 Survey response counts for "Section V: Production Challenges" identifying production constraints (non-infectious pests) to organic vegetable production in the Northeast.



Amaranth Beetle
Animal pests
Aphid
Asian Lady Bug
Asparagus Beetle
Beet Armyworm
Bloat Nematode
Cabbage Looper
Cabbage Maggot
Cabbage Moth
Cabbage Worm
Carrot Rust Fly
Colorado Potato Beetle
Corn Armyworm
Corn Earworm
Cross Striped Cabbage Worm
Cucumber Beetle
Cutworm
Cyclamen Mites
Diamondback Moth
European Corn Borer
Flea Beetle
Grasshopper
Harlequin Bug
Hornworm
Imported Cabbage Worm
Japanese Beetle
Leafhopper
Leafminer
Leek Moth
Marmorated Stink Bug
Mexican Bean Beetle
Onion Maggot
Onion Thrips
Pepper Maggot
Potato Bug
Seed Corn Maggot
Slugs
Sow Bug
Spotted Wing Drosophila
Squash Beetle
Squash Bug
Squash Vine Borer
Swede Midge
Tarnished Plant Bug
Tomato Hornworm
Weeds
Wireworm
Worms
Pest
0
20
40
60
80
# of Responses
Certified Organic (n = 231)
Non-certified Organic (n = 127)

While there were 72 distinct pests and diseases identified through the survey, a subset of them appeared more often in the responses (Table 2.2). It is unclear the extent to which each response represents a correct positive identification of the pest in question; it is possible that the frequency of some is due in part to the ease of their identification. Many different cabbage pests were identified; even if some were misidentified, the responses point to growers having the extension support (in the form of in-person agents or printed/online material) necessary to be able to name the pests specifically. Growers are certainly familiar with many pests, which is encouraging.

Finally, as the Northeast continues to experience changing weather patterns, we can expect conditions to impact the geographical ranges of agricultural pests, leading to greater incidence in some. Knowing the major pest and disease challenges faced by growers will allow breeding efforts to prioritize the resistance traits being incorporated into new cultivars.

Table 2.2 Most frequently listed pests for "Section V: Production Challenges"

Pest	**Crop type most affected**	**Count of responses (of 411 total)**
Flea Beetle	Solanums and Brassicas	60
Cucumber Beetle	Cucurbits	51
Colorado Potato Beetle	Solanums	29
Squash Bug	Cucurbits	23
Leafhopper	Potato	14
Japanese Beetle	Berry crops	12
Aphid	All	11
Late Blight	Tomatoes	11
Mexican Bean Beetle	Bean	11
Onion Thrips	Alliums	11
Swede Midge	Brassicas	11

Rating Resistance Traits

Growers were asked to rate the importance of particular resistance traits, from 'Focus on this in your breeding!' to 'This disease/pest is not a problem'. These particular resistance traits are priority areas of focus for the Mazourek lab at Cornell University in order to gauge whether our work in cucurbits and peppers is aligned with grower needs. Of the biotic stresses listed, resistance to downy mildew in cucumber & melons (Figure 2.13) and striped cucumber beetles in cucurbits (Figure 2.14) was rated as being of particularly high importance. Powdery mildew resistance in cucumbers, melons or squash was also rated as a critical priority (Figure 2.15), though such resistance already exists in commercially available cultivars. This rating points to a lack of information for growers and highlights the need to improve the accessibility of cultivar information; it is also possible that powdery mildew resistance is not yet available in grower-preferred cultivars. For organic growers, resistance against bacterial wilt in cucumbers, melons and/or squash (Figure 2.16), Phytophthora blight in peppers, squash and/or pumpkin (Figure 2.17), and viruses in all crops (Figure 2.18) were not as highly prioritized by respondents.

Figures 2.13-2.18. Response counts rating the importance of specific resistance traits as breeding priorities.

Key for Figures 2.13-2.18

1 - Resistance is a critical priority – please focus on this in your breeding!
3 - Resistance would be helpful
5 - This pest/disease is not a problem
6 - Unsure
7 - I don't grow this crop

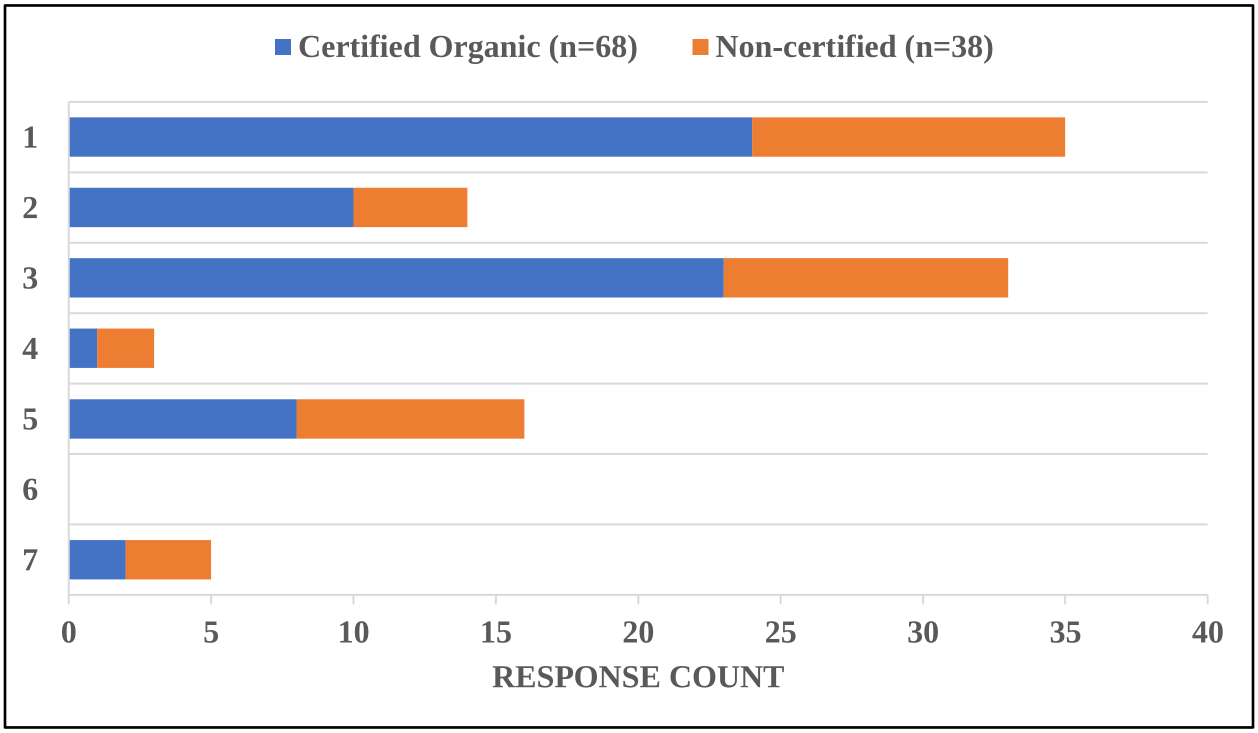


Figure 2.13 Survey response counts rating the importance of downy mildew in cucumbers and melons as a breeding priority

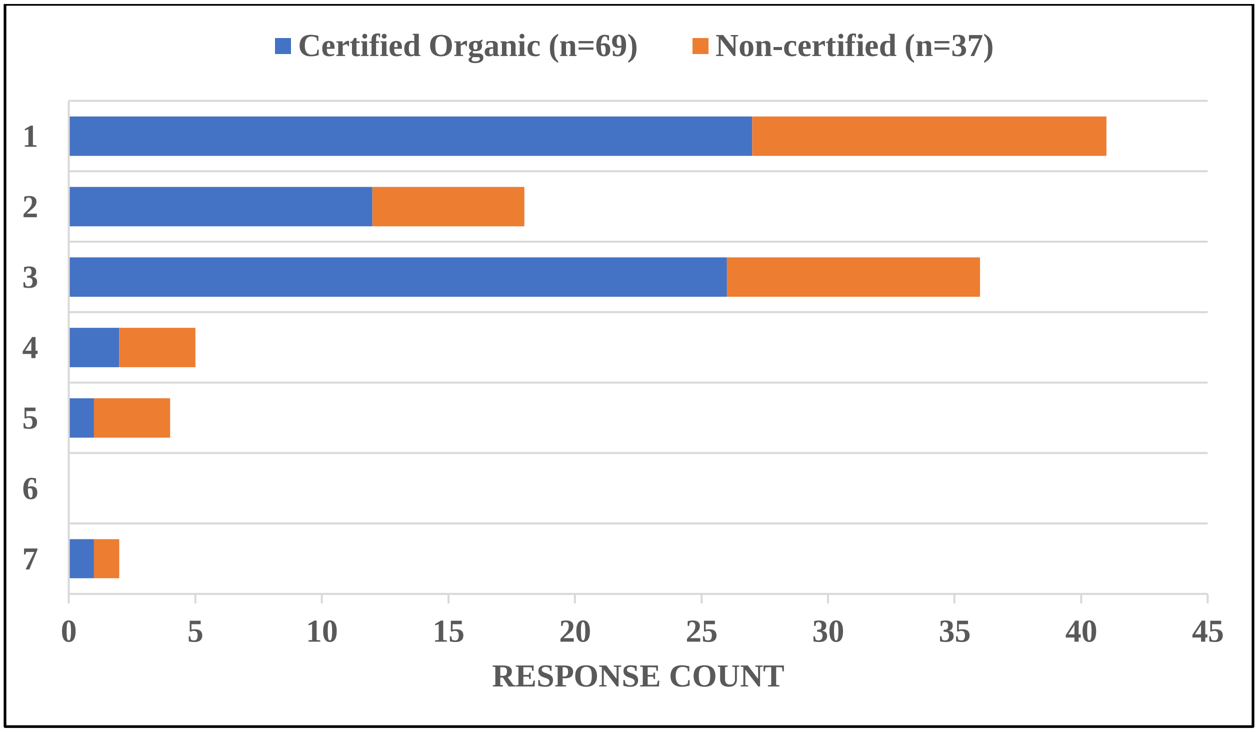


Figure 2.14 Survey response counts rating the importance of resistance to striped cucumber beetles in cucumbers, melons and/or squash

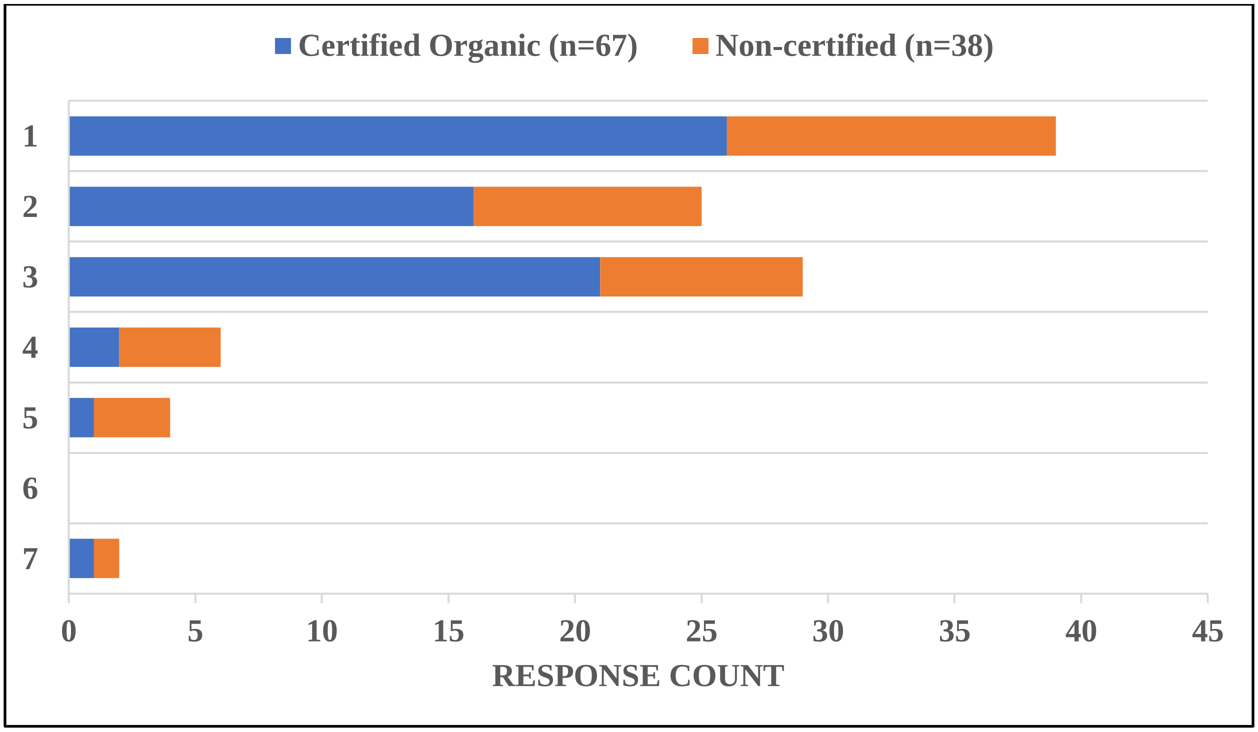


Figure 2.15 Survey response counts rating the importance of resistance to powdery mildew in cucumbers, melons and/or squash

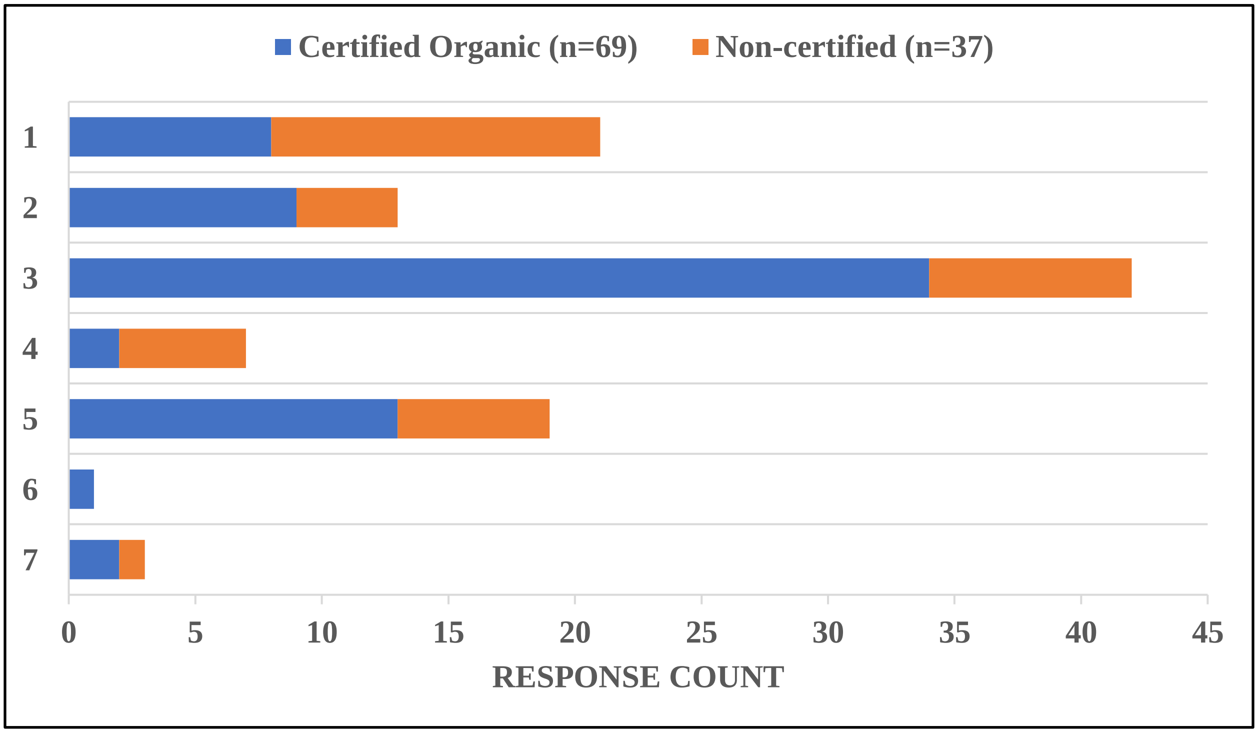


Figure 2.16 Survey response counts rating the importance of resistance to bacterial wilt in cucumbers, melons, and/or squash

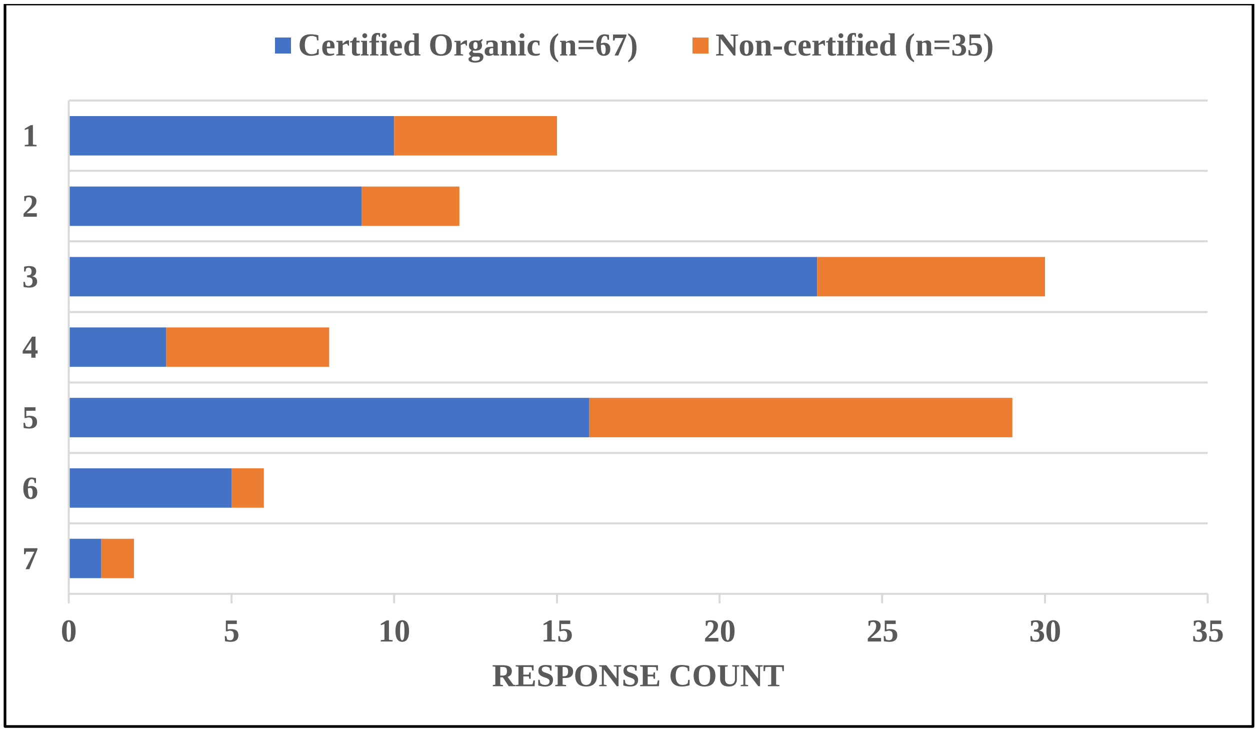


Figure 2.17 Survey response counts rating the importance of resistance to Phytophthora blight in peppers, squash and/or pumpkin

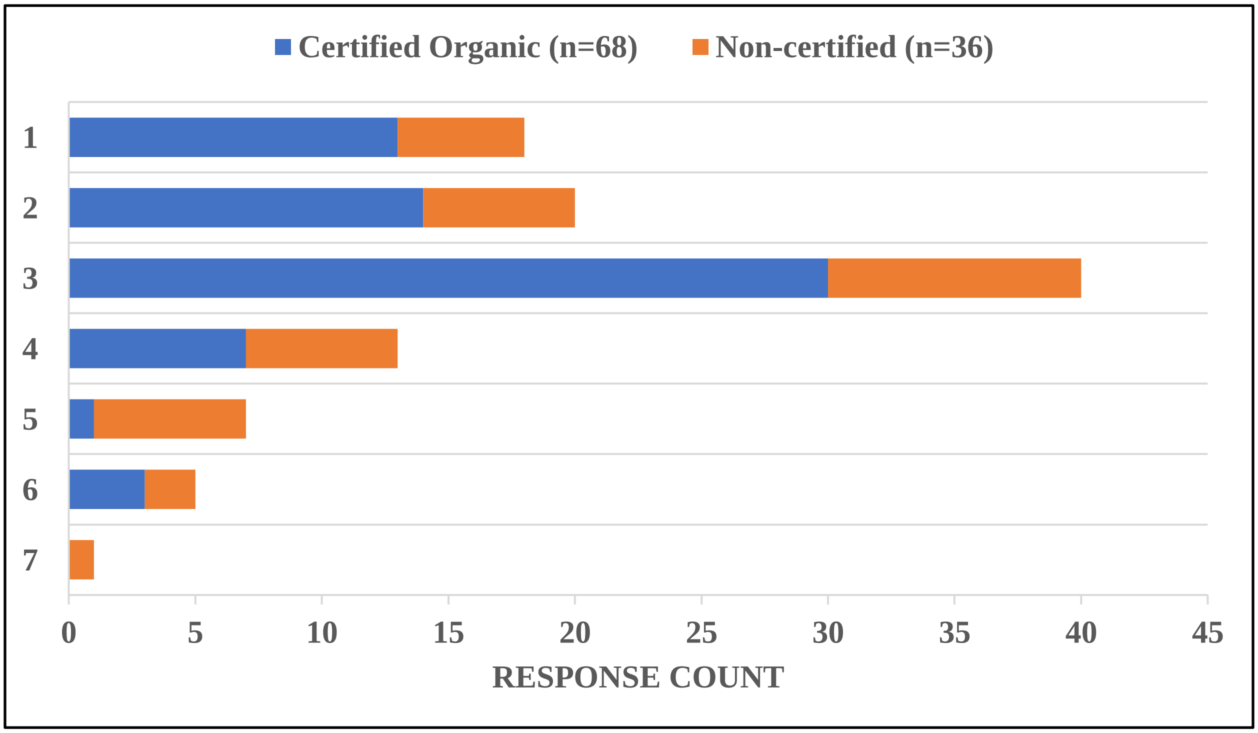


Figure 2.18 Survey response counts rating the importance of resistance to viruses in all crops

Organic Vegetable Breeding Needs Assessment Working Group meeting

We heard directly from many growers through the survey about the specific crop traits needed to support organic vegetable production in the NE. To facilitate a conversation about the challenges surrounding the delivery of these traits to growers and the actions needed to strengthen the seed production system here in the NE, we held a meeting with representatives of the organic vegetable seed production community.

The Organic Vegetable Breeding Needs Assessment Working Group meeting was held in Saratoga Springs, NY on December 7 & 8, 2015 to discuss themes arising from survey results and to identify opportunities for the seed community. (It was held in eastern NY to facilitate representation from across the Northeast.) The meeting was attended by 26 participants, including organic vegetable growers, representatives of NOFA chapters, cooperative extension agents, public plant breeders, and seed company representatives. The meeting's major outcomes were twofold: prioritization of specific traits needed by organic vegetable growers in the most important 18 vegetable crops (see Table 2.3), and identification of infrastructural challenges and opportunities around the effective delivery of those traits to growers.

The meeting also fostered a connection between Northern and Southern states to increase understanding of how familiar challenges are magnified by warmer weather and without the benefit of very cold winters that reduce pest and pathogen populations. To better learn from other regions, Erin Enouen (a NE farmer and Hudson Valley Seed Library sales and trials manager) attended the Southern Sustainable Agriculture Working Group (SAWG) winter conference to learn how growers in different regions are managing production constraints; she presented at the meeting about her experience. Edmund Frost of Common Wealth Seed Growers in Virginia spoke at the meeting about his on-farm breeding work on disease resistance in cucurbits to bring a perspective from outside the NE.

Table 2.3 Specific Traits Needs, prioritized by crop at December 2015 meeting
(Traits with the same number have equal priority; traits prioritized top to bottom with 1 being highest priority)

1	- Broccoli: Stress tolerance
2	- Carrots: Flavor in colored carrots - Winter Squash: Long-term storability
3	- Arugula: heat tolerance - Beans: More east-adapted and/or produced seed - Tomato: Blight resistance - Tomato: resistance to gray mold in greenhouse
4	- Beet: Cercospera resistance
5	- Cabbage: Insect pest resistance (Diamondback moth, cabbage looper, cabbage moth, flea beetles) - Lettuce: Salad mix: reliable weight, packaging quality (color, loft) - Peas: Alternatives to sugar snap cultivars (too few cultivars grown now) - Spinach: Damping off /fusarium resistance - Spinach: Multiple (5+) cuttings - Spinach: Bolting resistance
6	- Broccoli: Black rot / black leg resistance - Cabbage: Processing - Carrots: Alternaria resistance - Cucumbers: Disease resistance - Eggplant: Flavor and education about varieties - Kale: Sweetness in summer - Lettuce: Downy-mildew resistance (research into what races are infecting lettuce in the NE) - Peppers: Strong scaffold / structure
7	- Arugula: Flea beetle resistance - Arugula: Tolerance of low light conditions - Arugula: Succulence / thick leaves - Bean: More organic seed with disease resistance - Bean: Genetics for bean beetle management: earliness, non-preference - Bean: Cool soil emergence - Broccoli: Resilience - Cabbage: Fresh market early red - Cabbage: Storage - Cabbage: Consistent sizing - Carrot: Rust fly resistance - Carrot: Flavor in long-term storage carrot - Cucumber: Climate change (increased heat) tolerance - Eggplant: Earliness / lower temperature adaptation (eggplant for the Northeast!)

7 (cont.)	- Kale: Flea beetle resistance - Lettuce: Bolting / heat tolerance without loss of quality (especially Romaine) - Onion: Thrips resistance - Onion: Downy mildew resistance - Onion: Storability - Onion: Lack of organic sets is a limitation - Peas: Non-trellising types - Radish: Heat tolerance (bolting resistance, maintain spice & texture) - Tomato: Crack resistance (vine holding or consistent growth - Winter Squash: Downy mildew resistance
8	- Arugula: Cold hardiness - Arugula: Aphid resistance - Bean: Higher pod set for mechanical harvest - Bean: White mold resistance - Bean: Concentrated / uniform pod set - Beets: Germination improvement (especially golden beets) - Beets: Improve consistency of Chiogga - Cabbage: Field holding (summer heads that don't split, winter varieties that can handle freezing - Carrot: Strong tops - Cucumber: Understand changing diseases (Phytophthora) - Eggplant: Soil borne diseases (i.e. verticillium) - Eggplant: High tunnel breeding - Eggplant: Insect pests (esp. flea beetle and Colorado Potato Beetle) - Kale: Seed availability (aside from Winterbor) - Kale: Downy mildew resistance - Kale: Longer stems for bunching - Kale: Good shelf life - Lettuce: Less brittle red leafed lettuce - Lettuce: Narrow leaf base (architecture) - Onion: Purple blotch resistance - Onion: Botrytis resistance - Onion: Red onions (improved color) - Onion: Larger / consistent size - Peas: True to type seed - Peas: Foliar disease resistance - Peas: Eating quality (flavor, texture, string-less) - Peas: Longer season / better field holding - Pepper: Early harvest / consistent timing - Pepper: Maintain flavors - Pepper: Cool season production - Pepper: Strong against weeds (reduce need for black plastic) - Pepper: Disease resistance (viral) - Potato: Leaf hopper resistance - Potato: Colorado potato beetle resistance - Potato: Disease/pest-resistant yellow potato

8 (cont.)	- Potato: Scab resistance - Potato: Seed-rot resistant red and blue potatoes - Radish: Uniformity - Radish: Crack resistance - Radish: Crisp texture - Spinach: Overwintering: Tolerance of temperature dips / fluctuations, low light - Spinach: Bacterial spot resistance - Spinach: Aphid resistance - Tomato: Yield - Tomato: Flavor with open architecture - Winter Squash: Striped cucumber beetle resistance - Winter Squash: Gummy stem blight resistance - Winter Squash: Powdery mildew resistance

Working Group Recommendations

In addition to the prioritized list of specific trait needs (Table 2.3), the working group meeting discussions generated a list of thematic areas where actions are needed to address gaps to meet major production constraints. Among these were the development and production of more regionally adapted, organically produced cultivars, open-pollinated population maintenance, the need for simplified and fairly compensated on-farm variety trials, and the need for education and training opportunities for farmers wanting to produce vegetable seed.

1. Develop and produce more regionally and organically adapted cultivars

Cultivars are most productive under the conditions for which they were bred. This central concept of plant breeding points to the need for Northeast growers to have regionally-adapted varieties that were bred to thrive in the Northeast, with the climate and pests unique to our region. Furthermore, cultivars bred under conventional management – aided by synthetic fertilizer, herbicides and pesticides – will likely not be as productive under organic management. The working group recommended increased research to investigate whether organically bred varieties are better than conventionally bred varieties under organic management.

2. Maintain and improve open-pollinated populations

Open-pollinated varieties play a valuable role in strengthening regional food security; the seeds of these cultivars can be saved by farmers and carried by multiple companies, protecting growers from the possibility of losing an important variety. If a hybrid variety is picked up by a company and then discontinued, the resources that were involved in its development are no longer available to the community. It became clear during the working group meeting discussions that not all growers prioritize saving their own seeds, instead appreciating the productivity and uniformity of hybrids when cost-effective. However, the group cautioned against shifting entirely towards hybrids and away from the development and maintenance of open-pollinated cultivars, calling instead for a balanced approach.

The survey results provide insight into the demand for both open-pollinated and hybrid varieties. One notable trend in the critical varieties is the predominance of hybrid cultivars; of the varieties most frequently listed for the top 16 non-clonal crops, 11 were hybrids (Table 2.1). When asked to rate the importance of a given variety being available as open-pollinated, responses were mixed (Figure 2.19). It is possible that growers feel that hybrid cultivars are currently secure (despite previous disappearances) because of the investments that have been made in a regional system that will provide continuous support for hybrid production.

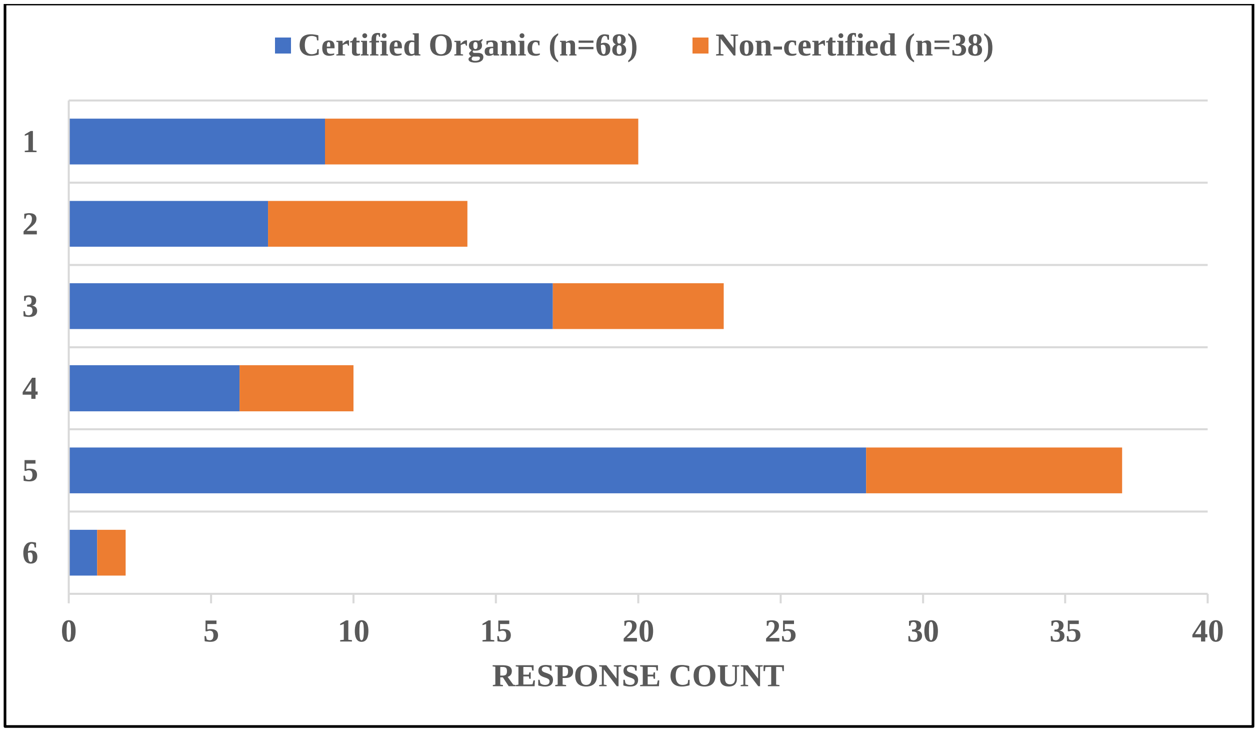


Figure 2.19 Response counts rating the importance of availability of a given cultivar as an open-pollinated variety.
Key for Figure 2.19
1 - High priority - Please focus on this in your breeding!
3 - Somewhat important
5 - Not important
6 - Unsure

Though the survey did not ask specific clarifying questions about the desire for open-pollinated vs. hybrid varieties, some growers included further thoughts on the topic in the final comments section. The demand for OP cultivars may be attributable to the contribution OP's make to regional food security and their relatively low cost, though it is difficult to say which of these is the primary driver of demand.

"We've relied on many hybrids… that aren't necessarily bred for local conditions and come and go for various reasons. We would much prefer locally adapted open pollinated varieties that have the same attributes, if possible."

"I find more and more crops are hybrids… The seed is so expensive."

Open-pollinated populations must be intentionally and skillfully maintained in order to effectively capitalize on their potential to adapt to local conditions. This maintenance and improvement of existing open-pollinated cultivars will not occur, however, without the intentional action of the seed production community. Education about the importance of the work is needed to engage growers in the work of evaluating and stabilizing open-pollinated strains.

3. Expand and strengthen system for simplified and fairly compensated on-farm variety trials

Another theme in the working group discussions was the need for improved variety trialing and data sharing. As new cultivars are developed, it is critical to evaluate them in the context for which they were bred to determine their relative value under particular conditions. This evaluation is therefore best performed on-farm, where growers can observe the variety within their system. To facilitate grower participation, trials need to be simple in design and fairly compensated. Recordkeeping can be cumbersome when evaluating a crop for multiple quantitative traits; trial coordinators may consider whether more basic, qualitative evaluations would be sufficiently informative to growers and breeding work. Projects ought to allocate sufficient funds to fairly compensate growers for the work of running trials.

There are seed companies developing organically-available cultivars with some of the traits prioritized in Table 2.3. Organic vegetable growers need information about the performance of these improved varieties to understand how they might appropriately replace older, more familiar cultivars (and be worth the investment such replacement would require). The adoption of newly developed varieties with the specific disease/quality traits desired by Northeast organic growers would be supported by both coordinated evaluation of those varieties, and broad communication of the results of such trials. Word of mouth among growers about successes and failures is helpful, but to allow growers to more broadly learn from one another, it is critical that a system exist that supports the sharing of trial data with similar growers in the region. The Variety Trial Reports site hosted by eOrganic is an example of such a system for organic crops in the U.S.; the extent to which public and private breeding projects use this resource to share their results will determine its utility.

4. Increase education and training opportunities for farmers wanting to produce vegetable seed

Our discussions highlighted the need for improved capacity for seed production in the Northeast. Growers commented on the need for more 'Northeast-adapted cultivars'; regional adaptation requires that seed be produced in the Northeast, and this would be addressed in part by having more seed producers participate in the formal seed sector. As noted in the 2011 State of Organic Seed Report, the flexibility of regional seed companies is an asset to organic production; smaller companies are able to focus on niche markets (like organic producers), and on more specific environmental conditions. The more decentralized seed production in the Northeast becomes, the more regionally self-sustaining it will be. Currently, too few resources exist for farmers wanting to begin to grow and sell vegetable seed. Increased education and training opportunities are needed to support the growth and strengthening of seed production in the Northeast. High quality seed production requires growers to have knowledge in appropriate harvesting, seed processing and seed storage techniques, germination testing, variety maintenance through proper isolation distances, rouging off-types, and disease management, and on-farm breeding strategies to continue to adapt varieties to the Northeast. Seed producers also need to be connected with available land, and with existing companies to learn best practices. We are encouraged by recent discussions to plan the upcoming Northeast Organic Seed

Conference to provide for these learning opportunities for interested growers, and recognize that such capacity-building will require long term support for concerted and sustained efforts.

Conclusion

This work addresses recommendations in the "Proceedings of 2014 Summit on Seeds and Breeds for the 21st Century Agriculture" (Tracy and Sligh, 2014), the purpose of which was to increase the availability and accessibility of regionally adapted cultivars. Among the recommendations made at that summit was that of "identifying on-the-ground regional priorities and challenges to ensure that our solutions meet the needs of stakeholders in each region". The survey, meeting, and this report have identified such priorities for organic vegetable breeding for the Northeast. The Seeds and Breeds proceedings suggest that such an identification of priorities would aid in building "public awareness of the importance of public cultivar development" and we hope this is the case.

Impact of farmer participation on establishing breeding priorities*

We expect that this work will contribute to the goal of "Effective targeting of user needs" (Sperling et al., 2001) and therefore result in "higher degree of farmer's satisfaction" with the varieties available to them. This will, of course, depend on the effective communication of the needs assessment results to all relevant stakeholders, and upon their ability to act upon the information in the report. We pursued several paths of outreach to disseminate the report after its release, including sending the eCommon's URL to the initial listserv that we used to solicit survey participation, contributing to a joint press release with Organic Seed Alliance in order take advantage of their large social network (Organic Seed Alliance, 2016), and presenting on the report at the 2017 NOFA-NY winter conference. Determining whether a farmer's

*This section was not included in the 'Breeding Research and Education Needs Assessment for Organic Vegetable Growers in the Northeast' report when it was originally published 31 August 2016.

satisfaction does, in fact, increase will take time, as the process of developing new cultivars to meet these needs will require years. Future surveys may ask specifically for farmers to give an estimate of past and present levels of satisfaction with the availability of cultivars suited to their production. A proxy for this may be the number of new cultivars released as a result of these needs becoming clearer; this, too, would take creativity to estimate in a meaningful way.

The second potential outcome from the grower trials is in the area of “production gains” through “faster uptake” (Sperling et al., 2001), that is, higher adoption rates for cultivars being developed. It is our hope that the traits and crops prioritized according to the needs of target beneficiaries (i.e. organic vegetable farmers) will become the objectives of future breeding and seed production efforts. This orientation is critical, as the breeding process can take many years; if needs are not well understood, time and money can be spent unnecessarily. Given the limited resources of the public sector and nascent-though-growing organic seed sector, the likelihood of adoption is an important consideration. This outcome, as with the previous, is one that will not be observable for years to come. As we note in the report, a regular effort to gauge growers’ needs will be important; we suggest that those involved in future assessments give consideration to how to best incorporate metrics of success for their, and future, work.

Additional grower comments from survey

We've relied on many hybrids, especially broccoli, cauliflower, cherry tomato and spinach, that aren't necessarily bred for local conditions and come and go for various reasons. We would much prefer locally adapted open pollinated varieties that have the same attributes, if possible. / Flavor is very important, but can be very localized due to soil and weather conditions. We've grown many varieties, especially of tomato and winter squash that have been described as having excellent flavor by seed companies that don't impress us.

The organic seed requirement is a real quandary-- so many of my favorite and most profitable varieties are not organic (black summer bac choi, Hakurei turnip, graffiti, cheddar, vita verde, Denali, marathon)

This is a long process. It has taken the organic farming movement decades to get where it is today. It is going to take the organic seed movement a long time too. In addition, there is the time delay that it takes to create new varieties. So, we have to be patient. Twenty years ago, for organic farmers, I think marketable yield was perhaps the greatest concern in selecting varieties. Now with the upsurge of local foods, flavor is back to being crucial. So, we really need a balance of concerns to many people (flavor, organic seed availability, open-pollinated seed availability) with commercial concerns (yield, disease resistance). They both have to be met. It is not an either/or situation. If we don't survive commercially, they we have failed. If we don't stay true to our values, then we have failed. We need both. Thank you for your work!
Please focus on maintaining adaptability to weather, climate, and seasonal conditions. I find the OPs are especially reliable in our every changing weather and climate patterns.

Finding organic seed is a major issue. Most of the varieties that wholesale growers use are not available organically, and our certifier says we need 70%+ organic seed. Most of the organic varieties will not produce vegetables that our wholesale buyers will accept. We have found only a few lettuce and squash ones.

I find more and more crops are hybrids (carrots, fennel, spinach, broccoli...) The seed is so expensive.

I would also like to see broader farmer collaboration in breeding and seed production in the region.

We need to have options that allow us to be resilient in the face of more volatile weather. I need to have varieties that grow and mature fast. / I am so grateful for this survey - finally a survey that's really worth the time to fill out. Thank you!!

Overall, organic growers in our area are in need of varieties bred for growing without conventional fungicides in humid, cooler Northeastern conditions. Early maturation without sacrificing storability would be great in crops like onions and winter squash, though I understand those two desires are often at cross purposes.

We need more organically certified varieties for storage carrots, & brassicas (mainly cauliflower [especially the colored ones, like Graffiti], & Brussels' Sprouts)

Breeding vegetables that can survive--even thrive--despite climate change seems like a huge priority. We have experienced inconsistent rainfall, snowfall, and unseasonable high and low temperatures since we started farming in our current location in 2010 and some varieties (even within certain crops) obviously do much better in the face of those challenges.

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Table S2.1: Certifying agencies contacted with request for updated lists of certified growers, and farmer organizations contacted with request to share survey with their members

Organization	**Type**
A Bee Organic	Certifier
Baystate Organic Certifiers	Certifier
CCOF Certification Services, LLC	Certifier
Ecocert ICO, LLC	Certifier
GOA - Global Organic Alliance, Inc.	Certifier
International Certification Services, Inc.	Certifier
MOFGA (Maine Organic Farmers and Gardeners Association) Certification Services	Certifier
MOSA - Midwest Organic Services Association, Inc.	Certifier
New Hampshire Department Of Agriculture, Division Of Regulatory Services	Certifier
New Jersey Department Of Agriculture	Certifier
NOFA New York, LLC	Certifier
OCIA - Organic Crop Improvement Association	Certifier
OEFFA - Ohio Ecological Food and Farm Association	Certifier
Oregon Tilth	Certifier
Organic Certifiers, Inc.	Certifier
PCO - Pennsylvania Certified Organic	Certifier
Pro-Cert Organic Systems Ltd.	Certifier
Quality Assurance International	Certifier
Quality Certification Services	Certifier
Stellar Certification Services	Certifier
Vermont Organic Farmers, LLC	Certifier
NOFA Vermont	Farmers Org
NOFA/RI	Farmers Org
NOFA-NY	Farmers Org
NOFA-NJ	Farmers Org
NOFA-NH	Farmers Org
NOFA-MA	Farmers Org
NOFA-CT	Farmers Org
MOFGA - Maine Organic Farmers and Gardeners Association	Farmers Org
PASA – Pennsylvania Association of Sustainable Agriculture	Farmers Org
Cornell Small Farm Programs	Farmers Org
Northeast Beginning Farmer Project Office	Farmers Org

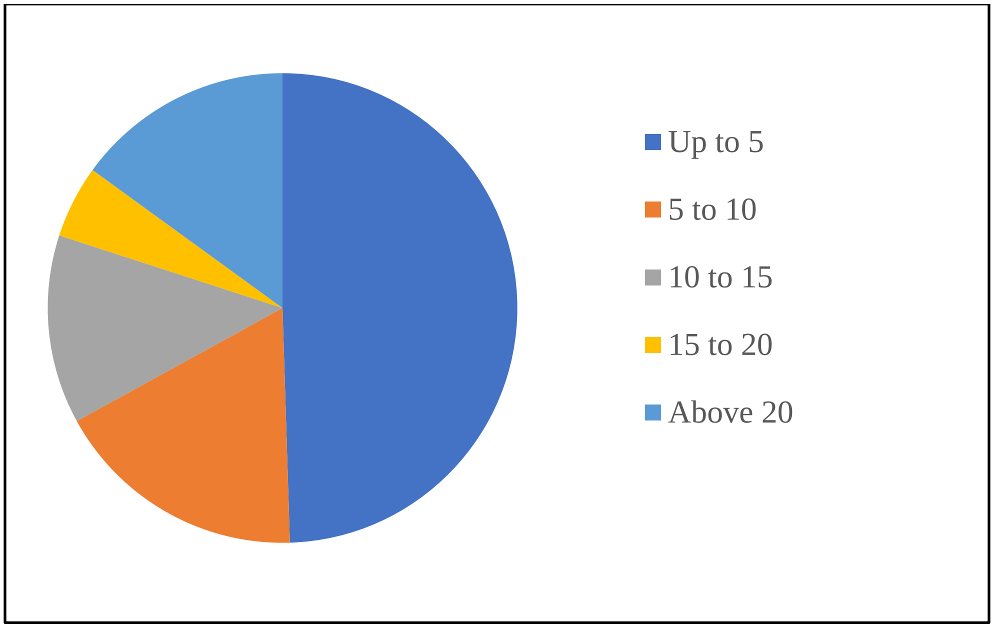

Figure S2.1 Survey respondents by acres in vegetables

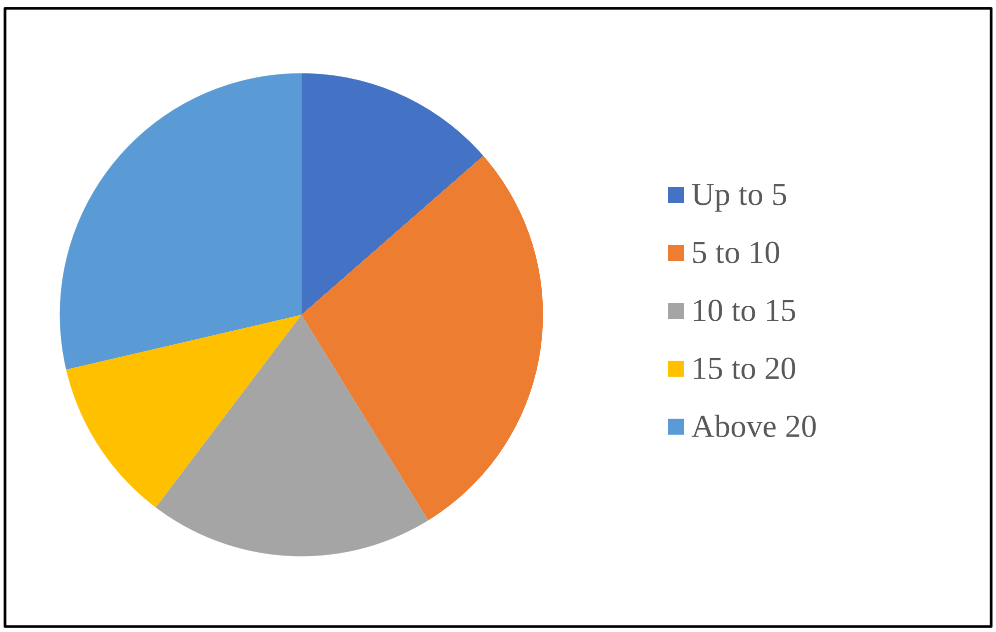

Figure S2.2 Survey respondents by years farming

Supplemental Table S2.2 Specific Traits Needs, prioritized by crop at December 2015 meeting (Crops have equal priority; traits prioritized within crop, top to bottom)

Peas	- Alternatives to sugar snap cultivars (too few cultivars grown now) - Non-trellising types - True to type seed - Foliar disease resistance - Eating quality (flavor, texture, string-less) - Longer season / better field holding
Eggplant	- Flavor and education about varieties - Earliness / lower temperature adaptation (eggplant for the Northeast!) - Soil borne diseases (i.e. verticillium) - High tunnel breeding - Insect pests (especially flea beetle and Colorado Potato Beetle)
Cabbage	- Insect pest resistance (Diamondback moth, cabbage looper, cabbage moth, flea beetles) - Processing - Fresh market early red - Storage - Consistent sizing - Field holding (summer heads that don't split, winter varieties that can handle freezing)
Spinach	- Damping off /fusarium resistance - Multiple (5+) cuttings - Bolting resistance - Overwintering: Tolerance of temperature dips / fluctuations, low light - Bacterial spot resistance - Aphid resistance
Tomatoes	- Blight resistance - Resistance to gray mold in greenhouse - Crack resistance (vine holding or consistent growth) - Flavor and open architecture - Yield
Arugula	- Heat tolerance - Flea beetle resistance - Low light conditions - Succulence / thick leaves - Cold hardiness - Aphid resistance
Kale	- Sweetness in summer - Flea beetle resistance - Seed availability (aside from Winterbor) - Downy mildew - Longer stems for bunching - Good shelf life

Winter Squash	- Long-term storability - Downy mildew resistance - Striped cucumber beetle resistance - Gummy stem blight resistance - Powdery mildew resistance
Potatoes	- Leaf hopper resistance - Colorado potato beetle resistance - Disease/pest-resistant yellow potato - Scab resistance - Seed-rot resistant red and blue potatoes
Lettuce	- Salad mix: reliable weight, packaging quality (color, loft) - Downy-mildew resistance (research into what races are infecting lettuce in the NE) - Bolting / heat tolerance without loss of quality (especially Romaine) - Less brittle red leafed lettuce - Narrow leaf base (architecture)
Beets	- Cercospera resistance - Germination improvement (especially golden beets) - Improve consistency of Chiogga
Cucumbers	- Disease resistance - Climate change (increased heat) tolerance - Changing diseases (Phytophthora)
Peppers	- Strong scaffold / structure - Early harvest / consistent timing - Maintain flavors - Cool season production - Strong against weeds (reduce need for black plastic) - Disease resistance (viral)
Carrots	- Flavor in colored carrots - Alternaria resistance - Rust fly resistance - Flavor in long-term storage carrot - Strong tops
Radish	- Heat tolerance (bolting resistance, maintain spice & texture) - Uniformity - Crack resistance - Crisp texture
Bean	- More east-adapted and/or produced seed - More organic seed with disease resistance - Genetics for bean beetle management: earliness, non-preference - Cool soil emergence - Higher pod set for mechanical harvest - White mold resistance - Concentrated / uniform pod set

Broccoli	- Stress tolerance - Black rot / black leg resistance - Resilience
Onion	- Thrips resistance - Downy mildew resistance - Storability - Lack of organic sets is a limitation - Purple blotch resistance - Botrytis resistance - Red onions (improved color) - Larger / consistent size

CHAPTER THREE

EARLY, BLOCKY BELL PEPPERS FOR NORTHEAST ORGANIC PRODUCTION

Introduction

Bell peppers are a popular vegetable in the United States. Eaten both fresh and cooked, sweet (non-pungent) bells are chosen by consumers for their bright colors (Frank et al., 2001) and nutritional content, especially Vitamin C (Crosby, 2008). According to the USDA Economic Research Service, Americans ate, on average, over 5 kg per capita in 2012 (Correll & Thornsbury, 2013). Bell peppers are available in a wide variety of colors, which are dependent on the maturity at time of harvest; immature fruit are green, while mature fruits can range in color, including red, yellow, orange, and brown. In 2016, the majority (53%) of domestically produced fresh bell peppers were produced in California; New York was the eighth highest producer of fresh bell peppers, producing 261,000 CWT in 2016 (USDA, 2017a). According to the U.S. Department of Agriculture's annual organic surveys, the acreage dedicated to organic bell pepper production in New York has increased slightly in recent years, from 14 acres on 25 farms in 2015 to 20 acres on 36 farms in 2016 (USDA 2016, USDA 2017b).

Bells in the northeastern U.S.

The 2015 Breeding Needs Assessment survey results showed that bell peppers are an important crop to organic vegetable growers in the Northeast (Chapter Two). Critical varieties include 'Ace', 'Red Knight', 'New Ace' and 'CalWonder', which are valued for their reliability in unpredictable or short seasons. Growers who participated in the survey indicated a demand for a new cultivar that combined the earliness and reliability of currently grown cultivars with larger, heavier fruit. The report's results also identified strong plant architecture as an important trait to growers. This need was echoed in conversations with NE growers who expressed that the appearance of 'Ace' fruit could be improved.

Demand for organic bell pepper cultivar

In February 2016, we shared information about this work with growers from across the U.S. and Canada at the Organic Seed Growers' Conference in Corvalis, OR. There, we participated in the Pacific Northwest Organic Plant Breeding Symposium, which served as a needs assessment for organic vegetable growers in the area. In those discussions, we also heard a desire for an early blocky bell pepper (Brouwer and Colley, 2016). Finally, the conference provided us the opportunity to connect with a group of growers from Ontario, Canada who had met Dr. Mazourek at the 2015 Ecological Farmers of Ontario conference, and expressed interest in taking a pepper breeding project forward themselves.

Many commercially available bell pepper cultivars are hybrids (Crosby, 2008). While offered as untreated seeds, these are available to certified organic growers, but they represent a potential vulnerability to these growers, as seed companies with the trade secret to produce a given hybrid can decide to stop producing the seed in an appropriate form for organic growers, thereby depriving growers of the opportunity to grow that cultivar. Furthermore, many of these hybrids were not developed under organic conditions, and therefore may not be well-suited to those systems.

Genetics of bell peppers relevant to this breeding need

Bell peppers are a market class of the species *Capsicum annuum*. *C. annuum*'s center of diversity is in Mexico (Andrews, 1984; Crosby, 2008), from which a variety of morphotypes were domesticated, selected and later spread around the globe for culinary purposes. Bell peppers, like the other market classes of *C. annuum*, are diploid. While they are predominantly self-pollinating, up to 80% outcrossing can occur under field conditions in the presence of pollinating insects (Pickersgill, 1997). Bell peppers are cultivated as an annual crop in temperate regions where cold winter temperatures prohibit field production outside of the summer months.

Previous studies (Ben-Chaim and Paran, 2000; Barchi et al., 2009; Yarnes et al., 2013; Vilarinho et al., 2015) have shown that earliness, fruit shape and percent soluble solids are quantitatively inherited in other pepper germplasm. These findings are salient to the breeding process, as the heritability and number of quantitative trait loci (QTL) associated with each trait impacts the potential efficiency of selection; the degree to which the traits are correlated with one another (and the direction of that correlation) further informs the likelihood of progress toward breeding goals.

Studying an F_2 population from the intraspecific cross of two heirloom *C. annuum* cultivars, Vilarinho et al. (2015) observed that fruit width was positively correlated with fruit weight, but negatively correlated with fruit length and percent soluble solids. Fruit length was itself positively correlated with percent soluble solids. These findings suggest that selecting for increased fruit width may involve trade-offs in fruit length and percent soluble solids.

Ben Chaim and Paran (2000) studied F_3 families derived from a different intraspecific cross (‘Maori’ x ‘Perennial’, both *C. annum*), and reported the heritabilities of ten traits, including fruit shape (length to width ratio), earliness (days to first ripe fruit), and percent soluble solids. The narrow-sense heritability of earliness was low both years of the study (0.40 in 1996, 0.27 in 1997), indicating that environmental conditions likely have a large influence on this trait. To maximize gains for earliness, selection should be done between and subsequently within families rather than individuals. Days to ripe fruit was moderately negatively correlated with fruit shape (length to width ratio) in this study; suggesting that both earliness and blockiness could be reasonably increased in this population or other, similar *C. annuum* populations.

Barchi et al. (2009) found that flowering date was not significantly correlated with any of the fruit quality traits they measured on recombinant inbred lines (RILs) derived from an intraspecific *C. annuum* cross. In this study, five QTL (on chromosomes 1, 2, 4 and linkage group 17) were identified for days to flowering time. In addition to fruit length and fruit width, fruit shape (length to width ratio) was measured as a distinct trait in this study, and eight QTL associated with this trait were found on five chromosomes (2, 3, 4, 10, and 11) and two linkage groups (17 and 25). One of these fruit shape QTL (Frs 2.1) was co-located with a fruit diameter QTL (Frd 2.1), but the other seven did not co-locate with other fruit trait QTL, suggesting that genetic control of fruit shape is more complex than the sum of fruit length and fruit diameter. The linkage of fruit shape and earliness QTL on chromosomes 2 and 4 suggests that for crosses where desirable alleles are in repulsion, progress may be slow for efforts to select on both these traits, as more meiotic events will be required to successfully break these linkages up.

Finally, Yarnes et al. (2013) measured fruit size and shape traits, flowering time and days to breaker stage in RILs from a *C. annuum* x *C. frutescens* cross. Though the QTL identified in this study for flowering time and days to breaker stage were located on separate chromosomes, the authors reported that plants that flowered early tended to have early maturing fruit, indicating that using earliness of flowering as a proxy for earliness of fruit maturation may be an reasonable indirect selection strategy.

Organic vegetable growers in the Northeast have expressed a desire for an early, blocky bell pepper. In this chapter, I will outline the breeding process we undertook through the

Northern Organic Vegetable Improvement Collaborative (NOVIC) in response to this call, and present the results of our efforts thus far.

Materials and Methods

Parental Selection

Commercially available varieties of bell peppers were grown during the summer of 2015 under organic conditions at the Homer C. Thomson farm in Freeville, NY in a replicated trial and evaluated for the traits of interest and to identify appropriate parent lines. Seedlings were transplanted into single rows at 45.7 cm spacing, 12 plants per plot. Black plastic mulch and drip irrigation was used on all rows; row cover was used to increase ambient temperatures for the first four weeks of the season. Cultivars were evaluated for earliness, yield, and fruit quality (shape and percent soluble solids). Earliness was measured in two ways: flowering date and date of first marketable harvest, as described in Greenleaf (1986), Barchi et al. (2009) and Yarnes et al. (2013). Marketable fruit were harvested weekly from the center 10 plants of each plot; fruit count and weight were recorded per plot. Fruit were considered marketable if they were uniformly red (ripe) with no visible rot, sunscald or insect damage. At least ten representative fruit were chosen across the season from each plot for quality measurements. Percent soluble solids were measured on representative fruit with an Atago PAL-1 pocket refractometer; fruit shape was determined by the maximum width / length, an index similar to the shape indexed used by Ben-Chaim and Paran (2000) and Barchi et al. (2009). Fruit with a ratio of 1.0 were considered “blocky”, the desired phenotype (Figure 3.1).

‘Ace’ was, as expected from conversations with growers and the 2015 survey results, the earliest maturing cultivar in the 2015 trials (Figure 3.2). To complement this earliness, we selected a cultivar with blocky pepper fruit for the second parent: ‘Aristotle’, another hybrid

(Figure 3.1). In addition to the desired fruit shape, ‘Aristotle’ offers intermediate tolerance to *Phytophthora capscisi* (Dunn et al., 2013).

Figure 3.1 ‘Blocky’ peppers (‘Aristotle’)

Figure 3.2 Non-blocky peppers (‘Ace’)

In parallel with field trialing, crosses were made in the CU greenhouse between all possible pairs of initial trial entries. After parental selection, (‘Ace’ x ‘Aristotle’) seeds were grown out during the winter of 2016. Given that both ‘Ace’ and ‘Aristotle’ are hybrid cultivars, the F_1 generation was variable, and as these were grown in an off-target environment, we did not select heavily. Self-pollinated seeds were collected from 22 of the F_1 plants.

2016 Field Evaluation and Selection

During the summer of 2016, twenty-two F_2 families were evaluated at the Thomson farm under organic management, using the same agronomic practices as described above. The plots were evaluated for plant architecture, and families with condensed crown set were not evaluated for yield or fruit characteristics. Flower counts were taken for all plots, and yield potential was evaluated at the point of first harvest. Plots with high yield potential and visibly blocky fruit were harvested and quality measurements were taken on representative fruit. The conditions during the 2016 season were unusually hot and dry for the region; during the severe drought, plants were irrigated as necessary via drip irrigation to avoid water stress.

Two F_2 families (16-606 and 16-620) were chosen for advancement based on earliness, yield potential, fruit shape and % soluble solids (Figures 3.3 and 3.4). Five plants from each family were dug up from the field and transplanted to pots in the Cornell University greenhouse on 28 September 2016. These were allowed to self-pollinate, and seeds were collected in May 2017.

Figure 3.3 Representative fruit from selected F_2 breeding plot 16-606

Figure 3.4 Representative fruit from selected F_2 breeding plot 16-620

2017 Field Trial

Seed was collected from four plants per F_2 family for use in the 2017 field trial; however, given that there was insufficient seed to include single F_3 families as trial entries, the trial entries were composites. Entry CU#1 contained equal numbers of the F_3 seeds from 16-606 plants; equal number of seeds 16-620 plants comprised CU#2. F_3 seed was shared with NOVIC partner programs to be included in the pepper trials (see Chapter One).

Seedlings were transplanted on 31 May 2017 at 55 days from seeding, using the same agronomic practices as above. Harvests began when plants had red ripe marketable fruit (1 August), and were conducted weekly for nine weeks. All marketable fruit were counted and weighed at harvest on a per plot basis (reported per plant yields were calculated by dividing plot yields by stand counts). Over the course of the season, at least ten representative fruit were collected for quality measurements (weight, length, width, and percent soluble solids) and photographs. The trial plants lost many fruit to soft rot. We observed insect damage on many of these fruit; it is likely that such damage was the precursor to soft rot. The 2017 season was a cold, wet summer that ended in hot dry weather in late September.

In addition to measuring the number of plants flowering on a given date, the percent of the season's total ripe fruit harvested by a certain date is used as a measure of earliness (Greenleaf, 1986). As a measure of earliness, we compared the yield of the entries (in number of marketable fruit and weight) harvested by week 7 (12 September).

Statistical analysis was performed using R version 3.4.1 (2017-06-30) – "Single Candle" (R Core Team, 2017). Measurements taken at the plot level were analyzed using the Type I 'anova' function ('stats' package is part of R (R Core Team, 2017)) on the linear model :

$$y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

where y_{ij} is the value of the trait being observed, μ is the overall mean, α_i is the effect of the i^{th} replicate, β_j is the effect of the j^{th} trial entry, and ε_{ij} is the random error associated with the observation. Least-squares means for the entries were calculated using the 'lsmeans' function (package: lsmeans (Lenth, 2016); Tukey's Honestly Significant Difference (HSD) was performed using the 'cld' function (package: multcomp (Hothorn et al., 2008)) for pairwise comparisons between least squares means when entry effects were significant at the α=0.05 level. Measurements taken on individual fruit were aggregated to the plot level, and analyzed in the same way.

2017 Field Trial Results

Earliness

'Ace' was the earliest flowering cultivar in the trial. By 27 June, 'Ace' plots were, on average, at 83% flowering. On that same date, 3.3% of plants, on average, in 'Aristotle' had an open flower; 'Aristotle' plots did not reach > 50% flowering until 3 July, a week later. CU#1 plots were 47% flowering on the first count date (27 June) when the row cover was removed, and

70% flowering, on average, on 3 July. CU#2 was more similar to ‘Aristotle’, reaching > 50% flowering on 3 July (Figure 3.5).

Fruit quality

On average, representative CU#1 fruit (0.15 kg) and CU#2 fruit (0.17 kg) were significantly smaller than ‘Aristotle’ fruit, but not significantly different from ‘Ace’ fruit or each other (Table 3.1). CU#1 and CU#2 fruit (8.92 cm and 9.17 cm respectively) were significantly shorter than both ‘Ace’ and ‘Aristotle’ fruit, but not significantly different from one another (Table 3.1).

The fruit shape was measured with the unitless ratio of maximum width (cm) to length (cm), denoted as “W:L”. ‘Ace’ fruit are generally longer (L) than they are wide (W), with deeply grooved lobes; they had, on average, a W:L ratio of 0.71. ‘Aristotle’ fruit were significantly blockier on average, with a W:L ratio of 0.89. Though they were shorter than ‘Aristotle’ and ‘Ace’ fruit, CU#1 representative fruit had a W:L ratio of 0.92, and CU#2 representative fruit had a W:L ratio of 0.95; these were significantly more blocky than ‘Ace’, but not significantly different from ‘Aristotle’ or one another (Table 3.1, Figure 3.6). Entries did not differ significantly in the percent soluble solids (data not shown).

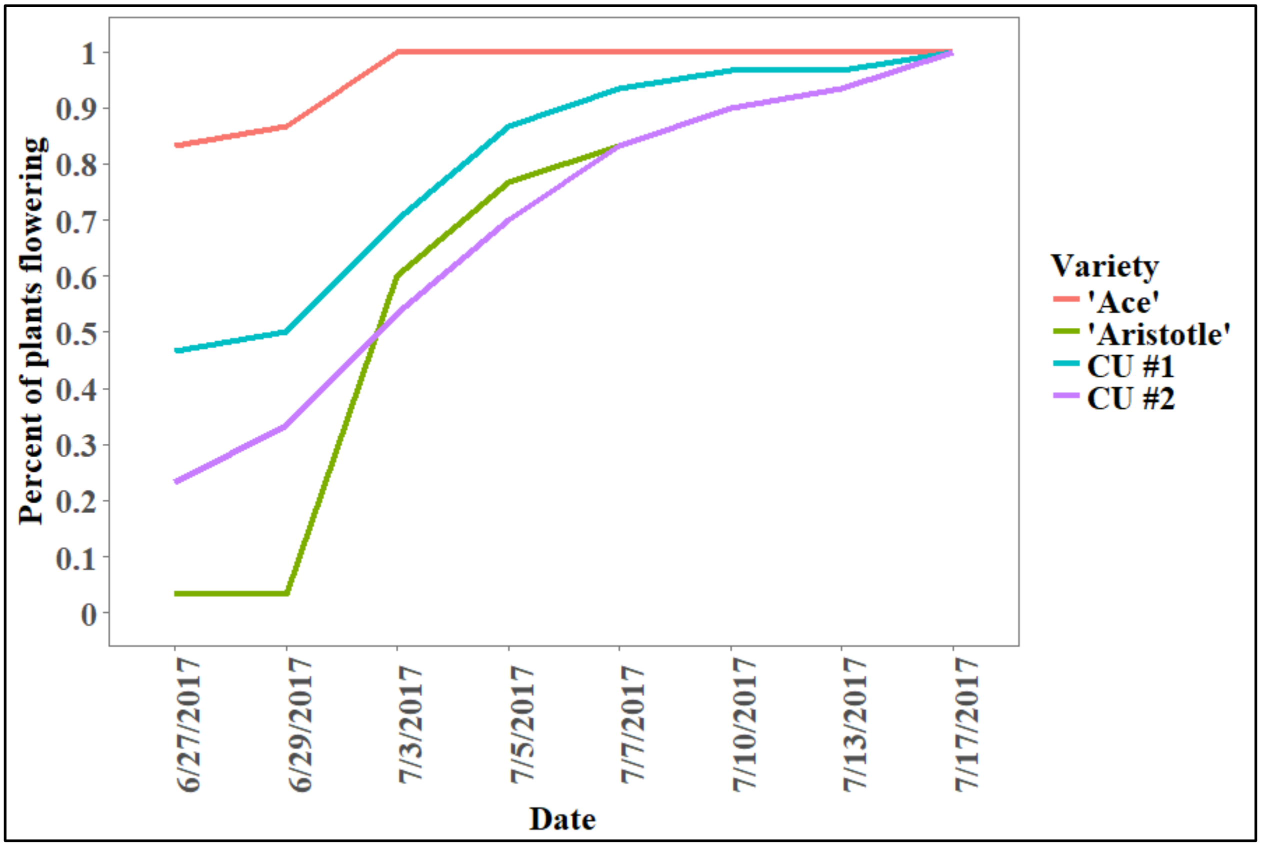

Figure 3.5 Mean percent flowering per plot for 2017 pepper trial entries over first three weeks of the season

Table 3.1 Means, standard deviations and Tukey's HSD categories for quality traits on representative fruit of breeding composites and parental lines 'Ace' and 'Aristotle'. Entries that share a letter are not significantly different at $P \leq 0.05$.

Entry	**Weight (kg)**	**Length (cm)**	**W:L Ratio**
'Ace'	0.15 ± 0.03 a	11.4 ± 1.1 b	0.71 ± 0.09 a
'Aristotle'	0.29 ± 0.09 b	11.4 ± 1.4 b	0.89 ± 0.14 b
CU#1	0.15 ± 0.04 a	8.9 ± 1.5 a	0.92 ± 0.15 b
CU#2	0.17 ± 0.05 a	9.2 ± 1.6 a	0.95 ± 0.17 b

Figure 3.6 Representative fruit from ‘Ace’, ‘Aristotle’, CU#1 and CU#2

Yield

‘Ace’ plots yielded the most fruit per plant on average over the course of the season (Table 3.2). By week 7 (12 September), ‘Ace’ plants had produced significantly more than the number of marketable fruit per plant produced by ‘Aristotle’ (Table 3.2). CU#1 and CU#2 had produced intermediate amounts of marketable fruit per plant by that same date (not significantly different from either ‘Ace’ or ‘Aristotle’). Furthermore, the cumulative mean marketable weight produced by ‘Ace’ was significantly higher than produced by ‘Aristotle’ in kilograms per plant by 12 September (Table 3.2). There was no significant difference among entries for total season weights.

Between 1 August and 12 September, the ‘Ace’ plants yielded 59%, on average, of their total marketable fruit; by that same date, ‘Aristotle’ plants had yielded far less (7% of their total season fruit count). CU#1 plants yielded 30% of their total season marketable count by 12

September; CU#2 plants yielded 24% of their total marketable count by the same date (Figure 3.7).

Table 3.2 Means, standard deviations and Tukey's HSD categories for cumulative yields per plant of breeding composites and parental lines 'Ace' and 'Aristotle' by week 7 ("Early Harvest") and week 9 ("Late Harvest"). Entries that share a letter are not significantly different at $P \leq 0.05$.

	Early Harvest		Late Harvest	
Entry	**Number of fruit**	**Fruit weight (kg)**	**Number of fruit**	**Fruit weight (kg)**
'Ace'	3.2 ± 1.3 a	0.44 ± 0.17 a	5.5 ± 0.9 ns	0.79 ± 0.11 ns
'Aristotle'	0.2 ± 0.2 b	0.06 ± 0.06 b	2.9 ± 1.4 ns	0.89 ± 0.54 ns
CU#1	1.3 ± 0.7 ab	0.19 ± 0.12 ab	4.4 ± 0.7 ns	0.64 ± 0.15 ns
CU#2	1.2 ± 0.9 ab	0.17 ± 0.11 ab	5.0 ± 2.2 ns	0.88 ± 0.42 ns

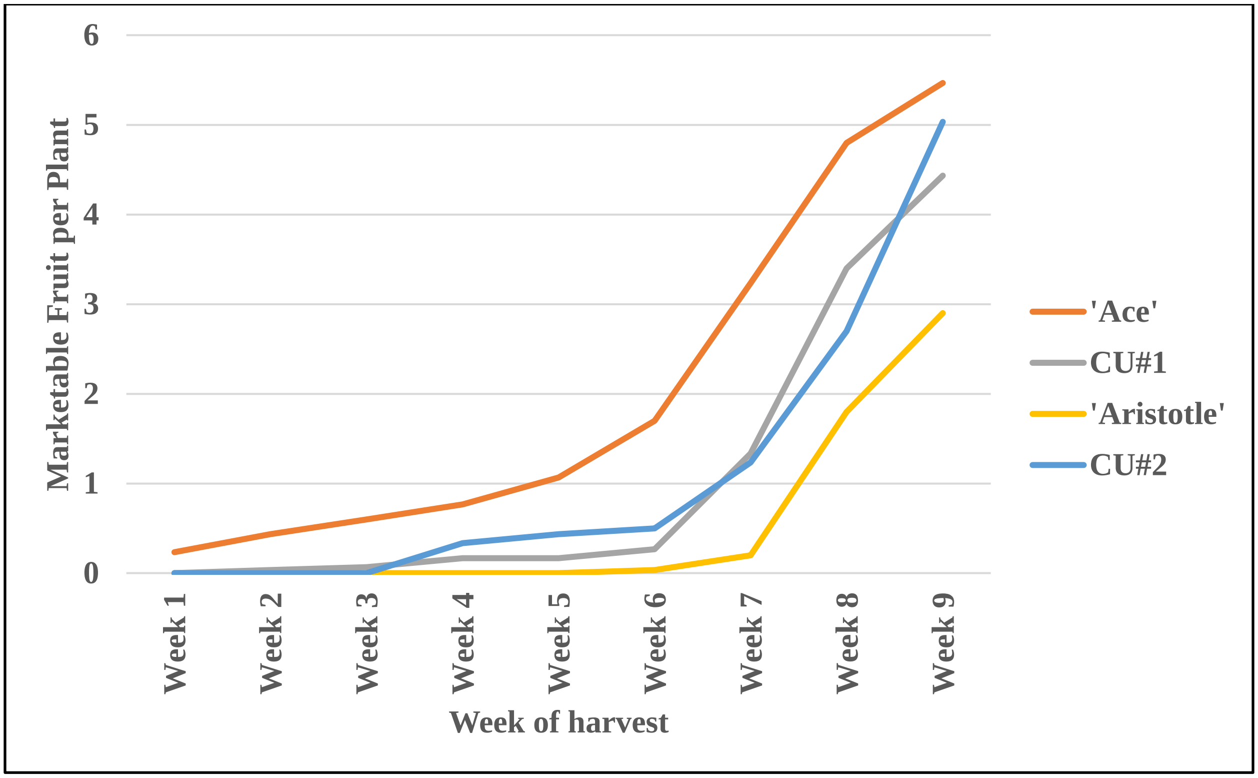

Figure 3.7 Mean cumulative marketable yield (number of fruit per plant) for entries of 2017 pepper field trial

Discussion

Selection strategies

Pedigree selection allows for families with poor mean expression to be eliminated early in the breeding process, thereby ensuring more rapid gain from selection. By growing out F_2 family progeny rows in 2016, we were able to identify and discard families that were segregating for the recessive *y* allele, which leads to decreased carotenoid accumulation and mature yellow fruit (Hurtado-Hernandez and Smith, 1985; Lefebvre et al., 1998; Wang and Bosland, 2006; Ha et al. 2007). By evaluating F_2 families, we were able to take advantage of more of the additive genetic variance underlying the quantitatively inherited traits of interest, thereby improving our ability of making progress on these traits.

Working with organic growers

The composites and 'Ace' were also trialed at small scale in 2017 by organic growers in NY (see Chapter One). At the end of the season, the growers were enthusiastic about the breeding entries, particularly noting their fruit shape and thick walls. The growers noted that despite the season's cool and wet conditions, they were satisfied with the yield of the composites, and that they would be interested in growing them again. Conversations with these growers indicate an encouraging level of acceptance for these composites in spite of their current variability, suggesting that a more genetically diverse cultivar may be appropriate for release, from which growers interested in seed sovereignty might select their own cultivar. Organic growers selling through various channels may have more freedom to grow a greater diversity of cultivars on their farm – or a higher level of acceptable variation within a given cultivar. Whereas many large growers selling large volumes to wholesale clients are often obliged to grow either a particular cultivar or choose a cultivar with narrowly defined characteristics to meet uniformity requirements, this is not usually the case for organic growers. This may lead to a higher acceptance of new cultivars bred for organic production.

In addition to working with growers through the NOVIC on-farm trials, we partnered with a small group of ecological Ontario farmers to initiate their own pepper breeding project. After discussions at the 2016 Organic Seed Growers' Conference made clear that they wanted to collaboratively develop an early, blocky bell pepper for their region, we provided them with (Ace x Aristotle)F_1 seeds to use as a starting population. Over the past two years, these farmers consulted with us as they deemed necessary on topics of evaluation and selection techniques. This project is an example of farmer-led (rather than formal-led) participatory plant breeding; the farmers themselves defined their objectives, chose the strategy for pursuing those objectives, and are making selections on their own farms; importantly, the timing and extent of researchers' involvement is determined by the farmers.

Several of the goals enumerated in Sperling et al. (2001) are relevant to this project, including "Capacity building and knowledge generation", and "Empowerment"; unlike other, potential, outcomes discussed in this thesis, the impacts of this project can already be observed. Through this partnership, growers have gained knowledge about accessing germplasm, and direct experience in all of the stages of the breeding process. Ashby (2009) notes that farmer empowerment "hinges on decision-making authority"; the authority to make decisions impacting the direction and strategy lies entirely with the farmers participating in the project. Over these two years, they have made meaningful progress toward their goal, and are enthusiastic about beginning new breeding projects for their community.

The PPB process itself can be seen as a valuable result independent of the scientific outcomes of a breeding project if it enhances the agency of farmers to control the system that they operate in, and contributes to the democratic development of public goods. As farmers gain experience and skill through training in germplasm evaluation, selection and experimental design, their capacity to engage meaningfully in plant breeding increases. Participatory plant breeding recognizes that farmers have intimate knowledge of the ecology of their farm, and the traits most desired by their markets; formal plant breeders can help build the capacity of farmers to actively observe, evaluate and select on complex criteria.

Breeding for organic systems

'Ace' and 'Aristotle' are currently both available as untreated seed, but not as organically certified seed. The 2017 NY trial results suggest that 'Ace' does better under organic conditions in the Northeast than 'Aristotle', though multiple location trials would be necessary to further evaluate whether this holds true across the Northeast. The CU#1 and CU#2 composites represent progress toward a bell that could be used in the Northeast under organic management for vegetable and seed production. Further work is needed to evaluate the stability of these populations across environments; analysis of the results of the 2017 NOVIC trials in WA, OR, and WI will begin to answer the question of whether these populations may be appropriate for growers across the northern United States.

Conclusion

Organic vegetable growers benefit when they can access many diverse cultivars and choose the varieties that best fit their production and market. Through this work, we have made progress toward our goal of a new early blocky bell pepper by developing two breeding populations, which are earlier than 'Aristotle' and blockier than 'Ace'. The CU #1 and CU#2 composites may be acceptable as varieties themselves or advanced to pureline cultivars; the amount of variation still present in these composites suggests that more work can be done to make further gains in earliness, yield, and size.

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CHAPTER FOUR

HIGH-QUALITY, DISEASE-RESISTANT DELICATA SQUASH

Introduction

Delicata squash is a market class belonging to *Cucurbita pepo,* a species also represented by summer squash, jack-o-lanterns, zucchini, and acorn squash. *C. pepo* is classified as a "New World" crop, given that its center of origin is in North and Central America (Ferriol and Picó, 2008); the subspecies *C. pepo* ssp. *texana*, to which delicata and acorn squash belong, was domesticated in northeastern Mexico and the eastern United States (Ferriol and Pico, 2008). A diploid, its genome has 2n = 40 chromosomes (Whitaker and Robinson, 1986). Though *C. pepo* has been agriculturally important in North America for millennia (Smith, 1997), delicata squash was developed more recently, and introduced in the United States in 1894 (Tapley, 1937).

As winter squash, delicata fruit are harvested and eaten at maturity, about 8 weeks after anthesis (Loy, 2004). Fruit are oblong and ridged, with skin color ranging in color from light cream to golden, and are usually striped with dark green and orange (Paris, 2009). Some cultivated varieties of delicata are vining plants, while others have a bush habit. This trait, which is mediated by internode length, is controlled by a single gene (designated *Bu*) in *C. pepo* (Denna and Munger, 1963; Paris and Kabelka, 2009). The *Bu* allele is incompletely dominant to *bu*, resulting in a 'developmental reversal of dominance' (Shifriss, 1947) in which young heterozygotes appear more similar to bush homozygotes, but have longer internodes than true bush plants, resulting in a mature vining phenotype.

New York produced 527,000 CWT of squash for fresh market and processing in 2016, making it the sixth highest squash-producing state in the U.S. (USDA, 2017). While the USDA statistics do not make explicit the breakdown of which varieties of squash growers are producing, it is clear that squash is an important crop for the Northeast. Through the 2015 organic vegetable breeding needs assessment survey organic growers in the Northeast indicated that delicata is popular with their customers, and that it is a market class of squash critical to the success of their production (Chapter Two). Growers also indicated that current delicata varieties could be improved through better disease resistance, and rated powdery mildew in squash as a critical priority for breeding efforts (Chapter Two).

Powdery mildew

Powdery mildew is a major disease in all cucurbit crops. It reliably occurs every growing season in the Northeast, as wind disperses the pathogen northward from the southeastern US. In the United States, it is most often caused by the ascomycete *Podosphaera xanthii* (Cohen et al., 2004).

The symptoms of powdery mildew infection on delicata squash are easily recognizable. Powdery mildew affects the top and bottom surface of leaves, as well as the petioles. Mats of hyphae are seen initially as white spots on the surface of leaves, similar in appearance to powdered sugar; late in the season these spots eventually merge on susceptible hosts to cover the entire leaf surface. As a biotrophic pathogen, powdery mildew does not quickly kill host plants, instead causing reduction in marketable fruit yield and decreased fruit quality due to direct loss of nutrients to the fungus, and decreased photosynthetic activity of tissues covered in mycelial growth (Jahn et al., 2002). In resistant varieties, a hypersensitive response is observed; haustorial recognition by the host plant leads to a build-up of reactive oxygen species and cell wall reinforcement, inhibiting the fungus' ability to successfully obtain nutrients (Pérez-Garcia et al., 2009).

Dry warm summer days are conducive to powdery mildew establishment and growth, The disease is polycyclic; after initial conidia arrive in growers' fields (usually landing first on plants at the edges of fields), resulting mycelia give rise to further conidia (secondary inoculum), which are dispersed aerially and spread to neighboring plants.

There are multiple races of powdery mildew on cucurbit crops in the United States. To date, seven races of the pathogen infecting cucurbits have been identified in the US; these were characterized using a panel of various melon (*Cucumis melo*) cultivars. While there is race/resistance specificity in melons, it seems that all races infect the genus *Cucurbita* (including winter squash) (Cohen et al., 2004).

Genetically resistant cultivars can play an important role in production for both conventional and organic growers, by reducing the amount of pesticide sprayed at the individual farm level and therefore landscape scale. Additionally, powdery mildew-resistant hybrid varieties of summer squash (also *C. pepo*) have been shown to produce more fruit per plant than susceptible hybrids in the presence of the pathogen (Paris and Cohen, 2002). Resistance to powdery mildew is measured in terms of reduction of spore production on the host plant; varieties with low levels of powdery mildew coverage on the adaxial and abaxial surfaces of leaves, and little-to-no sporulation on the petioles are considered resistant (Cohen et al., 2003; Jahn et al., 2002). There is currently one commercially available powdery mildew-resistant delicata cultivar ('Bush Delicata'), which carries the incompletely dominant allele of *Pm-0* (Holdsworth et al. 2016), introgressed from a wild relative of cultivated squash (Contin, 1978). No studies to date have shown race specificity for this resistance.

The goal of the delicata breeding project under the Northern Organic Vegetable Improvement Collaborative (NOVIC), has been to develop new potential options of high-quality, disease-resistant delicata for organic vegetable growers. One aspect of the work described herein has been to incorporate powdery mildew resistance in the breeding material, using ‘Bush Delicata’ as a source of that resistance, and utilizing marker-assisted selection to make rapid gains in this trait. Additionally, two different strategies were pursued - pedigree selection and recurrent selection – to compare their results in breeding high-quality, disease-resistant delicata cultivar for northeastern markets.

Materials and Methods

Initial Crosses and Population Establishment

In the winter of 2015, all possible pairwise crosses were made between ‘Bush Delicata’, ‘Zeppelin’, ‘Candystick’ and ‘Delicata JS’ using the hand pollination technique described in Whitaker and Robinson (1986). F_1 plants were grown under organic management at the Homer C. Thompson Farm in Freeville, NY during the summer of 2015. To create the pedigree selection material, three plants were self-pollinated from each of the following groups: (‘Delicata JS’ x ‘Bush Delicata’) F_1, (‘Candystick’ x ‘Bush Delicata’) F_1, and (‘Bush Delicata x Zeppelin’) F_1. To establish the recurrent selection scheme, crosses were made between F_1’s to create: ((‘Zeppelin’ x ‘Delicata JS’) F_1 x (‘Candystick’ x ‘Bush Delicata’) F_1) F_1’s, and ((‘Candystick’ x ‘Bush Delicata’) F_1 x (‘Zeppelin’ x ‘Delicata JS’) F_1) F_1’s (Table 4.1).

Table 4.1 Pedigree information about breeding material for pedigree and recurrent selection schemes

Pedigree	Source	Season evaluated	*Pm-0* genotype	Note
		Initial Breeding Materials		
‘Delicata JS'	Johnny's Selected Seeds	Summer 2015	PMS/PMS	
‘Candystick'	Adaptive Seeds	Summer 2015	PMS/PMS	
‘Zeppelin'	Wild Garden Seed	Summer 2015	PMS/PMS	
‘Bush Delicata'	High Mowing Organic Seeds	Summer 2015	PMR/PMR	
		Hybrid Population Establishment		
('Delicata JS' x 'Bush Delicata')F_1	Created winter 2015	Summer 2016	PMR/PMS	
('Candystick' x 'Bush Delicata')F_1	Created winter 2015	Summer 2016	PMR/PMS	
('Bush Delicata' x 'Zeppelin')F_1	Created winter 2015	Summer 2016	PMR/PMS	
		Recurrent Selection Populations		
Recurrent Selection population Cycle 1	Created summer 2015	N/A	Segregating	Equal contribution 'Candystick', 'Zeppelin', 'Delicata JS' and 'Bush Delicata'
Recurrent Selection population Cycle 2	Created winter 2016	Summer 2016	Segregating	
CU_Del17_3	Created winter 2017	Summer 2017	PMR/PMR	Recurrent Selection Population Cycle 3
		Pedigree Selection Populations		
('Delicata JS' x 'Bush Delicata')F_3	Created winter 2016	Summer 2016	PMR/PMR	
('Candystick' x 'Bush Delicata')F_3	Created winter 2016	Summer 2016	PMR/PMR	
('Bush Delicata' x 'Zeppelin')F_3	Created winter 2016	Summer 2016	PMR/PMR	
CU_Del17_1	Created winter 2017	Summer 2017	PMR/PMR	('Delicata JS' x 'Bush Delicata')$F_{3:5}$ composite
CU_Del17_2	Created winter 2017	Summer 2017	PMR/PMR	('Delicata JS' x 'Bush Delicata')$F_{3:5}$ composite

Marker-assisted selection for powdery mildew resistance and generation advancement

During the winter 2016 generation, seedlings under both selection schemes were screened for powdery mildew resistance using the *Pm-0* marker (Holdsworth et al., 2016). In the pedigree selection scheme, heterozygotes and homozygous susceptible plants were discarded, fixing the resistant allele in these populations. In the recurrent selection scheme, homozygous susceptible plants were discarded.

Pollinations began on 11 March 2016, and all possible pollinations were performed each morning until 25 March 2016. Plants in the pedigree selection scheme were self-pollinated when both a male flower shedding pollen and a receptive female flower were present. Recurrent selection plants were randomly intermated, and in order to keep the effective population size as high as possible, efforts were made to use each plant as both a female parent and pollen donor at least once. Fruit were harvested at maturity, 8 weeks post-pollination (Loy, 2004) starting 4 May 2016.

Recurrent selection

Thirty half-sib families were evaluated during the summer of 2016 in East Ithaca, NY. Ten seedlings per half-sib family were transplanted into rows with drip irrigation and black plastic at 107 cm within-row and 305 cm between-row spacing.

Once open flowers were observed in the field, rows were observed every morning to note the flowering status of each plant and first female flowering date was recorded. Individual plants were rated for growth habit early in the season before fruit set, and for adaxial leaf powdery mildew severity on 12 August.

On 17 September, all plots were harvested. Marketability of fruit was evaluated (evidently immature fruit and fruit with pest damage was discarded), and the number of marketable fruit was recorded for each plant. Three representative fruit per plot were used to evaluate percent soluble solids as a metric of fruit quality. To measure percent soluble solids, a piece of mesocarp tissue of each fruit was frozen, thawed, and pressed to express juice, which was read by an Atago PAL-1 pocket refractometer. An ad hoc selection index was used in which powdery mildew resistance was given most weight, followed by marketable fruit per plant yield, earliness of flowering, habit, and fruit quality. Four plots were selected for advancement.

The recurrent selection population was advanced in the greenhouse during winter 2017. To maximize gain from selection, remnant seed of the best four plots from the summer 2016 season was used instead of open-pollinated seed. To fix the *Pm-0* resistant allele in this population, seedlings were screened to identify 64 homozygous resistant plants (at least 12 per 2016 half-sib family); these were randomly intermated. Equal numbers of seed from each pollination were bulked to create a single entry for the 2017 NOVIC trials.

Pedigree Selection

Twenty-four F_2 plants were successfully self-pollinated during the winter 2016 generation; the 24 resulting F_3 families were grown in 12 plant plots at the Homer C. Thompson Organic Farm in Freeville, NY during the summer of 2016 (Table 5.1), using the same agronomic practices as above. Single plots of the F_1's were also grown and evaluated alongside commercial parent plots; yield per plant for those plots was calculated by dividing the plot yield by the end of season stand count.

Once flowering began, plots were observed every day and the date of first female flowering was recorded for every plant. Striped cucumber beetle pressure was severe during this season, and plants were not protected by row cover. SCB damage ratings (% leaf defoliation) were conducted on individual plants twice during the season. Plants were self-pollinated until each plot had at least six set pollinations.

Individual plants were rated for bush habit twice during the season, and twice for adaxial and petiole powdery mildew severity. From the ten plots with low powdery mildew severity, low SCB damage, early flowering and which were not fixed for vine habit, pollinations were harvested at maturity, and measured for percent soluble solids. Where plots had fewer than six pollinations, open pollinated fruit were harvested for quality measurements. Two individuals within each of the best two F_3 plots (both (‘Delicata JS’ x ‘Bush Delicata’)F_3’s) were identified for advancement.

In October, 2016, self-pollinated seed from these F_3 plants was advanced in an off-site greenhouse. Ten F_4 seedlings per F_3 plant were self-pollinated. Equal number of $F_{3:5}$ seed from each of the ten F_4 plants were bulked to create the two pedigree selection entries for the 2017 trials.

Summer 2017: NY trial evaluation

Final evaluation of the breeding populations took place at NOVIC research stations (see Chapter One) in replicated trials, alongside parent varieties and other commercially available delicata cultivars (‘Cornell’s Bush Delicata’, Hudson Valley Seed Company; ‘Piñata’, NE Seeds; ‘Jester’, Johnny’s Selected Seeds). $F_{3:5}$ composites of 16-301-3 and 16-304-8 were grown as trial entries CU_Del17_1 and CU_Del17_2, respectively. The recurrent selection population was grown as CU_Del17_3 (see Table 4.1).

Seedlings were transplanted to the organic farm in Freeville in June 2017, at 61 cm spacing in single rows. Varieties were each replicated three times, with twelve plants per plot (ten of which were harvested at the end of the season). These rows were covered with Agribon fabric to protect seedlings from striped cucumber beetle damage; row cover was removed at first flowering, at which point growth habit was noted for each plot. Powdery mildew was first observed in the field on 7 July; ratings of petiole and leaf powdery mildew severity on a per plot basis began 18 July and were conducted weekly for three weeks. The trial was harvested twice, with all fruit of a given cultivar harvested on the same day. The first harvest took place 6 September; the second took place 13 September. Marketable fruit were counted and weighed on a per plot basis (reported per plant yields were calculated by dividing plot yields by stand counts), and allowed to cure in a protected greenhouse for a week before being moved to a cooler. On 19 September, three fruit were taken from each plot and sampled individually for percent soluble solids and percent dry matter. To measure percent dry matter, a ~15g piece of mesocarp was weighed, diced and dried for 48 hours at 68° C before dry weight was recorded. Percent dry matter was recorded as dry weight / wet weight. Another set of three fruit per plot were sampled on 29 September.

Type I analysis of variance was conducted using the 'anova' function in R version 3.4.1 (2017-06-30) – "Single Candle" (R Core Team, 2017) on the linear model:

$$y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$$

where y_{ij} is the value of the trait being observed, μ is the overall mean, α_i is the effect of the i^{th} replicate, β_j is the effect of the j^{th} trial entry, and ε_{ij} is the random error associated with the observation. For traits where entry effects were significant at the α=0.05 level, comparisons between cultivar means were made using packages 'lsmeans' (Lenth, 2016) and 'multcomp' (Hothorn et al., 2008) to conduct Tukey's Honestly Significant Difference (HSD) tests. Individual fruit observations were aggregated to the plot level to evaluate the difference in means for fruit quality data.

2016 Results

2016 ‘Bush Delicata’ F_1’s

The intermediate bush F_1 plots had significantly lower petiole powdery mildew severity during the 2016 trial than their susceptible parents (Table 4.2). Additionally, (‘Candystick’ x ‘Bush Delicata’) F_1 had significantly lower leaf powdery mildew severity than ‘Candystick’.

Table 4.2 Powdery mildew severity, yield fruit per plant and percent soluble solids for ‘Bush Delicata’ and its F_1’s with ‘Zeppelin’, ‘Candystick’ and ‘Delicata JS’.

Pedigree	% petiole powdery mildew^z	% adaxial leaf powdery mildew^y	Marketable yield (fruit per plant)^x	Percent soluble solids
(‘Delicata JS’ x ‘Bush Delicata’)F_1	54.2 ± 9.7 bc^w	22.1 ± 7.80 bc	10.9	12.1 ± 1.0 ns
(‘Candystick’ x ‘Bush Delicata’)F_1	46.3 ± 12.5 ab	12.1 ± 7.20 ab	8.2	15.5 ± 2.3 ns
(‘Bush Delicata’ x ‘Zeppelin’)F_1	61.3 ± 14.2 bc	33.8 ± 14.0 c	7.2	12.3 ± 0.9 ns
‘Candystick’	67.5 ± 21.7 c	69.5 ± 29.1 e	9.1	13.7 ± 0.8 ns
‘Zeppelin’	51.5 ± 25.5 bc	53.5 ± 26.4 d	7.3	16.4 ± 0.8 ns
‘Delicata JS’	61.4 ± 30.9 bc	80.7 ± 42.6 e	9.1	11.9 ± 1.8 ns
‘Bush Delicata’	35.0 ± 19.9 a	5.2 ± 10.0 a	6.0	13.0 ± 2.1 ns

^{z}Percentage of petiole area coverage by fungal hyphae
^{y}Percentage of adaxial leaf area coverage by fungal hyphae
^{x}Yields were measured and analyzed on a per-plot basis; per plant yields were calculated by dividing plot yields by stand counts.
^{w} Entries whose means and standard deviations are followed by the same letter are not significantly different at $P \leq 0.05$.

2017 NOVIC Trial Results

Disease resistance

Throughout the season, the severity of petiole powdery mildew was lower in the breeding plots, ‘Bush Delicata’ and ‘Cornell’s Bush Delicata’ (Figure 4.1). At the final powdery mildew evaluation (7 August), these plots Delicata’ had significantly lower petiole powdery mildew severity than the susceptible ‘Zeppelin’, ‘Candystick’, ‘Delicata JS’, ‘Jester’ and ‘Piñata’.

Furthermore, CU_Del17_1 and CU_Del17_2 had significantly lower leaf powdery mildew severity than their high-quality parent, 'Delicata JS' on 7 August.

Growth habit

'Zeppelin', 'Delicata JS' and 'Candystick' plants were uniformly sprawling vines. 'Bush Delicata', and CU_Del17_1, CU_Del17_2 plants had bush habit; plants in the CU_Del17_3 plots had variable habit.

Quality measurements

The breeding entries had percent soluble solid and dry matter values that were not significantly different from those of any of the other entries in the trial (Table 4.3). The recurrent selection scheme had higher dry matter and brix on average than the pedigree selection entries, but these differences were not statistically significant.

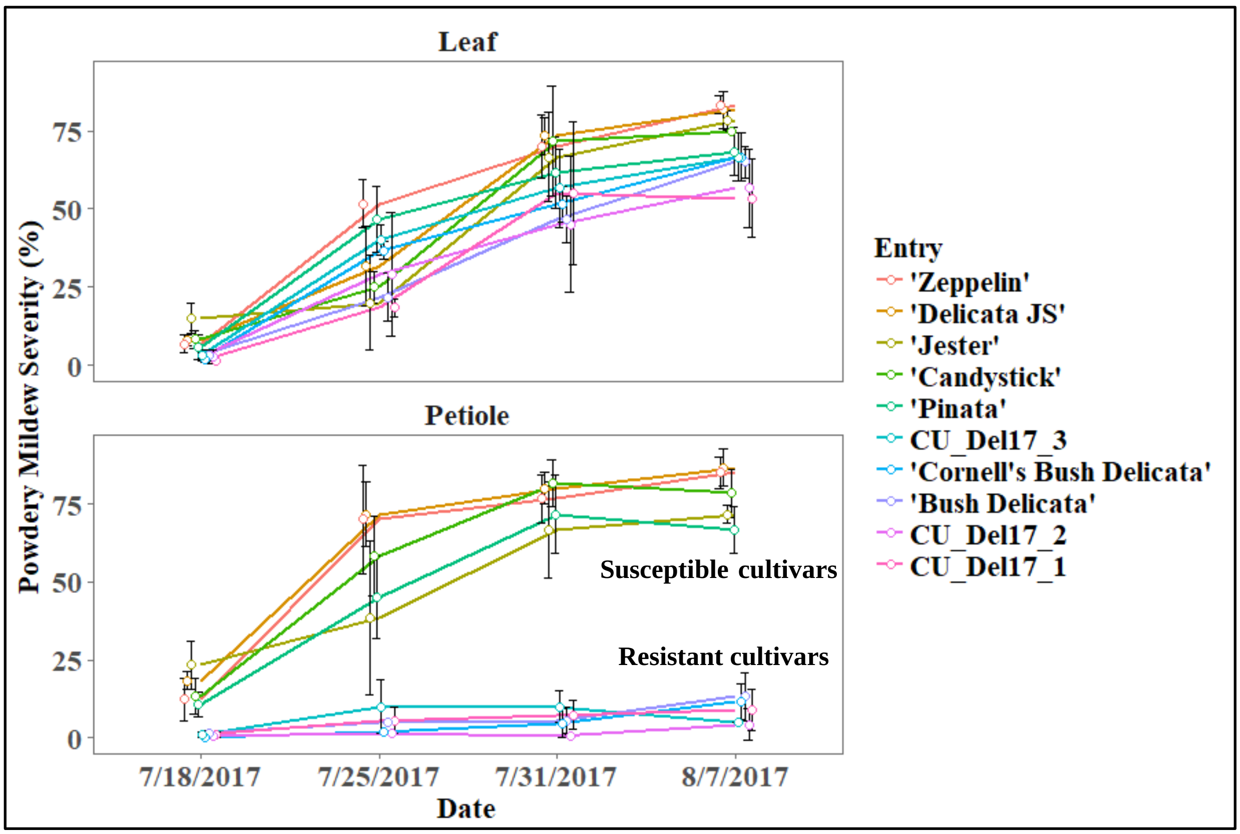

Figure 4.1 Mean powdery mildew severity (%) on adaxial leaf surfaces and petioles of 2017 squash trial entries over the growing season

Table 4.3 Means and standard deviations for percent soluble solids and percent dry matter for representative fruit of 2017 squash trial entries.

Cultivar	Percent soluble solids	Percent dry matter
‘Bush Delicata’	13.2 ± 3.5 ns	15.7 ± 4.3 ns
‘Candystick’	11.0 ± 4.4 ns	13.0 ± 5.7 ns
‘Cornell’s Bush Delicata’	12.5 ± 5.1 ns	14.9 ± 6.2 ns
CU_Del_17_1	9.3 ± 3.5 ns	13.2 ± 4.8 ns
CU_Del_17_2	11.8 ± 4.3 ns	14.0 ± 5.4 ns
CU_Del_17_3	12.9 ± 3.5 ns	15.3 ± 3.8 ns
‘Delicata JS’	10.1 ± 2.6 ns	12.1 ± 3.2 ns
‘Jester’	13.4 ± 3.8 ns	15.9 ± 4.8 ns
‘Piñata’	10.0 ± 3.2 ns	11.7 ± 4.0 ns
‘Zeppelin’	10.3 ± 3.2 ns	11.8 ± 3.7 ns

Yield in marketable count and weight

The mean number of marketable fruit harvested per plot did not differ significantly among varieties (Table 4.4). The mean marketable weight harvested from CU_Del17_2 was significantly lower than that harvested from ‘Zeppelin’, but not from ‘Bush Delicata’ and ‘Delicata JS’. There were no other significant differences among trial entries for marketable yield or weight.

Table 4.4 Means and standard deviations for total marketable yield per plant[z] for 2017 squash trial entries

Cultivar	Marketable Count	Marketable weight (kg)
‘Bush Delicata’	2.2 ± 0.7 ns	1.3 ± 0.5 ab[y]
‘Candystick’	3.3 ± 0.8 ns	1.9 ± 0.3 ab
‘Cornell's Bush Delicata’	2.4 ± 1.2 ns	1.4 ± 0.8 ab
CU_Del17_1	3.2 ± 1.0 ns	1.6 ± 0.6 ab
CU_Del17_2	1.9 ± 0.6 ns	1.0 ± 0.4 a
CU_Del17_3	2.9 ± 0.9 ns	1.6 ± 0.6 ab
‘Delicata JS’	4.4 ± 2.0 ns	2.3 ± 1.2 ab
‘Jester’	2.6 ± 1.2 ns	1.7 ± 0.9 ab
‘Piñata’	3.4 ± 1.1 ns	2.3 ± 0.9 ab
‘Zeppelin’	4.5 ± 1.3 ns	2.9 ± 1.1 b

[z]Yields were measured and analyzed on a per-plot basis; per plant yields were calculated by dividing plot yields by stand counts.
[y]Entries whose means and standard deviations are followed by the same letter are not significantly different at $P \leq 0.05$.

Discussion

Comparing breeding schemes

One of the objectives of this project was to compare the efficiency of pedigree and recurrent selection in delicata squash breeding. These parallel schemes differ in the speed to fixation of alleles, and the amount of effort per season required to advance material.

Pedigree selection requires squash to be self-pollinated; as squash is a monoecious crop, this is done by hand, which can be laborious in the field (Whitaker and Robinson, 1986). This controlled pollination is one of the major benefits of pedigree selection, as it allows for selection on both the male pollen donor and female plant. Pedigree selection provides effective isolation between interfertile squash planted at very close distances, which is critical for a breeding program pursuing many projects simultaneously. In general, pedigree selection decreases the effective population size drastically, increasing inbreeding. This is less of a concern in *C. pepo* than other outcrossing crops, as the species suffers from little inbreeding depression (Whitaker and Robinson, 1986, Robinson, 2000). A disadvantage of the scheme is that plants are pollinated long before final fruit quality evaluations; plants that are ultimately discarded are therefore needlessly pollinated.

The product of pedigree selection is a pureline cultivar with high genetic uniformity after relatively few generations. This uniformity will be desirable for those farmers whose markets and production demand it, but may hinder the cultivar's ability to produce well under varied conditions, as heterogenous populations may be more resilient than purelines (Dawson et al., 2012). In contrast, a cultivar developed through recurrent selection, in which individuals in a population are intermated in order to increase the likelihood of obtaining combinations of favorable alleles which give rise to trait values better than the starting material, can have either high or low genetic variability, depending on the goals of the breeder.

For traits controlled by many genes, such as fruit quality (Wyatt et al., 2015), recurrent selection may be a more appropriate strategy than pedigree selection (Sprague and Eberhart, 1977), assuming that there is sufficient additive genetic variation in the starting population. Our recurrent selection population included as parents two cultivars developed in the northeastern US ('Delicata JS' and 'Bush Delicata'), and two developed in the Pacific Northwest ('Candystick' and 'Zeppelin'). While there exists, in general, little genetic variation across all commercial delicata cultivars (M. Mazourek, personal communication), the use of lines selected under diverse environments was, in part, an effort to increase starting additive genetic variation.

We employed two techniques to improve gains in the recurrent selection population. First, we evaluated half-sib families during the summer 2016 season, which increased our ability to observe differences in traits with low heritability. Secondly, returning to remnant seed in the winter 2017 generation increased selection intensity and limited the genetic contribution of unselected families to the subsequent generation. In mass selection, superior individuals are advanced; this means that progress will be slow for traits heavily influenced by environment (Lonnquist, 1964).

Recurrent selection is a more ‘long-range’ strategy, according to Lonnquist (1964) than pedigree or mass selection. Our expectation, in the long run, is that the recurrent selection population would eventually yield higher quality fruit than the pedigree selections, so long as a sufficiently high population size is maintained. The likelihood of success in pedigree selection can be improved if many F_2-derived lines are evaluated and advanced. Here, we had limited space and time, so the results of the pedigree selection scheme are more affected by random chance.

The advantages of recurrent selection are significant. No time is spent on unnecessary pollinations, which may allow for more time to be spent evaluating lines. Additionally, because open pollinated fruit are removed from pedigree selection plants to encourage continued flowering and ensure good seed set on the hand-pollinated fruit (Whitaker and Robinson, 1986), field evaluation of certain traits is more accurate in recurrent selection. Powdery mildew severity, for example, can be affected by a plant’s reproductive status; setting fruit are a significant photosynthate sink, so plants whose open-pollinated fruit have been stripped may appear more resistant than they would if fruit were allowed to mature. For this same reason, it is meaningless to evaluate yield on plants being pollinated under pedigree selection, so this trait can only be evaluated in advanced generations. Lastly, fruit quality in *Cucurbita* can be affected by the number of fruit a plant produces; Loy (2004) reported that in a 1982 study of *C. maxima* cultivar ‘Gold Nugget’, plants that were allowed to take a natural set of fruit to maturity yielded fruit that had lower average percent dry matter than those that were pruned to just three or four fruit. Selection for quality in pedigree selection may be effective using relative ranking, but selections may not have high absolute quality values in final trial evaluations.

Pedigree selection was effective in selecting for bush habit plants. Given the simple genetic architecture of the trait (Denna and Munger, 1963) evaluation of plants in summer 2016 was straightforward, and we were able to fix the *Bu* (bush) allele for both trial entries CUDel_17_1 and CUDel_17_2 by selecting bush plants to advance. In the recurrent selection population, plants are segregating for this trait, as the most recent round of selection advanced remnant seed of half-sib families that were segregating for bush habit. We heard from NOVIC trial growers that a bush habit was desirable because it allows for both cultivation longer into the season, and for beds to be closer to one another, resulting in a higher density of planting. As noted by Loy (2004), bush plants often flower earlier and have more female than male flowers, and therefore have the potential to be higher yielding than their vine counterparts.

We observed few significant differences between the pedigree selection trial entries and the recurrent selection trial entry for the traits of interest. It is possible that with a greater number of replicates, greater differences between entry means would have been detectable. While Paris and Cohen (2002) concluded that powdery mildew-resistant summer squash had higher yields (kg/10m^2) than comparable susceptible plants, this study was done with heterozygous PMR/PMS hybrids. The significant difference seen in powdery mildew severity did not translate into a significant difference in fruit quality or yield. These results are from one season’s trials; more evaluation (both in years and in locations) will need to be done to get a better sense of the potential of the material. Given that these are composites, there is ample genetic variation to continue to select on for yield and fruit quality traits in the future.

Leveraging genomic resources for organic growers

This project provides an example of upstream genomic research benefiting organic growers. The *Pm-0* marker allowed us to effectively screen seedlings for powdery mildew resistance. Though selection is typically unadvisable during greenhouse generations, selection for highly heritable traits can be done to make gains even under a non-target environment; the marker enabled us to select for resistance during the winter greenhouse generations. Given that the marker is co-dominant, we were able to effectively score heterozygous plants in addition to homozygotes, which allowed the resistant allele to reach fixation in the population more quickly by facilitating a higher selection intensity.

Given the stance of the organic community against genetically-modified organisms (GMO's) – reflected in the NOP standards' identification of genetic engineering as an excluded method (Coleman, 2012)- some aspects of molecular technology are perceived negatively by members of the organic community (Lammerts van Bueren et al., 2010); we hope that the progress made by this project through the use of molecular-assisted selection will be an example of the potential for non-GMO biotechnologies to contribute positively to organically-adapted cultivar development. We have demonstrated that by enabling plant breeders to make quicker progress on traits of particular importance to organic growers (whose options for effective chemical control are limited for powdery mildew), this biotechnological tool can benefit organic agriculture.

Conclusion

The pedigree $F_{3:5}$ composites and recurrent selection population combine positive traits of their parents. Further stabilization of the $F_{3:5}$ pedigree composites will facilitate clearer comparisons with the parent cultivars; continued cycles of intermating and selection in the recurrent selection population may lead to higher fruit quality. The results from the other NOVIC research station trials will shed light on whether these composites are well-suited to production across the northern US, or more specifically-adapted to the Northeast.

Previously, growers looking to grow powdery mildew-resistant delicata had only one cultivar available to them. As a result of this work, three powdery-mildew resistant, high-quality hybrids have been added to that list of options, as well as three populations that, though still under development, are agronomically competitive with high-quality commercial cultivars and offer additional disease resistance to an important pathogen in the Northeast.

Ultimately, these disease-resistant materials (the 'Bush Delicata' F_1's, pedigree $F_{3:5}$ composites and recurrent selection population) may have potential in the future as stand-alone cultivars, or as the starting point for further breeding work.

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CONCLUSION

Looking forward

During my time here at Cornell, I have considered the different ways that plant breeders support farmers. By incorporating farmers in the process of plant breeding, first by asking them to define what's important, then by focusing on goals that are likely to produce varieties that fit their needs, plant breeders increase the likelihood that their work will be relevant. The process of developing a new cultivar – the unique summation of many individual traits – involves trade-offs, and each of these is an opportunities for farmers, our target beneficiaries, to inform the decisions that get made. This points to the need for farmers to be engaged throughout a breeding project – not only in the establishment of priorities, but in the iterative process of evaluation and selection.

This active relationship between plant breeders and farmers is particularly critical to efforts to increase regional food self-sufficiency and security. The necessarily finite resources of any university or breeding program inherently limit the number of distinct goals it can pursue at once. The 'Breeding Research Education Needs Assessment for Organic Vegetable Growers in the Northeast' report (Chapter Two), for example, identified far more crops and traits than a given breeding program could address. The vital impact that a land grant university (or other breeding-focused organization) has through providing cultivars to farmers in their state or region can be multiplied by adding a focus to its work – that of partnering even more closely with farmers to empower them to lead their own breeding projects. By providing training and support to growers who express interest in saving seed and improving cultivars, the possibilities for parallel progress become much greater. This is a role into which I am excited to see the land grant universities and other institutions continue to grow.

APPENDIX I

Hultengren, R.L., Wyatt, L., and M. Mazourek. 2016. A Suite of High-quality Butternut Squash. HortScience 51(11):1435–1437.
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This paper describes the results of NOVIC I to develop new high-quality butternut squash varieties for the Northeast. The trial data indicate that a hybrid, as well as several of the inbred lines, have potential to be useful new options for organic vegetable growers. For more information, the paper can be accessed using the URL below.

http://hortsci.ashspublications.org/content/51/11/1435.short