Critical Experiences in Participatory Approaches to build up Organic Plant Breeding and Seed Systems

Micaela Ruth Colley

Propositions

1. Managing agronomic and social diversity is both the challenge and opportunity of participatory plant breeding.
   (this thesis)

2. Breeding carrot for early seedling growth improves yield in organic systems.
   (this thesis)

3. Excessive use of technology for medical assessments reduces the quality of care.

4. Scientists can only meaningfully collaborate with farmers, citizens and other stakeholders if they are willing and able to reflect on the limitations of the scientific method.

5. Government interference in women's reproductive choices increases women's poverty.

6. Beauty is as important as food for human well-being.

Propositions belonging to the thesis, entitled

Critical Experiences in Participatory Approaches to build up Organic Plant Breeding and Organic Seed Systems

Micaela Colley

Wageningen, 23 November 2022

Critical Experiences in Participatory Approaches to build up Organic Plant Breeding and Seed Systems

Micaela Ruth Colley

Thesis committee

Promotor

Prof. Dr Edith T. Lammerts van Bueren

Emeritus professor Organic Plant Breeding

Wageningen University & Research

Co-promotors

Dr Conny J. M. Almekinders,

Associate professor, Knowledge, Technology and Innovation

Wageningen University & Research

Prof. Dr Julie C. Dawson

Associate professor, Horticulture

University of Wisconsin-Madison, USA

Other members

Prof. Dr Katrien K. E. Descheemaeker, Wageningen University & Research

Prof. Dr Pedro M. R. Mendes Moreira, Polytechnic Institute of Coimbra, Portugal

Dr Abco J. de Buck, Louis Bolk Institute, Bunnik

Dr Eva Weltzien-Rattunde, University of Wisconsin-Madison, USA

This research was conducted under the auspices of the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC).

Critical Experiences in Participatory Approaches to build up Organic Plant Breeding and Seed Systems

Micaela Ruth Colley

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 23 November 2022
at 16 p.m. in the Omnia Auditorium.

Micaela Ruth Colley

Critical Experiences in Participatory Approaches to build up Organic Plant Breeding and Seed Systems,

243 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2022)

With references, with summary in English

ISBN 978-94-6447-441-1

DOI 10.18174/578477

Table of contents

Chapter 1 .... **1**

General Introduction **1**

Background 2

Problem Description 12

Research Objectives and Questions 15

Research Design and Methodology 16

Outline of the Thesis 20

References 21

Chapter 2 .... **29**

Exploring the emergence of participatory plant breeding in countries of the global North – a review **29**

Abstract 30

Introduction 31

Materials and methods 33

Results 38

Discussion 63

References 69

Chapter 3 .... **85**

Carrot performance in organic and conventional management systems and implications for organic plant breeding **85**

Abstract 86

Introduction 87

Materials and methods 92

Discussion 127

References 131
Supplemental Materials..140
Chapter 4 149
Suitability of a network model to facilitate testing and increase adoption of organic seed: reflections from 12 years of the Northern Organic Vegetable Improvement Collaborative (NOVIC) 149
Abstract 150
Introduction..151
Materials and methods 157
Results...159
Discussion 169
Conclusions..173
References 174
Chapter 5 181
How the seed of participatory plant breeding found its way in the world through adaptive management 181
Abstract 182
Introduction..183
Materials and methods 188
Results...188
Discussion 198
References 203
Chapter 6 209
General Discussion 209
Main findings of the studies...210
Discussion of the research findings..216

Research gaps, needs, and future research pathways 223

References 226

Summary 233

Acknowledgements 239

Education Statement 242

Chapter 1

General Introduction

Introduction

The research in this thesis aims to expand our understanding of how participatory approaches can aid in developing and disseminating improved cultivars that address the agronomic, market, and social needs of organic farmers in the USA. The body of research presented begins with a review of the state of the art of participatory plant breeding (PPB) in the Global North and then draws upon critical experiences from participatory and organic plant breeding and testing networks in the USA to address additional research questions. Technological and social aspects of the field are explored. To apply the research questions in a crop-specific context, case studies of five crops (potato, tomato, corn, broccoli/cabbage, and wheat) are highlighted in the review of literature, carrot is used as a model crop for technological analysis and a case study in commercialization of a PPB corn is described as an example of a cultivar release in PPB. In this chapter the background and current state of prior research is presented, and the problems addressed by this thesis are introduced. The specific research objectives, and research questions are then clarified, and the research design and methodologies are described. Finally, an outline of the thesis and relationship of each chapter with the overall research objective is explained.

Background

Over the last five decades, the important role of seed and plant breeding in organic agriculture and sustainable agroecosystems has gained awareness and momentum in the US and Europe. During this time the organic seed movement grew from a grassroots initiative into a small, but established, sector of research and industry. Expansion of organic seed systems is in part motivated by the implementation of organic seed regulations by the USDA National Organic Program (NOP) (7 CFR § 205.204) and the European Union (USDA-NOP, 2002; EC, 2020). Public and private breeding initiatives are challenged to fulfil the diversity of cultivar needs of organic farmers and most still rely on non-organic seed of cultivars developed for conventional agriculture for at least a portion of their production (Hubbard et al., 2022; Orsini et al., 2020; Solfanelli et al., 2021). While conventional agriculture has greater means to adjust the growing environment through inputs, organic agriculture needs cultivars that adapt to a given environment to enable productivity (Lammerts van Bueren and Myers, 2012). Furthermore, the organic sector is grounded in the principles of health, ecology, fairness and care as described by the International Federation of Organic Agriculture Movements (IFOAM Organics International, 2022). Thus, organic agriculture is not simply an input substitution method, but embraces philosophical values including honoring the importance of ecological and human health, fair practices, diversity, and resilience in agroecosystems. Ideally organic plant breeding provides benefits beyond delivering the targeted traits and does not only perform within the system but contributes to the overall resilience of the system. At the same time, organic breeders must also deliver product qualities demanded by the organic stakeholders including flavor and nutrition. A systems approach to breeding is thus proposed to develop appropriate methods, addresses production and ecological goals, and at the same time build equitable social and financial models to support on-going breeding needs while delivering broad benefits to society (Koopmans et al., 2014; Lammerts van Bueren et al., 2018).

Compared with conventional agriculture, organic farms are often smaller, highly diversified in the crops and cultivars within a farm, serving diversified markets, and decentralized geographically (and climatically). Breeding efforts must thus employ efficient and economic as well as philosophically acceptable methods to deliver the diversity of suitable cultivars necessary to address farmers needs and fulfil the diverse market demands of organic consumers.

Organic breeding methods

Choice of crop genetics is a critical tool in managing an organic agricultural system. While desirable traits overlap between organic and conventional management systems researchers often report that the prioritization of traits is not always the same, and with greater emphasis on weed competitiveness, nutrient use efficiency, durable disease resistance, and leveraging plant-soil microbial interactions in organic systems (Lammerts van Bueren et al., 2002; Dawson et al., 2008ab; Lammerts van Bueren et al., 2011; Abdelrazek et al., 2020b). As public and private breeding programs are often limited in capacity and striving to address the needs of both organic and conventional farmers there is a need to better understand the genotype by environment by management system interactions influencing cultivar performance in organic systems and implications for testing and selection environments (Murphy et al., 2007; Lorenzana and Bernardo, 2008; Renaud et al., 2014). The question is whether separate breeding programs are needed to breed for organic systems or if it is only important to pay attention to organically prioritized traits in conventional selection environments (Baenzinger et al., 2011; Muellner et al., 2014; Crespo-Herrera and Ortiz, 2015). In other words, is the heritability for selection traits in conventional systems correlated with performance in organic systems?

The ranking of cultivar performance in organic versus conventional systems sometimes differs due to genotype by management system interactions (Murphy et al., 2007; Vlachostergios and Roupakias, 2008), though not always (Renaud et al., 2014). There is evidence that selection under organic environments can more rapidly improve yields for organic systems in certain situations (Reid et al., 2010; Baenzinger et al., 2011; Kirk et al., 2012), but results are not consistent (Lorenzana and Bernardo (2008). Lorenzana and Bernardo (2008) found a high correlated response of selection in conventional for organic compared with direct selection in organic for yield, but not for more complexly inherited traits of root lodging and stay-green in maize. Renaud et al. (2014) found correlations close to 1 for horticultural traits in broccoli, yet in both studies the correlated response was never greater than 1, indicating that selection in conventional was a close approximation for organic response, but not better than direct selection. Przystalski et al. (2008) evaluated results of trials of a diversity of grain species seven European countries and found in general a high genotypic correlation between the organic and conventional management systems, but only moderate agreement in ranking of cultivar performance indicating that trial information from both systems is necessary to ensure identification of optimum cultivars for organic. Whether or not there is a difference in breeding goals between systems is also debated in the literature, as Crespo-Herrera and Ortiz (2015) contend that organic breeding priorities (such as nutrient use efficiency, disease and pest resistance, and stress tolerance) are becoming more and more important also in conventional programs. They state that furthermore conventional breeding also targets low-input and stressful conditions which, like organic systems, need robust cultivars (Crespo-Herrera and Ortiz, 2015).

The authors do acknowledge however, that organic environments often exhibit greater genotype by environment interactions due to the lack of external inputs and greater variation in resource cycling and quality of inputs regionally and thus warrant additional attention when breeding for adaptation to specific locations or regions is the goal.

Most studies comparing genotype by environment interactions in organic and conventional management are in grain crops (Murphy et al., 2007; Löschenberger et al., 2008; Reid et al., 2011; Kirk et al., 2012; Entz et al., 2018) with only select examples of horticultural crops (Lammerts van Bueren et al., 2012; Osman, 2008; Renaud et al., 2014). To date the body of literature assessing the genotype by management system interaction between organic and conventional leaves many gaps in the scope of crops and traits evaluated with mixed conclusions. Continued evaluation of the influence of organic management system on genetic variance and heritability is needed to clarify for which crops and traits selection in conventional systems is likely resulting in improvements for organic and when is direct selection in organic a necessary priority to address organic breeding goals.

Synergies between organic and participatory plant breeding

Participatory plant breeding (PPB) and participatory variety selection (PVS), historically rooted in subsistence agriculture in the South, holds promise as an efficient and effective methodology for organic breeding in the North based on similarities in production environments, and the need for diverse, robust cultivars developed with limited financial resources (Bocci and Chable, 2009; Shelton and Tracy, 2016; Ceccarelli and Grando, 2019). PPB and PVS are forms of participatory research in which stakeholders (farmers and others) are involved in the decision making and active participants in the breeding process (PPB) or providing input in evaluations on-farm of in the subsequent testing of cultivars (PVS) (Weltzien et al., 2003). From the 1980's until the mid-2000 the largest group of PPB practitioners stemmed from the Consultive Group on Plant Genetic Resources (CGIAR) applying PPB to address the needs of decentralized and marginalized farmers growing in low-input and subsistence agriculture, underserved by the green revolution (Weltzien et al., 2003; Ceccarelli and Grando, 2019). In a recent international review of the literature of PPB and PVS

(Ceccarelli and Grando, 2019) identified a trend of practitioners increasingly applying PPB methods in the Global North. Their review of the literature identified 60 institutions across nine developed countries where cases of PPB projects are cited in the literature, with USA among the top 10. As the authors reflect, this demonstrates that PPB methodologies are not restricted to developing countries but drawn upon to address farmers' needs, being underserved by mainstream breeding sector in developed countries as well. PPB in the global North is still nascent however and while there are parallels between subsistence farmers in the Global South and organic farmers in the Global North there is a need to consider the differences in socio-economic, market and regulatory environments between the two contexts. Organic farmers by and large are not subsistence farmers, but dependent on high value markets to operate in the high-level economies of the Global North. There is a need to better understand the motivations of PPB in the Global North, clarify if PPB is serving organic farmers needs in these countries, and assess methodologies and approaches to optimize implementation and institutionalization in organic agriculture.

There are several justifications for applying PPB in organic plant breeding from quantitative genetic selection theory (Dawson et al., 2008a; Shelton and Tracy, 2016). Conventional breeding programs aim to minimize genotype by environment interactions and select for broad adaptation across environments with optimum inputs. Whereas organic and low-input farming systems commonly experience greater within farm and across farm environmental heterogeneity due to varied inputs, on-farm practices, and non-uniform landscapes, and as such conventional varieties may not perform optimally (Dawson et al., 2008a). A key tenant of PPB is leveraging the potential for selecting under the environment of intended to enhance specific adaptation and improve yield stability in unique and decentralized environments (Atlin, 2001; Dawson et al., 2008a; Ceccarelli and Grando, 2022). The theory is that selection within the targeted, decentralized environment leverages the genetic correlation between genotype's expression in the environment and heritability of genotypic differences in the specific environment (Atlin, 2001). Such conditions are characterized by many small to medium size organic farms making PPB a suitable approach to addressing diverse and underserved needs of organic farmers (Chiffoleau and Desclaux, 2006; Dawson et al., 2008a; Shelton and Tracy, 2016). Whether selection is conducted on a single farm or as part of a decentralized farmer-breeding network awareness of the genotype by environment interactions, genetic correlations between locations and, and stability of performance under different environments is important in determining participatory breeding strategies (Dawson et al., 2008a; Lyon et al., 2019).

Organic Seed Systems in the USA and Europe

Many parallels exist between the United States (US) and Europe regarding the timing, motivations, and emerging models for developing organic seed systems (Renaud et al., 2016). However, the two geographic regions are influenced by important differences in the context of governance, history, and social factors impacting seed systems. For example, the US, unlike Europe, does not have a formal, governmental seed registry system. The absence of a required seed registry allows farmer-breeders and smaller seed companies in the US to commercialize genetically diverse varieties that may lack rigorous phenotypic uniformity. While recent exceptions for conservation of heirlooms and release of heterogenous cultivars has increased flexibility in the European system (EU, 2022) there is still greater freedom in the US for growers to practice on-farm seed saving and to commercialize a greater diversity of seed. At the same time, the lack of a registry system limits US efforts to track crop genetic diversity and organic seed availability. In the US, organic producers, and seed companies, unlike their European counterparts, also grapple with cross contamination from genetically modified crops not allowed in organic systems. Both regions face common, global issues regarding the impacts of consolidation in the seed industry, which has led to less genetic diversity in commercial crops and a greater dependence on the decisions of fewer breeders (Howard, 2015). Although barriers to fostering seed diversity exist, there are trends emerging across the US and Europe of seed initiatives aiming to reinvigorate on-farm seed management and embed cultivated diversity in the agricultural landscape. Recent initiatives include European collaborative projects, Dynaversity (http://dynaversity.eu), Diversifood (https://diversifood.eu), Eco Breeds (https://ecobreed.eu), and LiveSeed (www.liveseed.eu) and USA collaborative initiatives of Organic Seed Alliance (www.seedalliance.org), Seed Savers Exchange (www.seedsavers.org), and Utopian Seed Project (www.theutopianseedproject.org), and the Experimental Farm Network (www.experimentalfarmnetwork.org) just to name a few. In both Europe and the USA university researchers, along with non-governmental organizations (NGOs) are frequently involved in or leading these projects. In the USA an emerging movement is also reconnecting Indigenous communities and people of color with their culturally significant seeds and examples include the Indigenous Seed Keepers Network (https://nativefoodalliance.org/our-programs-2/indigenous-seedkeepers-network/) and Ujamaa Cooperative Farming Alliance (https://ujamaafarms.com).

State of Organic Seed in the US

Every five years Organic Seed Alliance (OSA), an NGO in the USA, releases the State of Organic Seed report as part of an ongoing project to monitor the status of organic seed nationally and provide a roadmap for increasing the diversity, quality, and integrity of organic seed available to US farmers (Hubbard et al., 2022). According to the most recent (2022) report, organic farmers increased organic seed usage from 2011 to 2016, but over the last 5 years no meaningful increases are apparent. The report also identified higher percentage organic seed usage by smaller scale growers (less than 20 hectares) while the largest scale growers (greater than 200 hectares) use very little organic seed. Across all crops organic farmers surveyed reported only an average of 37% of organic growers are using entirely organic seed for their production. In other words, 63% still rely on conventional seed sources. Reasons cited include specific varieties are not available in organic form, insufficient quantities in seed, and a lack of desirable traits. Key findings of the report that highlight challenges to the development of organic seed systems including, 1) research investments in organic plant breeding and organic seed are insufficient to address the research needs; 2) producers and researchers alike are concerned about utility patents; 3) cross contamination from genetic engineering poses risks to organic seed integrity; 4) seed industry consolidation reduces healthy competition in the marketplace; and 5) climate change is impacting organic seed production. Organic farmers responding to surveys however reported a belief that organic seed is important to the integrity of organic food.

The report additionally conducted a network analysis of the organic seed system, led by Wood (2022) and found, “the current structure of the seed network mostly reflects a vision of a resilient seed system, but regions other than the West are still small, and resources along the supply chain could stand to be diversified". Wood found that supply chain connections held the lowest crossover of kinds of connections between regions and lowest diversity of professions. This reflects the decentralized, regionally based nature of the organic seed supply chain network which may serve organic growers within a region, but leaves gaps in supply access in under-represented regions. The State of Organic Seed survey results and Wood's network analysis point to the complexity of issues impacting organic farmers access to suitable forms of organic seed and the need to further investigate if and how organic and participatory breeding and seed system efforts can aid in addressing these obstacles.

Trends in organic plant breeding

Despite the gaps in supply revealed by the SOS report, organic plant breeding expanded over the past decade with private seed companies striving to address the burgeoning organic seed market. In parallel with private sector efforts, USA research activities grew at universities, supported by public and private investments (Hubbard et al., 2022). These programs are generating a new wave of graduate students entering the job market with training in organic plant breeding. Two universities in the USA now hold endowed chairs in organic plant breeding, including Dr. Stephen Jones at Washington State University and Dr. Bill Tracy at the University of Wisconsin-Madison. The private company, Clif Bar & Company, partially funded endowments for these two positions with matching funds from the organic food industry. The Clif Bar Family Foundation has additionally supported 16 graduate student fellowships since 2011. These graduate students are helping to build the body of scientific literature on organic plant breeding and carving professional paths in this sector as well. In 2012, a group of students launched the Student Organic Seed Symposium (SOSS) to create an annual gathering of students, professors, and members of the broader organic seed community to share research, learn about the burgeoning organic seed community and trade, and network with members within it. In 2016, SOSS launched the Society of Organic Seed Professionals (SOSP) to create a professional space outside of the symposium for organic seed students, researchers, and others (Luby et al., 2013).

The broader field of plant breeding is also rapidly changing with the growth of molecular techniques and trends toward consolidation of the private sector. The juxtaposition of growth in the field of organic plant breeding and trends in the broader landscape of the seed industry has raised discussion on the definition; appropriateness and effectiveness of methods, and overarching objectives of organic plant breeding (Lammerts van Bueren et al., 2010; Nuijten et al., 2017). Researchers, organic stakeholders, and policy makers are grappling with defining allowable methods in organic plant breeding and identifying where genetic tools have the greatest potential to benefit organic breeding efforts. Manipulation of the genome through cell fusion, microencapsulation and macroencapsulation, and recombinant DNA technology (GMO) is not allowed in organic methods (including gene deletion, gene doubling, introducing a foreign gene, and changing the positions of genes when achieved by recombinant DNA technology) (USDA/NIFA, 2002). Other techniques such as gene editing, mutagenesis, and induced cytoplasmic male sterility are also under debate as the organic regulatory bodies grapple with balancing scrutiny of organic integrity with impacts on organic agriculture and limited genetic options (NOSB, 2018; IFOAM, 2020). It is imperative for the continued growth of the organic sector to develop effective methods that are acceptable to organic stakeholders and address the breeding needs of organic agriculture with regard to ecological, economic, social and legal aspects. To this end organic breeding emphasizes further enhancing and developing classical, field-based breeding techniques in alignment with the principle of "care", but is also increasingly leveraging genetic information tools, including marker assisted selection that do not compromise the integrity of the whole plant through genome manipulation (Lammerts van Bueren et al., 2010).

While hybrid (F1) cultivars are allowed in organic production and private plant breeding are developing cultivars for organic production (ie. Bejo Seeds, 2022). Organic agriculture also values diversity as previously discussed and many organic breeding approaches emphasize the value of on-farm biodiversity conservation and the ability of seeds to evolve and adapt within an environment (Bocci and Chable, 2009; Bocci et al., 2012; Ceccarelli and Grando, 2022). For this reason, breeding of open-pollinated varieties is a common approach.

Participatory variety selection and on-farm variety trial methods

All breeding programs must devise a pathway of testing and dissemination of new cultivars to benefit the targeted stakeholders, yet organic seed systems are not as straightforward in market structure as conventional as evidenced by the decentralized nature of seed networks identified by Wood (2022). The decentralized structure means that variety testing is as challenging as breeding in terms of resource allocation and assurance of applicability of results. For this reason, participatory, on-farm trials for cultivar evaluation (PVS) frequently compliment organic plant breeding and PPB initiatives. On-farm evaluation often serves as an opportunity provide feedback to breeders of relevant traits for ongoing breeding efforts and to evaluate performance of advanced generation breeding selections as well as new cultivars directly under the conditions of intended use (Witcombe et al., 1996; Sperling et al., 2001). Farmer participation in this process has demonstrated to expedite adoption of new cultivars (Ceccarelli and Grando, 2007). There are challenges however from a research perspective to design effective on-farm trials within the constraints of a working farm environment (Lyon et al., 2019; Zystro et al., 2018; Rivière et al., 2021). The mother-daughter trial design is a scheme developed to combine on-farm data with on-station data to assess cultivar performance across decentralized farms and correlate results on-station evaluations (Snapp, 1999). Organic testing networks in the USA are adopting this approach for organic farmer-participatory testing strategies in the US (Lyon et al., 2019). The research station conducts replicated trials (mother site) and at least three farm locations in the region or village conduct single replications (daughter sites). The three or more daughter sites then serve as replications blocked by farm to account for environmental variability. On-farm trials present a high degree of variability in the environment between farms, on-farm heterogeneity, variability in agronomic methods, and variability in evaluators. For these reasons acquiring statistical significance from on-farm trials can be challenging (Rivière et al., 2015). Furthermore, the high cost of farming, particularly for horticultural crops, can limit capacity for increasing population size and number of replications on farm. There is however a clear potential benefit to conducting on-farm trials from the social and informational perspectives, but there is a need to refine trial methods to ensure the maximum value is achieved given the type of crop, trial feasibility, and goals of the breeder and farmer.

Problem Description

Participatory Plant Breeding (PPB) in the global North

The current state of the field of participatory plant breeding in the Global North is unclear and no prior reviews of the literature focused on this body of experience exist. While PPB is proposed as a good fit for organic plant breeding for technical and socio-economic reasons there is a lack of widespread institutionalization. PPB implementation, though expanding, is still nascent and finite in the Global North, with a few isolated exceptions. Exploring the motivations behind researchers, farmers, and other stakeholders to work together and to what end, the challenges confronted and overcome and benefits derived will aid in clarifying how and why PPB is emerging in countries where significant private and public investments in plant breeding and seed distribution is present. It is imperative to learn from the collective experience of practitioners to date to formulate hypothesis of how best to design future PPB efforts in an informed manner to have the greatest likelihood of addressing the context specific goals. Likewise, as researchers and farmers in these countries experience many parallel contexts of market dynamics, regulatory frameworks, and societal influences an assessment of potential challenges and barriers to implementation would aid in informing pathways to address common obstacles. From this general status, three sub-areas with specific knowledge gaps where participatory approaches were formulated and are addressed in this thesis: organic breeding strategy, cultivar testing networks and cultivar release and commercialization.

Organic breeding strategies

While organic markets continue to expand organic farmers experience gaps in availability of cultivars with qualities that suit their agronomic, market and regulatory needs (i.e. requirements to plant organic seed). While the organic seed industry and public initiatives are expanding research in organic plant breeding, they are unable to fully address the diversity of organic farmers' needs. The relatively small scale of organic farming combined with the decentralized nature of organic farms and diversity of cropping systems necessitates development of efficient and effective breeding strategies. For public and private breeders who are aiming to serve both organic and conventional farmers this raises the question of whether selection in conventional management is suitable to improve performance of cultivars under organic management systems. This question remains a gap in the literature for vegetable crops in specific, among which there is carrot, a high value crop grown by organic farmers in all regions across the USA. In addition to yield considerations organic farmers also need cultivars with traits that support the overall functioning of the organic agroecosystem. In organic carrot weeds are managed with mechanical and hand cultivation to achieve yield potentials, however this is a costly input and growers are at risk of crop loss if weed management is not addressed. There is a lack of literature on the genotypic variance of top growth traits and assessment of heritability of top growth response under different environments. Multi-environment trials are needed to address these gaps in the literature.

Participatory cultivar testing networks

In addition to presenting challenges in breeding capacity, the decentralized and diversified nature of organic farms presents additional obstacles in efficiently and effectively testing breeding populations and cultivars for suitability to the diverse growing environments and markets. Many research institutions in the US working in organic plant breeding have certified organic farms that function as research stations where there may be funding, capacity and infrastructure for organic cultivar testing. On-station trials allows researchers greater control in applying replicated field trial experimental designs and management of data collection. The results from research stations may not however be representative of the diversity of agro-ecological and socio-economic environments of organic stakeholders the researchers aim to serve. For this reason, participatory approaches for evaluating on-farm trials are frequently applied in collaborative organic breeding projects in the USA. Participatory cultivar testing networks commonly aim to achieve multiple goals of informing plant breeders of farmer's needs and suitability of advanced breeding populations as well as facilitating farmer adoption of cultivars best suited to their unique conditions. There are clear challenges however in implementing cultivar trials on a working farm, namely considerations of time, space, and capacity of farmers to conduct evaluations. There is need to evaluate the outcomes of these experiences inform future approaches and methodologies of PVS efforts in organic systems in the USA.

Variety release and commercialization

If new PPB projects do not have a pathway for release, dissemination, and maintenance of new cultivars then the technology is at risk of remaining limited in access and impacts on expansion of the collective availability of suitable organic cultivars. University and non-profit breeders are not generally in the business of production, marketing and distribution of seed and thus at risk of their PPB cultivars remaining a niche innovation benefiting select stakeholders directly involved in the breeding process. There are examples of shared access of PPB varieties through farmer networks, such as Réseau Semences Paysannes in France, the Red de Semillas in Spain and the Rete Semi Rurali in Italy (Bocci and Chable, 2009). In the USA there is evidence of resilient regional seed system, but even within these networks supply channels are limited (Wood, 2022). While regional seed companies may aid in dissemination of regionally developed PPB cultivars there remain gaps nationally in presence of regional networks and small organic seed companies to engage in distribution. Additionally, the extensive lack of suitable cultivar availability nationally as evidenced by the State of Organic Seed Report (Hubbard et al., 2022) points to the need to leverage breeding investments to achieve as broad of benefit as possible.

Successful commercialization of a cultivar generally requires that the market demand or royalties supports the ongoing costs related to maintaining the genetic quality of the cultivar, producing seed of adequate quality, and investing in infrastructure to market, store, and distribute seed. The conventional and larger-scale organic seed industry often justifies these investments by targeting cultivars that are either broadly adapted or hold a larger-scale production niche and applying intellectual property rights to ensure a return on investment through exclusivity of sales. The grassroots organic seed community by and large rejects overly restrictive intellectual property such as patents. Even if intellectual property was accepted by the organic market the cost of patents and plant variety protection (PVP) is prohibitive given the likely scale of adoption of a PPB cultivar. There is a need to explore alternative market channels to support the cultivar maintenance, production, and distribution of new PPB cultivars to expand organic farmers' diversity of cultivar choices.

Research Objectives and Questions

The overall objective of this thesis is to expand understanding of the challenges and opportunities to participatory approaches in organic plant breeding and seed systems.

Research Question 1: What are the outcomes and impacts of PPB implementation in the Global North to date and what can we learn from prior experiences?

Objective: A state of the art review of PPB in the Global North aims to assess whether there is evidence that PPB is addressing the agronomic needs of farmers, whether it is motivated by societal goals beyond organic agriculture, and if there are trends in the experiences to date that may provide insights to inform the successful institutionalization of PPB in current in and future research programs. This objective is addressed in Chapter 2 of the thesis.

Research Question 2: Do carrot cultivars and breeding lines perform differently agronomically different under organic and conventional management practices across different locations and years?

Objective: To inform future selection and testing strategies for improvement of carrot for organic systems in the Midwest USA analysis of multi-environment trials serves to estimate genetic variance, broad sense heritability and adaptability of diverse carrot genotypes in two locations, (Wisconsin and Indiana), across 4 years under organic and conventional management practices. This objective is addressed in Chapter 3 of the thesis.

Research question 3: Is a participatory farmer-research network an effective approach to expand organic farmer's access to organic seed of vegetable cultivars that support their production system and markets in the USA? And is the mother-daughter trial design a suitable model for achieving this objective?

Objective: To inform the design of future organic trial networks the outcomes and lessons learned from a case study of 12 years' experiences of participants in a national vegetable trial network are assessed. This objective is addressed in Chapter 4 of the thesis.

Research question 4: How can PPB varieties become embedded in the broader operating environment to broaden impacts and expand access to organic seed of new cultivars?

Objective: To expand impacts of PPB technologies a case study is described to analyze the dynamic decision-making process and actions taken by actors involved that enabled successful, national commercialization of a PPB sweet maize cultivar.

Research Design and Methodology

This thesis integrates analysis of agronomic, social, and economic aspects of organic plant breeding and seed systems to address the overall and specific research objectives (Figure 1). Research design and methodologies to address each research questions and presented in the different chapters of this thesis have an exploratory character and use a mix of research methods that are described below. The author of this thesis has been involved in all studies presented in the different chapters as a participant in the research projects with research collaborators from multiple institutions. The author of this thesis wrote the research objectives and designed the research methodologies and framework. The author also conducted the analysis and interpreted results, with support from co-authors, and wrote the chapters. Research methods are detailed below following each research question.

The research first aimed to study prior collective experiences in implementation of PPB in the context of countries of the Global North to better understand if there is evidence that PPB is addressing organic seed system needs and if so, then how and what methodologies are achieving that goal (Chapter 2). We aimed to identify if and where barriers and challenges to implementation exist with the goal of exploring potential pathways forward to addressing those obstacles. The research then turns toward analysing critical experiences in the USA of efforts to develop and apply participatory approaches in organic plant breeding and seed systems. We aimed to better understand if environment and management practices influences carrot performance (Chapter 3). We then aimed to assess if there is evidence that participatory approaches in seed systems impact organic farmers access to suitable forms of seed. We address this objective through analysis of a national participatory vegetable trial network in the USA (Chapter 4). Subsequently, through a lens of adaptive management we analyze the experience of release and commercialization of a PPB cultivar of sweet maize in the USA to better understand how the technology of PPB may be embedded in the broader operating environment of commercially available seed (Chapter 5). Finally, we conclude by presenting key outcomes of each chapter and discussion of results (Chapter 6).

What are the outcomes and impacts of PPB implementation in the Global North to date and what can we learn from prior experiences?

To address research question 1 a critical review of the literature served to analyze the breadth of experience of PPB implementation in the Global North. The review process entailed a stepwise process including, 1) conducting a systematic search for peer review literature and popular press to collect the body of information for analysis, 2) constructing an inventory of projects categorized by crop species, location, researchers and institutions involved, methodologies applied, and outcomes, 3) analyzing the collective inventory and related literature to generate results necessary to address the key research objectives, 4) constructing case studies of 5 crop species to deepen analysis and compare across contrasting biological reproductive types of crops including self and cross pollinating, annual and biennial reproductive cycles, and seed and vegetatively propagated species. An analysis of the results was then leveraged to describe the breadth of PPB experiences and outcomes to date and draw conclusions regarding the underlying motivations, challenges, and lessons learned from collective experiences.

Do carrot cultivars perform agronomically different under organic and conventional management practices across different locations and years?

To address research question 2 we conducted multi-environment trials of carrot in two locations (Indiana and Wisconsin), for four years (2012-2015) and under both conventional and organic management practices for a total of 16 field trials. The study aimed to test interactions of genotype, environment and management system to inform the Carrot Improvement for Organic Agriculture (CIOA) project in the USA (https://eorganic.info/group/7645). University research stations at Purdue and University of Wisconsin-Madison served as trial locations with the organic and conventional fields paired to minimize differences in location and soil types between systems. To assess a wide range of genotypes including a diversity of colors, we included F1 hybrids, open-pollinated (OP) cultivars, and breeding lines from the United States Department of Agriculture/ Agricultural Research Service (USDA/ARS) carrot program. Field trial design constituted a randomized complete block design with three replications (blocks). Soil analysis included chemical and biological characteristics. Evaluations included measurements of top growth at ~30 days after planting, ~60days after planting and at time of harvest. Yield evaluations included weights of foliar tops and roots at time of harvest. To address our research objectives, we conducted assessed variances for genotype, location, year, and management system by applying an analysis of variance and various other mixed linear models to calculate coefficients of variation, repeatabilities and analysis of mixed models and additive interactions (AMMI). To compare performance of genotypes in organic and conventional management we applied tests of Spearman's Rank Correlation, Finlay Wilkinson regression for adaptability analysis, and calculated correlated response of direct versus indirect selection, ie. selecting in conventional for improved performance in organic systems and vice versa. Implications of results for organic plant breeding are discussed drawing upon the literature on organic breeding strategies.

Is a participatory farmer-research network an effective approach to expand organic farmer's access to organic seed of vegetable cultivars that support their production system and markets in the USA? And is the mother-daughter trial design a suitable model for achieving this objective?

To address research question 3 we analyzed the experience of a 12 year-long participatory cultivar testing network that involved researchers (plant breeders), trial coordinators and farmers. The network operated under the Northern Organic Vegetable Improvement Collaborative (NOVIC) with support from the USDA (https://eorganic.info/novic/about). The network research design followed an adoption of the mother-daughter trial design first described by Snapp (1999). In the NOVIC network research stations conducted replicated trials with at least 3 on-farm sites conducting single replications in each region. Crops tested included Research partners included collaborators from four states including three universities and an NGO: Oregon State University (Oregon), University of Wisconsin-Madison (Wisconsin), Cornell University (New York) and Organic Seed Alliance, an NGO in Washington State. The research tools included surveys, interviews and participant observations. Surveys, conducted through the online tool Survey Monkey, queried farmer participants (n=36) on their experiences, outcomes, and perceptions of involvement in the trial network. We then followed up with select farmers to conduct semi-structured interviews (n=9) to provide a deeper assessment of farmers experience and explore critical lessons from the farmer's perspectives. We interviewed plant breeders involved in the project (n=3) to assess impacts on plant breeding activities, their experience working with the farmers and lessons learned from their experience. Trial coordinators provided critical input as participant observers, a methodology described by Spradley (1980), as they were pivotal in their interactions with the project plant breeders, farmers, and external stakeholders (seed companies, chefs, and additional farmers beyond trial hosts. To quantify results, we analyzed the survey data to address our research questions. We reviewed the transcribed interviews and notes from participant observations to reflect on and deepen interpretation of the survey results and to identify salient themes and unexpected outcomes. The collective body of results is then discussed with an emphasis on reflecting on implications for design and management of future participator trial networks.

How can PPB varieties become embedded in the broader operating environment to broaden impacts and expand access to organic seed of new cultivars?

A case study of a PPB project that resulted in a variety release and commercialization is analyzed through the lens of strategic management theory (Ocvirk, 2018). The project history, objectives and evolving roles of participants are first recounted to provide context of the PPB experience and partners involved. The experience was then analyzed to identify key point in the variety release and commercialization process which required participants to take strategic actions and collectively navigate decisions necessary to address obstacles and enable commercialization of the cultivar. We then present the outcomes and impacts after more than 10 years of commercialization on a national, and subsequently international, scale, including stimulating additional PPB initiatives resulting in additional organic cultivars.

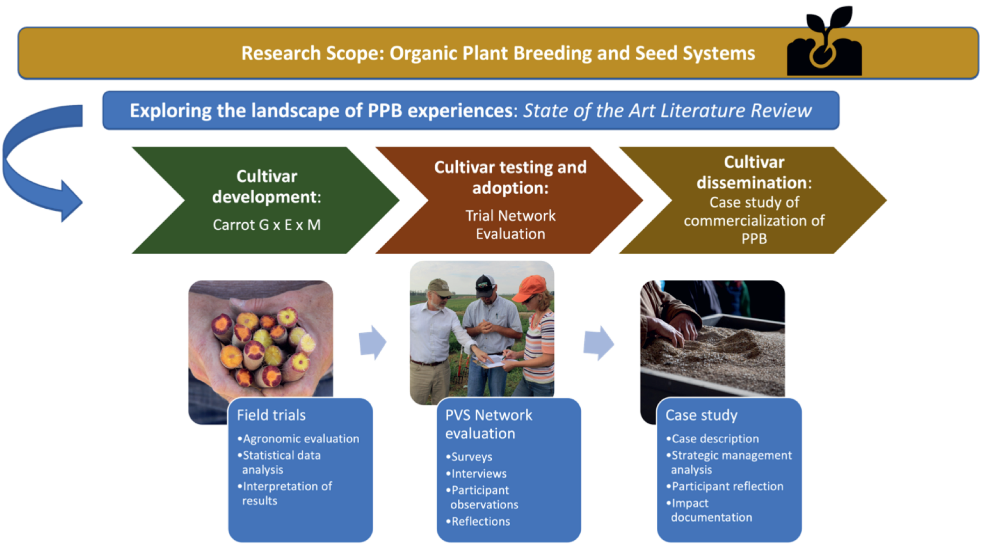


Figure 1. Schematic overview of research design and methodologies to explore the role of participatory plant breeding in organic plant breeding and seed systems and flow of chapters of the thesis.

Outline of the Thesis

The results of the research of this thesis are presented in four articles, each a separate chapter addressing the four key research questions described above. **Chapter 1** (this chapter) introduces the topic and presents the background on the current state of research and broader operating environment leading to the research questions. It then details the objectives, research framework and methods applied within this thesis. **Chapter 2** provides a broad view of the research field reviewing on the breadth of experiences to date in implementation of PPB in the Global North. **Chapter 3** dives into technological and agronomic considerations in designing organic plant breeding in a carrot as a model crop. **Chapter 4** explores the critical bridge from plant breeding to variety adoption by analyzing a long-term (12 years) participatory trial network in the USA. **Chapter 5** touches upon institutional and socio-economic barriers to embedding PPB in the broader operating environment (the seed system). **Chapter 6** provides a recap of outcomes of the research and provides a synthesis of the body of research with reflection and discussion of the contributions to the broader body of science and implications to society. Each chapter explores inter-related aspects of the organic seed systems with an emphasis on exploring participatory methodologies (Figure 1).

References

Abdelrazek S, Choudhari S, Thimmapuram Y, Simon P, Colley M, Mengiste T, Hoagland L (2020) Changes in the core endophytic mycobiome of carrot taproots in response to crop management and genotype. *Scientific Reports* **10** doi.org/10.1038/s41598-020-70683-x.

Atlin GN, Cooper M, and Bjørnstad A (2001) A Comparison of Formal and Participatory Breeding Approaches Using Selection Theory, *Euphytica* **122**, 463-475.

Baenziger PS, Ibrahim S, Little RS, Santra DK, Regassa T and Wang MY (2011) Structuring an Efficient Organic Wheat Breeding Program. *Sustainability* **3** (8), 1190–1205. https://doi.org/10.3390/su3081190.

Bejo Seeds (2022) Organic Seeds. Available at: https://www.bejoseeds.com/organic-0.

Bocci R and Chable V (2009) Peasant Seeds in Europe: Stakes and Prospects. *Journal of Agriculture and the Environment* **103**, 81-93.

Bocci R, Chable V, Kastler G and Louwaars N (2012) Farm Seed Opportunities, Recommendations for On-farm Conservation in Europe. In: *Agrobiodiversity Conservation: Securing the Diversity of Crop Wild Relatives and Landraces*; CAB International: Wallingford, OS, UK; pp. 137–141.

Ceccarelli S (1994) Specific Adaptation and Breeding for Marginal Conditions. *Euphytica* **77**, 205-219.

Ceccarelli S and Grando S (2007) Decentralized-Participatory Plant Breeding: An Example of Demand Driven Research. *Euphytica* **155** (3), 349–60. https://doi.org/10.1007/s10681-006-9336-8.

Ceccarelli S and Grando S (2019) Participatory Plant Breeding: Who Did It, Who Does It and Where? *Experimental Agriculture*, **56** (1), 1–11. https://doi.org/10.1017/S0014479719000127

Ceccarelli S and Grando S (2022) Return to Agrobiodiversity: Participatory Plant Breeding. *Diversity* **14** (2), 126. https://doi.org/10.3390/d14020126.

Chiffoleau Y and Desclaux D (2006) Participatory Plant Breeding: The Best Way to Breed for Sustainable Agriculture? *International Journal of Agricultural Sustainability* 4 (2, 119–30. https://doi.org/10.1080/14735903.2006.9684795.

Crespo-Herrera lA and Ortiz R (2015) Plant Breeding for Organic Agriculture: Something New? *Agriculture & Food Security* **4** (1), 25. https://doi.org/10.1186/s40066-015-0045-1.

Dawson JC, Murphy KM and Jones SS (2008a) Decentralized Selection and Participatory Approaches in Plant Breeding for Low-Input Systems. *Euphytica* **160** (2), 143–54. https://doi.org/10.1007/s10681-007-9533-0.

Dawson JC, Huggins DR and Jones SS (2008b) Characterizing Nitrogen Use Efficiency in Natural and Agricultural Ecosystems to Improve the Performance of Cereal Crops in Low-Input and Organic Agricultural Systems. *Field Crops Research* **107** (2), 89–101. https://doi.org/10.1016/j.fcr.2008.01.001.

Entz MH, Kirk AP, Carkner M, Vaisman I and Fox SL (2018) Evaluation of Lines from a Farmer Participatory Organic Wheat Breeding Program. *Crop Science* **58** (6), 2433. https://doi.org/10.2135/cropsci2018.04.0241.

EC (2020) New European Regulations for Organic Production and Marketing (EU 2020/460); European Commission, Brussels, Belgium. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020R0464

EU (2022) Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. EUR-Lex - 32018R0848 - EN - EUR-Lex (europa.eu)

Howard PH (2015) Intellectual property and consolidation in the seed industry. *Crop Science* **55**, 2489-2495.

Hubbard K, Wood L and Zystro J (2022) *State of Organic Seed*. Organic Seed Alliance: Port Townsend, WA, USA. Available online: www.stateoforganicseed.org

IFOAM (2020) Genetic engineering and genetically modified organisms. International Federation of Organic Agriculture Movements. https://www.ifoam.bio/genetic-engineering-and-genetically-modified-organisms

IFOAM Organics International (2022) The Four Principles of Organic Agriculture. Available at: www.ifoam.bio

Kirk AP, Fox SL and Entz MH (2012) Comparison of Organic and Conventional Selection Environments for Spring Wheat. *Plant Breeding* **131** (6), 687–94. https://doi.org/10.1111/j.1439-0523.2012.02006.x.

Koopmans CJ, Van Veluw K and Wijnands FG (2014) Participatory development as a way to innovations: five key elements for success. In: Rahmann G and Arsoy U (eds.) *Proceedings of the 4th ISOFAR Scientific Conference. 'Building Organic Bridges' at the Organic World Congress* 2014, 13-15 Oct., Istanbul, Turkey (eprint ID 23816).

Lammerts van Bueren ET, Struik PC and Jacobsen E (2002) Ecological concepts in organic farming and their consequences for an organic crop ideotype. *Netherlands Journal of Agricultural Science* **50**, 1–26.

Lammerts van Bueren ET, Østergård H, Goldringer I and Scholten O (2008) Plant Breeding for Organic and Sustainable, Low-Input Agriculture: Dealing with Genotype–Environment Interactions. *Euphytica* **163** (3), 321–22. https://doi.org/10.1007/s10681-008-9731-4.

Lammerts van Bueren ET, Backes G, de Vriend H, and Østergard H (2010) The role of molecular markers and marker assisted selection in breeding for organic agriculture. *Euphytica* **175**, 51–64.

Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C and Messmer MM (2011) The Need to Breed Crop Varieties Suitable for Organic

1

Farming, Using Wheat, Tomato and Broccoli as Examples: A Review. *NJAS - Wageningen Journal of Life Sciences* **58** (3–4), 193–205. https://doi.org/10.1016/j.njas.2010.04.001.

Lammerts van Bueren ET, Struik PC, van Eekeren N and Nuijten E (2018) Towards resilience through systems-based plant breeding. A review. *Agronomy for Sustainable Development* **38**, 42. Available at: http://doi.org/10.1007/s13593-018-0522-6

Lammerts van Bueren ET and Myers JR (2012) *Organic Crop Breeding*. Chichester, West Sussex: Wiley-Blackwell. ISBN: 978-0-470-95858-2

Lorenzana RE and Bernardo R (2008) Genetic Correlation between Corn Performance in Organic and Conventional Production Systems. *Crop Science* **48** (3), 903-910.

Luby CH, Lyon AH, and Shelton AC (2013) A new generation of plant breeders discover fertile ground in organic plant breeding. *Sustainability* **5**, 2722-2726.

Lyon A, Tracy WF, Colley M, Culbert P, Mazourek, M, Myers, J, Zystro J and Silva EM (2019) Adaptability analysis in a participatory variety trial of organic vegetable crops. *Renewable Agriculture and Food Systems* **35**, 296-312. Available at: https://doi.org/10.1017/S1742170518000583

Muellner AE, Mascher F, Schneider D, Ittu G, Toncea I, Rolland B and Löschenberger F (2013) Refining breeding methods for organic and low-input agriculture: analysis of an international winter wheat ring test. *Euphytica* **199**, 81-95 https://doi.org/10.1007/s10681 -014-1169-2

Murphy KM, Kimberly G, Campbell KG, Lyon SR and Jones SS (2007) Evidence of Varietal Adaptation to Organic Farming Systems. *Field Crops Research* **102** (3), 172–77. https://doi.org/10.1016/j.fcr.2007.03.011.

NOSB (2018) Formal recommendations from the National Organic Standards Board (NOSB)to the National Organic Program (NOP). Available at:

https://www.ams.usda.gov/sites/default/files/media/CSStrengtheningOrganicSeedRecOct2018.pdf

Nuijten E, Messmer MM, and Lammerts van Bueren ET (2017) Concepts and Strategies of Organic Plant Breeding in Light of Novel Breeding Techniques. *Sustainability* **9** (18). doi:10.3390/su9010018

Ocvirk G (2018) *Strategic Management of Market Niches: A Model Framework*. Springer Gabler: Weisbaden, Germany, pp. 1–230. https://doi.org/10.1007/978-3-658-20364-1.

Osman AM, Struik PC, Almekinders CJM and Lammerts van Bueren ET (2008) Can conventional breeding programmes provide onion varieties that are suitable for organic farming in the Netherlands? *Euphytica* **163**, 511-522. https://doi.org/10.1007/s10681-008-9700-y

Orsini S, Costanzo A, Solfanelli F, Zanoli R, Padel S, Messmer MM, Winter E and Schaefer F (2020) Factors Affecting the Use of Organic Seed by Organic Farmers in Europe. *Sustainability* **12** (20), 8540. https://doi.org/10.3390/su12208540.

Przystalski M, Osman A, Thiemt EM, Rolland B, Ericson L, Østergård H and Levy L (2008) Comparing the Performance of Cereal Varieties in Organic and Non-Organic Cropping Systems in Different European Countries. *Euphytica* **163** (3), 417–33. https://doi.org/10.1007/s10681-008-9715-4.

Reid T, Yang R-C, Salmon D, Navabi A and Spaner D (2011) Realized gains from selection for spring wheat grain yield are different in conventional and organically managed systems. *Euphytica* **177**, 253-266. https://doi.org/ 10.1007/s10681-010-0257-1

Renaud ENC, Lammerts van Bueren ET and Jiggins JJ (2016) The meta-governance of organic seed regulation in the USA, European Union and Mexico. *International Journal of Agricultural Resources Governance and Ecology* **12**(3), 262-291.

Renaud ENC, Lammerts van Bueren ET, Paulo MJ, van Eeuwijk FA, Juvik JA, Hutton MG and Myers JR (2014) Broccoli Cultivar Performance under Organic and Conventional Management Systems and Implications for Crop Improvement. *Crop Science* **54** (4), 1539–1554. https://doi.org/10.2135/cropsci2013.09.0596.

Rivière P, Dawson JC, Goldringer I and David O (2015) Hierarchical Bayesian Modeling for Flexible Experiments in Decentralized Participatory Plant Breeding. *Crop Science* **55**: 1053-1067. Available online from: https://doi.org/10.2135/cropsci2014.07.0497

Rivière P, Goldringer I and Rey F (2021) *Selecting the appropriate methodology for organic on-farm cultivar trials.* Rey F and Flipon E (eds.) LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/07/PUBLICATIONITAB_LIVESEED.final_.pdf

Shelton AC and Tracy WF (2016) Participatory Plant Breeding and Organic Agriculture: A Synergistic Model for Organic Variety Development in the United States. *Elementa Science of the Anthropocene* **4**, 1–12. https://doi.org/10.12952/journal.elementa.000143.

Snapp S (1999) Mother and baby trials: a novel trial design being tried out in Malawi. *Target – Newsletter of the Soil Fertility Research Network for Maize-based Cropping Systems in Malawi and Zimbabwe*. **17** (8).

Solfanelli F, Orsini S, Zanoli R and Schaefer F (2021). *The State of Organic Seed in Europe*. Petiti M, Ortolani L, and Schaefe F (eds.) LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/03/Booklet2-LIVESEED_2021_web.pdf

Spradley JP (1980) *Participant Observation*. New York, USA. Holt, Rinehart and Winston.

Sperling LJ, Ashby A, Smith ME, Weltzien E and McGuire S (2001) A framework for analyzing participatory plant breeding approaches and results. *Euphytica* **122**, 439–450.

USDA/NIFA: United States Department of Agriculture/ National Institute of Food and Agriculture. National Organic Program (2002) Available at: https://www.ams.usda.gov/about-ams/programs-offices/national-organic-program

Vlachostergios DN and Roupakias DG (2008) Response to Conventional and Organic Environment of Thirty-Six Lentil (Lens Culinaris Medik.) Varieties. *Euphytica* **163** (3): 449–457. https://doi.org/10.1007/s10681-008-9712-7.

Weltzien E, Smith ME, Meitzner LS and Sperling L (2003) *Technical and Institutional Issues in Participatory Plant Breeding-From the Perspective of Formal Plant Breeding: A Global Analysis of Issue, Results, and Current Experience*. pp. 208. Centro International de Agricultura Tropical (CIAT), Cali, Colombia.

Wood L (2022) Assessing the Resilience of the Organic Seed System: A Network Perspective. In. *Proceedings of the 11th Organic Seed Growers Conference*. Hubbard, K. (ed). February 4th-11th, 2022. pp. 128-133.

Witcombe JR, Joshi AKD and Sthapit BR (1996) Farmer participatory crop improvement 1. Varietal selection and breeding methods and their impact on biodiversity. *Experimental Agriculture* **32**, 445–460

Zystro J, Colley M and Dawson J (2018) Alternative Experimental Designs for Plant Breeding. In: Goldman I (ed) *Plant Breeding Reviews.* pp. 87–117. Wiley. https://doi.org/10.1002/9781119521358.ch3.

Chapter 2

Exploring the emergence of participatory plant breeding in countries of the global North – a review

Published as:
Colley MR, Dawson JC, McCluskey C, Myers JR, Tracy WF and Lammerts van Bueren ET (2021) Exploring the emergence of participatory plant breeding in countries of the Global North–a review. *The Journal of Agricultural Science* **159**(5-6), 320-338.

Abstract

Participatory plant breeding (PPB), commonly applied in the Global South to address needs of underserved farmers, refers to the active collaboration between researchers, farmers and other actors throughout the breeding process. Despite significant public and private investments in crop variety improvement in the Global North, PPB is increasingly utilized as an approach to address cropping system needs. The current study conducted a state-of-the-art review, including a comprehensive inventory of projects and five case studies, to explore the emergence of PPB in the Global North and inform future PPB efforts. Case studies included maize (*Zea mays*), tomato (*Solanum lycopersicum*), Brassica crops (*Brassica oleracea*), wheat (*Triticum aestivum*) and potato (*Solanum tuberosum*). The review identified fourty-seven projects across the United States, Canada, and Europe including 22 crop species representing diverse crop biology. Improved adaptation to organic farming systems and addressing principles and values of organic agriculture emerged as consistent themes. While projects presented evidence that PPB has expanded crop diversity and farmer's access to improved varieties, obstacles to PPB also emerged including challenges in sustained funding as well as addressing regulatory barriers to the commercial distribution of PPB varieties. Agronomic improvements were only one lens motivating PPB, with many projects identifying goals of conservation of crop genetic diversity, farmers' seed sovereignty, and avoidance of certain breeding techniques. The authors conclude that a multidisciplinary approach is needed to fully understand the social, political and agroecological influences driving the emergence of projects in the global North and factors impacting success.

Key words: Participatory plant breeding, genetic diversity, seed sovereignty, organic seed

Introduction

Plant breeders, farmers, and other stakeholders across the United States (US), Canada (CA) and Europe are working together to breed new or improved crop varieties, an approach commonly known as Participatory Plant Breeding (PPB) (Chiffoleau and Desclaux, 2006; Dawson et al., 2011; Shelton and Tracy, 2016). Participatory plant breeding is a collaborative relationship between professional plant breeders or researchers, farmer-breeders and other stakeholders to share and leverage knowledge, decision making and resources in breeding efforts. Participatory plant breeding methodologies are more commonly applied in countries with low-income economies, particularly employed by the Consultive Group on International Agricultural Research (CGIAR), to improve the adaptation of crops grown in marginal and heterogeneous environments and to bolster seed security of farmers underserved by the Green Revolution (Weltzien et al., 2003; Morris and Bellon, 2004). A recent global review of the literature on PPB (Ceccarelli and Grando, 2019) identified 66 countries where PPB has been implemented, including nine countries with high-income economies – the US, CA and several European countries. Despite the strong economies, significant public and private investments in modern breeding programs and consistent seed availability in the global North, PPB projects are employed to address farmers' needs throughout the region. This raises the question of what is driving researchers and farmers to collaborate.

Many of these projects focused on breeding for organic agriculture. Organic farmers are more and more legally obligated to use organically produced seed as part of their certification requirements in Europe (EC 2018/848) and in the US (7 CFR § 205.204). They increasingly have access to commercially available organic seed sources. Additionally, producers are allowed to use conventionally grown, untreated seed when suitable organic sources are not available. The organic seed industry is also growing and organic farmers report using an increased quantity of organic seed over the last decade (Hubbard and Zystro, 2016). Yet, access to seed does not always mean that farmers are satisfied with their seed options. As Shelton and Tracy (2016) point out, many organic seed options are cultivars bred in and for conventional systems where seed is simply produced in organic systems, and there is evidence that performance in conventional systems does not always translate to optimum performance under organic conditions (Murphy et al., 2007; Lammerts van Bueren et al., 2011). In addition, organic breeding programs are still relatively young and the size of the organic market, as well as lack of pressure from organic seed regulations, often limits the research investments of larger commercial seed companies (Mendum and Glenna, 2010; Hubbard and Zystro, 2016).

Organic farm environments in countries with high-income economies often, though not always, hold environmental similarities to subsistence and low input farms in countries with low-income economies. There is also often greater variation among farms than in conventional systems because farm management practices are more site specific. Many organic farmers are also in locations outside of major production regions targeted by breeding companies. Thus, organic breeding efforts often strive for either specific adaptation or the use of crop genetic diversity to mitigate risks and address crop challenges (Dawson et al., 2008; Wolfe et al., 2008). Organic markets also value greater diversity in crop species and cultivar type including minor crops (Shelton and Tracy, 2016). At the same time certain socioeconomic factors influencing farmers in countries with high gross domestic product must be noted, including the high value of organic products and land costs, the dynamics of governance of farming and seed, variable access to research support for agriculture, as well as philosophical values of the organic movement and citizen concerns for environmental impacts (Mendum and Glenna, 2010). Lastly, it must be acknowledged that unequal wealth distribution within countries with high-income economies often leave some sectors of society marginalized, operating in low-income economic environments, and underserved by public and private agricultural research and policies (Horst and Marion, 2018; Lyon et al. 2021).

The growing number of PPB cases in the US, CA and Europe provides the opportunity to assess who is engaging in PPB; what the scope of crop types is, and methods applied; what is motivating the actors engaged in PPB; and what the outcomes and impacts are to date. The current study aimed to conduct a comprehensive inventory and state of the art review of PPB projects in these countries to analyze and inform future PPB efforts. Objectives of the current study were to assess whether there is evidence that PPB is addressing the agronomic needs of farmers, whether it is motivated by societal goals beyond organic agriculture, and if there are trends in the experiences to date that may provide insights to inform the successful institutionalization of PPB in current in and future research programs.

Materials and methods

The current study presents a state-of-the-art review of PPB projects in the US, CA and Europe. A review of scientific and grey literature served to develop a comprehensive inventory of PPB projects. Five case-studies of PPB projects with different crop species provided deeper analysis across crop biological types. The inventory allowed reflection on the magnitude and scope of PPB implementation while the case studies provided deeper context for exploring the motivations, experiences and outcomes of PPB projects across a diversity of crop biological types.

The literature review included a search of the following databases Agricola (National Agricultural Library), ABI/INFORM and CAB Abstracts. Key search words included ‘participatory plant breeding’, ‘community breeding’ and ‘multi-actor breeding’. The database searches produced 311 articles and articles related to specific projects outside of the US, Europe and Canada were eliminated. An internet search with Google and Google Scholar followed using the same key words as the scientific databases in order to capture projects described in grey literature and online sources such as reports, proceedings and websites not included in peer reviewed journals. The online search was limited to the years 2000–2020 with the search as in-title or in-text and in quotations to limit hits to the full term. The search of Google and Google Scholar produced 184 and 992 links, respectively. Sources that did not identify a specific project and those that did not fit the criteria of collaboration between researchers and farmers or other actors in both the decision making and activities of the selection in plant breeding were eliminated. Projects exclusively involving farmers in the variety-evaluation phase, commonly referred to as participatory variety selection (PVS) or solely farmer-managed breeding activities without researchers participating in the breeding activities were also excluded. The resulting full list of citations is provided as “complete bibliography” in supplemental materials. As plant breeding takes time to set goals, implement methods, and result in outcomes, only projects with more than three years duration were included in the inventory of projects (Table 1).

Remaining articles from the full search were selected for review based on the above criteria, including articles covering both applied research projects and those addressing the broader methodology, organizational, institutional, policy or conceptual aspects of PPB within the context of the US, CA or Europe. Information on crop types and locations, actors involved and their roles, the motivations driving PPB, whether projects were conducted in organic agriculture, breeding goals and methods and reported outcomes were tracked. The inventory of projects including location, actors and drivers is presented in Table 1. Additional details on each project including the project goals, methods and reported outcomes, are presented as "PPB project details" in supplemental material. After compiling the inventory of projects from the literature review, the preliminary list was shared with 36 researchers who were either primary authors of published PPB projects or recommended by an author as a researcher familiar with the field of participatory plant breeding. The contacts were asked to review the list, identify missing projects and contribute any relevant literature covering their own projects or other topics pertinent to the current study. Twelve researchers provided clarification and additional details on projects through personal communications.

Many research institutions manage several breeding projects within one crop species in which case each crop was only counted as one case so that the resulting inventory represents both the breadth of crops as well as the breadth of institutions that have implemented PPB and their locations.

The crops selected for case studies represent diverse crop reproductive biology (mating systems and life cycles) including annual, biennial, self-pollinated, cross-pollinated and vegetatively propagated examples as well as grain, vegetable and arable crops. The authors selected crops that had multiple projects to compare and the diversity of species in order to compare across contrasting crops. Crop case studies included *Brassica oleracea* (cabbage, cauliflower, kale, and sprouting broccoli), *Zea mays* (maize, both grain and sweet types), *Solanum tuberosum* (potato), *Solanum lycopersicum* (tomato), and *Triticum aestivum* (bread wheat).

Table 1. PPB projects identified in the United States, Canada and Europe

Crop common name and species	Mating system/Life cycle[a]	Country	Institution(s)	Year initiated	Actors[b]	Drivers[c]
Apple and Pear (*Malus pumila, Pyrus communis*)	OB, P	DE	University Agroscope Changins-Wädenswil; University of Oldenburg, Saat:gut	–	FN, PR	OA, AB
Barley (*Hordeum vulgare*)	IB, A	IT	Rete Semi Rurali	–	F, FN, NR	OA, RA, UC, AB
	IB, A	IT	Italian Association for Organic Agriculture	2013	F, FN, NR	OA, RA, UC, AB
Beet root (*Beta vulgaris*)	OB, B	US	University of Wisconsin-Madison	–	F, PR, Cu, EU	CQ
Broccoli (*Brassica oleracea*)	OB, A	US	Oregon State University	2008	F, PR	OA, RA, BM, SS
Broccoli, Purple Sprouting (*B. oleracea*)	OB, A	US	Organic Seed Alliance	2009	F, NR	OA, RA
	OB, A	FR	French National Research Institute INRAE	2011	F, PR, FN	OA, RA
Buckwheat (*Fagopyrum esculentum*)	OB, A	FR	French National Research Institute INRAE	2018	F, PR, Cu, Ps	RA, AB, CQ
Cabbage (*B. oleracea*)	OB, B	FR	French National Research Institute INRAE	2001	F, FN, PR, SN	BM, RA, SS, AB
	OB, B	US	Organic Seed Alliance	2014	F, NR	BM, RA, SS
Cauliflower (*B. oleracea*)	OB, B	FR	French National Research Institute INRAE	2001	F, FN, PR, SN	RA, BM, SS, AB
Clover, Yellow Sweet (*Melilotus officianalis*)	OB, A	US	United States Department of Agriculture/ Agricultural Research Service USDA/ARS	2017	FN, PR, NR	OA, RA, UC
Einkorn (*Triticum monococcum* sp.)	IB, A	IT	Rete Semi Rurali	–	F, NR, Cu, Ps	OA, RA, SS, CQ
	IB, A	FR	French National Research Institute INRAE	2014	F, FN, PR, Ps	OA, RA, SS
Maize (*Zea mays*)	OB, A	PT	Polytechnical Institute of Coimbra IPC, University of Lisbon ITQB NOVA	1984	F, PR, Cu	AB, CQ, SS
	OB, A	US	University of Wisconsin-Madison	2012	F, PR, NR	OA, RA, CQ

	OB, A	FR	Organic Food and Farming Institute ITAB	2017	F, FN, PR	RA, AB
Oat (*Avena sativa*)	IB, A	CA	University of Manitoba	2011	F, PR, NR,	OA, RA, UC
Onion (*Allium cepa*)	OB, B	IT	Italian Research Institute CREA	2012	F, PR	OA, RA
Peas (*Pisum sativum*)	IB, A	IT	Italian Research Institute CREA	2013	F, PR	OA, RA
	IB, A	US	United States Department of Agriculture/ Agricultural Research Service USDA-ARS	2016	F, FN, PR, NR	OA, RA, UC
Pepper (*Capsicum annuum*)	OB, A	US/CA	Cornell University/SeedChange	2016	F, PR	OA, RA, SS
Potato (*Solanum tuberosum*)	V	CA	University of Manitoba	2013	F, PR	OA, RA, UC
	V	NL	Wageningen University, Louis Bolk Institute	2009	F, PR, NR, SC	OA
	V	US	University of Wisconsin-Madison	2014	F, PR	OA
	V	DE	State Research Institute of Bavaria	2012	F, PR	OA
Quinoa (*Chenopodium quinoa*)	OB, A	US	Washington State University	2014	F, PR	OA, RA, SS, DM, UC
	OB, A	US	Organic Seed Alliance	2014	F, NR	OA, RA, SS, DM, UC
Spinach (*Spinacea oleracea*)	OB, A	US	Organic Seed Alliance	2003	F, NR	OA, RA, SS
Sweet potato (*Ipomoea batatas*)	V	US	North Carolina State University	1997	F, PR	RA
Tomato *(Solanum lycopersicum)*	IB, A	IT	Italian Research Institute CREA	2012	F, PR	OA, RA
	IB, A	ES	Miquel Agustí Foundation/Polytechnic University of Catalonia	2011	F, PR	AB, RA, DM, CQ
	IB, A	IT	Rete Semi Rurali	2018	F, NR, SC	OA, RA
	IB, A	IT	Italian Research Institute CRA	2017	F, PR, SC	OA, RA
Wheat *(Triticum aestivum)*	IB, A	IT	Rete Semi Rurali	2006	F, NR, CU, PS	OA, SS, CQ,, AB
	IB, A	US	University of Nebraska Lincoln, Northern Plains Sustainable Agriculture Society Famer Breeder Club	1999	FN, PR	OA, RA, BM, SS, CQ, AB

	IB, A	UK	Organic Research Centre	2005	F, NR	OA, RA, AB
	IB, A	US	Washington State University	2002	F, PR	OA, RA
	IB, A	US	University of Vermont, University of New England, Cornell University	2008	F, FN, PR, CU, PS	OA, RA, DM, CQ
	IB, A	CA	University of Manitoba	2011	F, PR, NR	OA, RA, SS, AB
	IB, A	FR	French National Research Institute INRAE	2006	F, FN, PR, NR, SN, CU, PS	OA, RA, BM, SS, DM, CQ, AB
	IB, A	NL	Wageningen University, Louis Bolk Institute	2009	F, PR, NR	OA, RA
	IB, A	IT	Italian Research Institute CREA	2011	F, PR	OA, RA
	IB, A	FR	French National Research Institute INRAE	2001	F, FN, PR, PS	OA, RA, AB
Vetch (*Vicia villosa*)	OB, A	US	United States Department of Agriculture/ Agricultural Research Service USDA/ARS	2017	F, FN, PR, NR	OA, RA, UC
Zucchini (*Cucurbita pepo*)	OB, A	US	Organic Seed Alliance	2006	F, NR	OA, RA, SS
	OB, A	IT	Italian Research Institute CREA	2012	F, PR	OA, RA

a Mating system is categorized as either primarily inbreeding (IB) or primarily outbreeding (OB). The life cycle is categorized as either annual (A), biennial (B), perennial (P), or vegetatively propagated (V).
b Actors refers to those directly participating in the plant breeding project decision-making activities. Actors are categorized as individual farmers (F), farmer networks or cooperatives (FN), public researchers such as universities (PR), non-profit researchers (NR), seed companies with private breeders (SC), culinarians (such as chefs and bakers) (Cu), processors (such as millers) (Ps), retailers (Rt), and end-users (EU).
c Drivers refers to the motivation of the actors in engaging in PPB. Drivers include adaptation to organic agriculture (OA), regional adaptation (RA), avoidance of breeding methods (BM), seed sovereignty (SS), culinary qualities (CQ), and conservation of agrobiodiversity (AB).

Results

The resulting inventory of PPB projects includes an inventory of 22 crop species listed in Table 1, along with locations, actors involved and drivers of the projects. Additional details on projects are provided in supplemental materials. The current study identified 47 PPB crop projects with 25, 19 and 3 projects in Europe, US and CA, respectively. Canada holds a history of PPB approach in international aid in developing countries led by the Unitarian Service Committee of Canada (USC), but it is only in the last decade that a new initiative implementing PPB domestically has emerged, the Bauta Family Initiative on Canadian Seed Security. Additional projects were recently initiated in CA on carrot, broccoli, summer squash and winter squash, but are not reported here as there was less than three years of experience. Within Europe, programs in Italy and France are implementing PPB across the greatest number of crop types with 10 and five crops respectively. In the US, projects include grain, pulse, cover crops and horticultural crops, and are led by seven institutions.

Longevity of projects varied widely with at least six projects initiated in the last five years whereas the VASO project in Portugal started in 1984 and the sweet potato project in the US in 1997, with both projects still running at the time of the current study. Thirty-eight projects (84%) identify breeding for organic agriculture as a factor motivating the PPB project. A few projects reported that farmers received a share of royalties when varieties are commercialized.

The inventory does not suggest that the crop mating system influences the propensity for PPB as projects included a range of reproductive types with 21 projects on inbreeding crops, 18 on outbreeding crops and five on vegetatively propagated crops (Table 1). Crops also represent a diversity of species and crop types including vegetables, staple crops, cover crops, pulses, bread grains, other small grains as well as a project on apple and pear, an example of PPB in perennial tree fruit crops. The most frequent crops included wheat, tomato, and potato, with ten, four and four projects respectively, demonstrating that PPB is not limited to minor and novel crop types.

Actors, roles and methods in participatory plant breeding

The role of farmers and stages of involvement in the breeding process varied across projects. In addition to the information presented in Table 1, information on project methods and outcomes is provided as supplemental materials. In nearly all cases farmers provided input in setting breeding objectives. Therefore they often evaluated varieties in trials at the beginning of the project to identify traits for improvement and again after several cycles of selection to assess progress and determine if the population was ready for market. Researchers most frequently conducted the pre-breeding effort (making initial crosses or developing the initial breeding population or introgressing traits from wild relatives). In some projects including tomato, potato and sweet potato researchers advanced selections by conducting marker assisted selection (MAS) to select for key traits, such as disease resistance, in early segregating generations. Many projects involved diverse actors beyond farmers and researchers including farmer networks and cooperatives, seed companies, food processors such as millers and culinary professionals such as bakers and chefs. The role of the other actors focused primarily on informing breeding objectives, participating in variety evaluation that provided input into breeding selections and market development for novel and heterogeneous varieties.

In the North, specialization in plant breeding and seed production has clearly resulted in a loss of a direct relationship with seed and reinvigorating farmers' engagement in seed improvement often necessitates restoring knowledge gaps through education and training. Some projects are contributing new varieties to the seed trade, such as the case of potato in the Netherlands, sweet potato in the US, sweet maize in the US and wheat in the Northeast US, but for many projects expanding farmers' access to seed is not focused on development of commercial markets. The current study also provides examples of learning opportunities not only for farmers, but for researchers who reconsider methods in genetic advancements utilizing new approaches such as breeding for populations, evolutionary adaptation and developing novel statistical tools to adapt to decentralized models.

Drivers of participatory plant breeding

Researchers' reports of the drivers, or motivations, for initiating PPB consistently fell into distinct categories including addressing traits of priority to organic production, regional adaptation, avoidance of some breeding methods (cytoplasmic male sterility [CMS] in particular), seed sovereignty, culinary qualities desired by organic markets, diversification of crops by improving underserved crops and preservation or enhancement of agrobiodiversity (see Table 1 and supplementary materials). Several projects reported initiating PPB to address gaps in availability of cultivars with key traits prioritized by farmers to address organic production challenges (84% of all 45 projects) not fully met by the formal seed sector, such as late blight (*Phytophthora infestans*) resistance in market classes of importance to organic growers in potato and tomato, and seedling vigour under cold soil conditions in sweet maize. The need for adaptation to regional environmental conditions (88%) was frequently mentioned in grain crops reflecting the high genotype by environment interaction in grains. Regional adaptation also motivated breeding in crops newly introduced to a region such as quinoa in the US. Another example is sprouting broccoli, an overwintering type broccoli with narrow environmental conditions for overwintering success, recently introduced to northwestern France as well as the US Pacific Northwest as a diversification strategy for regional markets. Several projects targeted improvements in cover crops and minor food crops with low market value that are thus underserved by the formal seed sector. These crops include crimson clover, vetch, buckwheat and fava bean. Avoidance of cultivars with CMS motivated participatory breeding in Brassica crops, where CMS is utilized in breeding of F_1 cultivars. Researchers also reported farmers' desire for seed sovereignty, often related to breeding open-pollinated cultivars with market quality to avoid dependence on F_1 cultivars, most frequently in out-crossing vegetable crops where F_1 cultivars dominate the market such as Brassicas, maize, chard and zucchini. The goal of seed sovereignty motivated several grain breeding projects when farmers struggled with access to suitable planting stock and on-farm seed saving is feasible. Authors repeatedly discussed the important role of on-farm breeding and seed saving to efforts to preserve and enhance crop genetic resources. At least three projects targeted revival of heritage crops and preservation of agrobiodiversity including a reintroduction of

Brassicas in France from the French government seed bank, a reinvigoration of heritage tomatoes in Spain and the development of heritage maize in Portugal for traditional bread type called broa.

The current case studies also clarified that not all farmers want to grow their own seed, for example, in sweet maize in the US and potato in the Netherlands. In these cases, consideration of role of other aligned actors in the seed system involved in seed production, distribution and marketing were essential to support access to new appropriate varieties. Thus, the broader context of the seed system and roles of farmers engaged in PPB must be considered carefully in the development of projects from the start without assumptions of on-farm seed stewardship in order to ensure breeding outcomes are truly serving defined needs.

Case studies of participatory plant breeding in five crop species

An in-depth exploration of PPB experiences with five crop species revealed similarities and differences in the drivers, experiences and methodologies employed in participatory plant breeding. Case studies of maize, tomato, potato, Brassica and wheat are presented below.

Case study of maize (corn)

The morphology and reproductive biology of maize makes the breeding of maize relatively easy compared to other crops, but also create some limitations. The monoecious plants are large and produce large naked kernels that adhere to the ear (pistillate inflorescence). The staminate and pistillate inflorescences are physically separated on the plant making controlled pollination easy. The main downside is that pollen is dispersed by wind and while relatively heavy, can travel considerable distance, making isolation somewhat difficult. Maize also suffers from relatively severe inbreeding depression.

The first hybrid maize cultivars were developed and commercialized in the US in the 1920s. These varieties were largely tailored to the Upper Midwest region of the US. The early benefits of hybrid maize to farmers were uniformity and standability. Uniformity also provided more predictability in plant behaviour and yield. Uniformity has come with a price of reduced genetic diversity and access to germplasm.

Prior to the broad adoption of hybrid maize in the 1930s and 1940s, farmers planted open-pollinated maize. According to Martin and Leonard (1967), there were over 1000 different maize cultivars grown throughout the US in the early 1900s. Participatory plant breeding provides an alternative that centres farmers as active participants in variety development and seed production, rather than passive seed purchasers at the mercy of hybrid-dominant seed company offerings. The two maize cases reviewed cited meeting the needs of maize growers underserved by the dominant hybrid model.

The current study identified only two established maize PPB projects in the global North, one in the US and one in Portugal (Table 2). A third project has recently been initiated in France, but no results are reported yet (Rey pers. com, 2021). Farmers established breeding priorities in both projects indicating a common recognition of the importance of centring their input for successful projects. The US project was initiated and grown with equal partnership between the farmer and researchers. In contrast, researchers initiated the Portuguese project and then sought out equal partnership with and buy-in from the farmers.

Table 2. Farmer-breeders (FB) and researcher-breeders (RB) roles in PPB in maize

Project	**Organic Sweet Maize (UW) Madison/ Organic Seed Alliance), US**		**The Vaso project, PT**	
Start	**2012**		**1984**	
No. of farms	**1**		**>20**	
Breeding roles	FB	RB	FB	RB
Identify breeding goals	X		X	X
Select source germplasm		X	X	X
Pre-breeding		X	X	X
Early selection (F_{1-4})	X	X	X	X
Advanced selection (F_{5-8})	X	X	X	X
Variety evaluation/testing	X	X	X	X
Outcomes (Y/N):				
Variety release	Y	Y	N	N
On-farm use	Y		Y	Y
Royalties	Y	Y		

The Portuguese Sousa Valley Project (VASO), was launched in 1984 by Dr. Silas Pêgo (Mendes-Moreira, 2006). Underpinning the project is Pêgo's Integrant Philosophy, which he developed in contrast to the Productivist Philosophy that had driven maize monoculture on the US landscape (Pêgo and Antunes, 1997; Mendes-Moreira, 2006). The Integrant Philosophy model centres both the agricultural system and the farmer as the most important decision makers in the breeding process (Mendes-Moreira, 2006). Motivations for the Portuguese researchers and farmers were to establish the integrant approach in on-farm polyculture systems and to preserve genetic diversity in open-pollinated varieties that was eroded with the introduction of high yielding hybrid maize introduced to Portugal by US companies after World War II (Mendes-Moreira and Pêgo, 2012). The Sousa Valley region was selected in part because it is a traditional maize production area where maize still played a significant role in the polyculture system. In addition, the region's farmers were still growing traditional maize varieties used to make broa, a culturally significant Portuguese maize bread.

The project includes two parallel breeding programs developed by researchers and farmer-cooperators. The researcher's program combines three recurrent selection methodologies: phenotypic mass, S_1, and S_2 lines (Mendes-Moreira, 2006). The farmer's program uses an improved common mass selection methodology with two-parent control instead of the more traditional one parent control (Mendes-Moreira, 2006, 2017). The project has produced six improved populations that serve smallholder farmers growing for high-quality markets in sustainable systems (Mendes-Moreira, 2006). Researchers believe that populations coming out of the VASO project can also serve as germplasm sources for the hybrid seed industry (Mendes-Moreira, 2006). In this way the integrant and productivist models could complement one another and offer underserved farmers throughout the world economic opportunities in seed production. Additionally, this would also increase genetic resources instead of replacing them with varieties bred for high-input industrial systems.

Conventional maize production in the US operates in what Pêgo defines as the productivist model focused on maximizing yields (Pêgo and Antunes, 1997). As a response to being underserved by this model, organic farmers and public and independent plant breeders developed the 'Who Gets Kissed?' project to develop an open-pollinated sweet maize variety bred under organic systems (Shelton and Tracy, 2015).

The project was initiated by an organic vegetable grower in Minnesota and a scientist with a non-profit research institute, and later joined by a public sector university plant breeder. The farmer was known in the region for his sweet maize, but was frustrated because his favourite varieties were often dropped by seed companies as they merged or closed. The farmer defined the desired traits and the breeding began with two populations from the university program. Researchers designed a recurrent selection breeding program in which, during each summer season, 100 full-sib families from each population were grown in Minnesota. Remnant seed from each family was saved in cold storage in Wisconsin. Researchers and the farmer were involved in quality evaluations, which made this activity much more of a social process than most plant breeding activities. Based on the data, 15 to 20 families were selected in each population. Remnant seed saved from the selected full sib families was sent to winter nurseries in Chile where they were intermated within populations and full-sib families were generated for the next round of selection so that a full cycle of selection could be accomplished in one year (Shelton and Tracy, 2015). They completed five cycles of selection and in 2014 chose to advance one population as the new open-pollinated sweet maize variety under the name 'Who Gets Kissed?'.

Given the interests of many in the US organic vegetable farming community 'Who Gets Kissed?' was released with no intellectual property restrictions. Several regional breeding projects have grown out of 'Who Gets Kissed?'. Breeders and farmers in California, New Mexico, Oregon in the US, and in Australia are adapting it to their environmental conditions and local preferences (Colley et al., 2021).

Case study of tomato

Tomato (*Solanum lycopersicum*) has many different market classes as well as types within market classes making breeding more complex. The major market class split is between processing and fresh market tomatoes. The former tends to be grown on a large, highly industrialized scale to produce tomatoes for canning, soups, sauces and juices.

Fresh market tomatoes are diverse with cultivars varying for many traits including plant growth habit, fruit size, shape and colours. The predominant type in terms of area produced are large fruited red slicer types. These are often grown in southern temperate and subtropical regions for the winter fresh tomato market. Cherry tomatoes are the second most important market class. These have small red, yellow, orange or green fruit with round, oval or pear shapes. Most major seed companies have tomato breeding programs, but these are focused primarily on the larger conventional agricultural markets (California and Florida in the US; Spain and Italy in Europe), or on types that are not necessarily in demand by fresh market organic growers (processing, wholesale glasshouse).

Outside of these generalizations, many tomatoes that vary from common market types are grown and sold regionally. Generally classed as “heirlooms” in the US or “conservation varieties” in Europe, more accurate terms we will use for the remainder of the paper are “heritage” or “landrace” tomatoes. As documented in the European case studies described below, some of the types of tomatoes that have been the subject of PPB have specific characteristics that are valued on a regional basis by growers and consumers. The number of heritage or landrace tomatoes is truly astounding. Nearly all of these were developed without a formal breeding approach and the tradition continues today.

Tomatoes are self-pollinated and lend themselves to varietal development as pure lines or may be utilized as inbreds in crosses to create F_1 hybrids. Most contemporary commercial tomato cultivars are F_1 hybrids and hybrid seed is produced by hand; the high ratio of seed obtained per cross makes F_1 hybrids economically feasible.

Organic fresh market growers consistently rank tomatoes as first or second in terms of vegetable crops needing genetic improvement to meet their production and marketing needs in all regions of the US (Lyon et al., 2015; Brouwer and Colley, 2016; Hultengren et al., 2016; Dawson et al., 2017; Healy et al., 2017). Some organic growers may find that commercial F_1 hybrids are not adapted to their production or marketing needs or may wish to save their own seed from year to year, which cannot be done with F_1 hybrids. Some growers and researchers conducting tomato PPB have justified their projects because of the need to breed varieties for regional adaptation as well as having the capacity to save seed.

Farmer participatory tomato improvement projects have focused on both fresh market and processing types with the main emphasis being field grown medium- to large-fruited types. Most are red fruited although yellow fruited types have also been the subject of participatory plant breeding. In the US, the most important types for organic fresh market growers have been indeterminate large-fruited red slicers, while in Europe, there has been an emphasis on revival of traditional landraces, which vary in size and usage.

The current study identified seven projects in PPB of tomatoes (Horneburg, 2010; Campanelli et al., 2015, 2019; Lange et al., 2018; Casals et al., 2019; Healy and Dawson, 2019; Rodriguez et al., 2020; Petitti et al., 2021), four of which met our criteria for case studies (Table 3). Six of the seven projects were in Europe (Italy, Spain and Germany) and one in the US. The projects that were excluded were either too new to have achieved three years of activity, or they were primarily PVS rather than PPB projects. The pattern of activity compared to other crops is striking in that application of PPB to tomatoes is relatively recent and it is concentrated in Europe. None of these projects can be said to have matured; while farmers are locally using selections from these projects, there do not appear to have been any formal variety releases. Traits under selection included yield and other horticultural traits in the field, but there was especially strong emphasis on fruit quality traits including °Brix, dry matter, and flavour.

Some of the European activity has focused on revitalization of local landraces, and in some cases using these to breed improved forms of these landraces. For example, the Spanish project by Casals et al. (2019) began as an effort to revitalize the ‘Mando’ local landrace, whose production had dwindled to a single grower. During grow-out and increase, variation from spontaneous outcrossing was observed, and breeders and farmers continued selections over years to stabilize some different yellow flesh lines that farmers thought had potential for commercialization. However, these were rejected on the basis of poor flavour by consumers in the final year of testing. On the other hand, production of ‘Mando’ did increase and the project was successful in preserving the landrace.

Table 3. Farmer-breeders (FB), researcher-breeders (RB) and commercial-breeders (CB) roles in PPB in tomato

Project	**Miquel Agustí Found., ES**		**Council Res.Agric., IT**			**Rete Semi Rurali, IT**			**CRA/ISI Sementi, IT**		
Start	**2017**		**2012**			**2018**			**2017[b]**		
No. of farms	**3[a]**		**5**			**5**			**3**		
Breeding roles	FB	RB	FB	RB	CB	FB	RB	CB	FB	RB	CB
Identify breeding goals		X		X			X				X
Select source germplasm	X			X	X			X			X
Pre-breeding	X	X		X			X				X
Early selection ($F_{1–4}$)	X	X	X	X		X	X		X	X	
Advanced selection ($F_{5–8}$)	X	X	X	X		X	X		X	X	
Variety evaluation/testing	X	X	X	X		X	X		X	X	
MAS											X
Outcomes (Y/N):											
On-farm use	Y		Y			Y			Y		

a Farms for Participatory variety selection.
b Date of early variety selection

Campanelli et al. (2015) described a PPB project carried out in Italy to examine the significance of local adaptation in breeding for organic systems. Researchers first created four populations by selfing F_1s of four diverse crosses (a Cuor di Bue [Oxheart] fruit type, a long fruit type, a cherry fruit and a green salad fruit type). Seventy-two F_2s of each of the four populations along with check cultivars were planted in an unreplicated row-column design on four farms and a research station distributed across Italy. Both farmers and researchers evaluated populations and 201 selections over all locations were obtained. For the $F_{2:3}$ in on farm trials, three selections by farmers, three by researchers, three by both and three by researchers only on-station for each of the four populations were planted. On the research station, six selections per population previously made by researchers were planted back at that site. From these, 115 plants were selected on-farm by farmers and researchers. Extensive replicated trials of selections in year three identified three out of 15 $F_{2:4}$ families that out-yielded commercial check cultivars, and these were being further developed for release. This study compared researchers' selections as opposed to those selections of farmers alone, and farmers' and researchers' joint selections, and found that the best performing were farmers' selections grown in the location in which they were selected. There was a clear pattern of specific adaptation to locality and production system.

Another project in Italy examined the effect of human (farmer) selection vs. natural selection on specific adaptation (Petitti et al., 2021). Starting with the same base population, farmers at different locations selected desirable plants and fruit from these was saved, while simultaneously, a population of 400 plants was advanced by single seed descent to the next generation. This process was carried out for two cycles followed by a third evaluation generation where all populations were grown at all locations for evaluation and further selection. Results from the comparative trial had not been published at the time of writing, but Petitti et al. (2021) found that success of the project varied by region. There was strong interest by farmers and circulation of seed from selections in the southern region but in another region, researchers found that farmers did not use the types of tomatoes used to generate the breeding population, and that farm had to be replaced by another in the region after the second year.

The project reported by Campanelli et al. (2019) illustrates an interesting approach to combining PPB with genomic analysis. The researchers conducted PPB using a tomato MAGIC (multiparent advanced generation intercross) population originally developed by the commercial company, ISI Sementi. The eight founder lines included seven contemporary tomato lines (representing a combination of paste and slicer types) and one wild species (*S. cheesmaniae*) selected for its productivity and biotic and abiotic stress resistance. Public researchers' breeding efforts began with a grow-out of 400 plants from the final eight-way cross, from which 30 plants were selected. Farmer selections began in the next generation where seeds of 370 MAGIC population plants plus 30 selections from the researchers' efforts were grown along with 25 standard cultivars on three farms in Italy representing north, central and south geographic regions. Researchers and farmers jointly selected plants based on a set of visual traits, then fruit was brought back to the lab for testing °Brix, total solids and taste. Differences in mean values for plants selected in different regions were observed; those selected in the north had greatest vigour and productivity, whereas those selected in the south had highest brix and total solids. The objectives of this research spanned both researcher and farmer interests including developing a genetic resource for breeders and germplasm representing different market classes and traits of interest to farmers. Future research with these materials included growing all selections along with the eight parents and 500 highly inbred plants of the original MAGIC population, genotyping these and discovering SNPs associated with important field traits while examining the shift in allele frequencies as a function of selection in different regions.

In general, researchers considered tomato as a convenient crop for PPB, noting that the crop is well characterized genetically, that the reproductive biology and breeding methods for self-pollinated crops are translatable to on farm research, traits of interest are easy to discern, there is a plethora of germplasm in the form of local landraces, there is strong interest in tomato improvement in the organic community and farmers willing to participate in PPB, and consumers have an interest in novel tomato types. A disadvantage is the large plant size which limits the number of plants that can be grown in farmers' fields. Researchers indicated that small to medium farm operations were often motivated to develop their own varieties and could accommodate around 100 to 300 plants with minimal compensation. However, larger operations tended to have more rigid structure and tighter margins and were less inclined to engage in participatory plant breeding. One characteristic of the tomato PPB projects is that they tended to be more regionally focused, perhaps because the needs of organic farmers across Europe are many and varied, thus local projects are more important than one that encompasses Europe. In some cases, it was apparent that researchers were not targeting the needs of farmers with their choice of initial material. In every case, the parents for crosses to develop populations were selected by researchers without overt input from farmers. Researchers may have had some idea of farmers' needs for markets, but farmers were not brought in from the beginning to design the project. Bringing in farmers at an earlier stage would probably allow better targeting of the project. All of these projects are relatively young considering the decade long duration of most breeding projects and have not had time to develop and formally release varieties. However, farmers are informally saving seed and producing the lines that work best on their farm, so while difficult to measure, the projects are generating impact.

Finally, an interesting dynamic was observed that may not play out with other crops, but probably affects the PPB landscape for tomatoes. Tomatoes are a very popular crop in the US with breeders at public institutions and with independent plant breeders. About a half-dozen universities in the US support tomato breeders who release fresh market and processed varieties. With independent plant breeders, Deppe (2021) found that 11 of 35 breeders who release materials under an open seed source initiative (OSSI) agreement work on tomatoes. The Dwarf Tomato Project, an effort that began among growers on a tomato forum on Gardenweb, has released more than 100 varieties (Deppe, 2021). Seed Savers Exchange, a grassroots organization dedicated to preserving landrace varieties, lists 9911 entries of tomatoes on their Exchange website (SSE, 2021). It may be their popularity among independent breeders, and the ability of these breeders to satisfy growers and gardeners' needs that reduces the need for public/private PPB activities, especially in the United States. In Europe, the situation is somewhat different, with larger numbers of locally adapted landraces in need of adaptation to organic production. Also, the costs of the registration requirement for improved 'conservation varieties' for commercial sale in Europe can be a barrier to independent breeders (Petitti M, personal communication). Access to landraces may be more difficult because of the lack of a European-wide organization to preserve traditional varieties. Participatory plant breeding can play a vital role in preserving and improving traditional varieties and preventing their *in-situ* loss.

Case study of Brassica

Vegetable crops of Brassica (*Brassica oleracea)* are widely grown for premium organic markets across the US, CA and Europe including cabbage, cauliflower, broccoli and kale. Diverse landrace and heirloom varieties, originally domesticated in Europe, are still accessible for breeding (Chable et al., 2008). Until the 1980s open-pollinated varieties were grown commercially, but since then the seed trade focused almost exclusively on development of F_1 hybrids (F_1s). The shift toward F_1s was largely due to the allogamous nature of *B. oleracea*, development of CMS and use of double haploids to facilitate production of inbred lines. F_1 breeding is primarily focused on achieving crop uniformity and narrowing the maturity window for mechanical harvests, further incentivizing breeders toward F_1 development for large scale, mechanized agriculture (Chable et al., 2008, Myers et al., 2012; McKenzie, 2013). Yet, many organic producers seek quality traits with less emphasis on uniformity in timing of maturity (McKenzie, 2013). Cytoplasmic Male Sterility use in breeding is also not in alignment with organic principles as in B. oleracea it is commonly derived through protoplast fusion, though there are also now organic breeding companies producing F_1s through naturally derived self-incompatibility. The use of double haploids is also questioned by the organic sector (Chable et al., 2008; Myers et al., 2012; Sahamshirazi et al., 2018). All cases cited the avoidance of F_1 breeding techniques, lack of quality open-pollinated varieties, need for local adaptation and farmers' desire for greater control over their seed as reasons motivating participatory breeding (Chable et al., 2008; Myers et al., 2012; McKenzie, 2013; McKenzie, personal communication).

The current study identified five Brassica projects on PPB in the global North, all located in the Pacific Northwest region of the US and the Brittany and Normandy regions of France where the locations share an environment optimum for seed production of a diversity of *B. oleracea* crop types (Table 4). Farmers established breeding priorities in all projects indicating a shared recognition of the importance of farmers' input from the start to ensure the outcome suits the target market and production environment. Researchers sourced germplasm and developed initial crosses in four of the five projects. In the case of kale in the US, the farmer initiated the project and only involved researchers in the advanced stage after frustrations of not achieving adequate uniformity for a variety release. The stage of researcher involvement varied in the early to advanced breeding phases with the researcher coordinating early phase population development in the case of broccoli and cabbage in the US, but the farmer leading early progress through mass selection in the US kale and purple sprouting broccoli projects and French cabbage and cauliflower projects. In all cases early to advanced breeding was conducted on-farm to leverage selection under the target environment. Researcher involvement in advanced breeding phases employed coordination of half or full sib progeny selection methods with farmers' participating in the in-field evaluation and decisions in selection.

Table 4. Farmer-breeders (FB) and researcher-breeders (RB) roles in PPB in Brassica oleracea crops

Project	**Broccoli (OSU), US**		**Cabbage and cauliflower (INRAE), FR**		**Cabbage (OSA), US**		**Kale (OSA), US**		**Purple sprouting Broccoli (OSA), US**	
Start	**2001**		**2001**		**2014**		**2007**		**2009**	
No. of farms	**6**		**>10**		**1**		**1**		**4**	
Breeding roles	FB	RB	FB	RB	FB	RB	FB	RB	FB	RB
Identify breeding goals	X		X		X		X		X	X
Select source germplasm		X		X	X		X			X
Pre-breeding		X		X	X			X	X	X
Early selection (F1–4)	X		X		X		X	X	X	
Advanced selection (F5–8)	X	X			X	X	X	X	X	X
Variety evaluation/testing	X	X			X	X		X	X	X
Outcomes (Y/N):										
Variety release	Y		Y		Y		N		N	
On-farm use	Y	Y	Y		Y		Y		Y	
Seed network distribution		Y	Y		N		N		N	
Royalties	N		N		N		N		N	

Brassica crops are well suited to on-farm breeding as Myers et al. (2012) noted, since advancements can easily be made through mass selection if enough genetic diversity is created and maintained as selection occurs prior to flowering. Selection in on-farm production fields can also serve as an advantage as the large population size allows leveraging selection pressure while maintaining adequate heterogeneity to avoid inbreeding depression (McKenzie, personal communication). An added benefit is that farmers can harvest the crop for market, while evaluating quality and then subsequently harvest seed from select plants for breeding purposes (McKenzie, 2013). On-farm reproduction of biennial crop types, including cabbage and some cauliflowers, can however be a barrier to PPB as they require conditions suitable for vernalization, either in the field or by lifting and storing plants through the winter which is likely why projects are limited to conducive production regions. The promiscuous nature of *B. oleracea* can also present a challenge to manage isolation on farms with diversified Brassica crops in production or nearby (McKenzie, 2013). High levels of outcrossing, self-incompatibility, and propensity for in-breeding depression present challenges in breeding Brassicas for recessive traits and achieving high levels of uniformity in open-pollinated populations (Myers, personal communication; McKenzie, personal communication). For this reason, researcher involvement in advanced breeding stages can aid in implementation of progeny selection (Myers et al., 2012). These biological constraints may be one of the reasons there are not more examples of Brassica PPB projects.

It is unlikely that open-pollinated Brassica varieties will achieve enough uniformity to replace the demand for F_1 varieties in large scale production, so it is likely that there will remain two different markets for hybrids and open-pollinated Brassicas unless there is increased pressure from organic regulations to restrict use of CMS varieties or other market incentives. In spite of this fact three of the four projects have already resulted in release and commercialization of new open-pollinated varieties for specialized markets demonstrating the demand for alternatives to hybrid varieties.

Projects exhibited innovative breeding strategies that leverage farmers' and researchers' knowledge and resources while engaging multiple farmers as a participatory breeding network. The US broccoli breeding project followed a divergent-convergent scheme of population improvement, first described by Atlin et al. (2000), in which a genetically diverse breeding population is distributed to farmers for on-farm selection and then recombined annually (Myers et al., 2012). This allowed decentralized selection under diverse farm environments leveraging farmers' input in selection criteria in the pre-breeding phase. After seven years of population development the researchers and two of the farmers each continued breeding through half-sib progeny selection at least six years resulting in several new and distinct varieties. The cabbage and cauliflower projects in France similarly leveraged a farmer network, including seven farms, with breeding integrated into on-farm variety trials of heritage varieties from the French national seed bank. The researcher coordinated the farmers' variety evaluations.

Each farm then conducted mass selection and saved seed from one variety ensuring a different variety was selected by each farm to preserve as much diversity as possible. Based on farmer's input the research institute then also crossed similar, but complimentary lines to generate new F_1 breeding populations for further on-farm selection and development of improved varieties. In the US cabbage project, the researcher facilitated annual advancement of cabbage, a biennial, by lifting selected plants from the farmer's field and then reproducing in a greenhouse to advance the seed maturation early enough to again plant the following summer achieving annual selection. In the US kale project, the researcher self-pollinated plants by hand (bud pollination) to achieve full-sib progeny for repeated on-farm selection of families, a task too tedious to manage on a working farm. Each of these projects demonstrates the creative use of complementary skills and capacities to achieve greater advancement in *B. oleracea* development through farmer-researcher collaboration than could be achieved individually.

Case study of potato

Potato (*Solanum tuberosum* L.) is the fourth most important food crop worldwide, and also an important crop in organic farming systems. Consumers have different preferences as to tuber skin or flesh colour for consumption (including mealy to firm cooking types). But there are also special varieties for the processing industry such as french fries (long tuber shapes) or chips (round tuber forms).

Technically, making crosses in potato is not too complicated, but many factors influence success (Tiemens-Hulscher et al., 2013). Most varieties can be used as seed or pollen parents, but some varieties do not produce viable pollen. Some varieties only occasionally produce flowers and cannot be used for crossing. Sometimes flowers or berries are aborted, or pollen is not shed under conditions that are too moist or too dry. Most modern varieties are to a large degree self-pollinating, but in the field between 0–20% cross-pollination occurs by wind or bumble bees. Often the anthers are removed from the seed parent seed parent with a pair of tweezers to avoid self-pollination. Hand crossing can be done in the field early in the morning before bumble bees have visited the flowers. Parental tubers can also be planted in greenhouses in the ground or in buckets, enabling removal of the newly formed tubers to allow more inflorescences to be produced.

Potato is one of few vegetatively propagated root crops that are involved in participatory breeding programs in the global North: in the Netherlands (Lammerts van Bueren et al., 2008; Tiemens-Hulscher et al., 2012; Keijzer et al., 2021), Germany (Sieber et al., 2018) and CA (Entz, 2019), US (Genger, 2018) (Table 5). The reasons for starting such programs are lack of available organically produced seed potatoes (CA and US). In Europe, such as in the Netherlands and Germany, potato breeding companies are interested in the organic market and provide sufficient quantities of organic seed potatoes, but their breeding programs do not prioritize late blight resistance which is of high priority for most organic growers.

Table 5. Farmer-breeders (FB), researcher-breeders (RB) and commercial-breeders (CB) roles in participatory breeding projects on potato

Project	**WUR, LBI, BioImpuls, NL**			**LfL Bayern, Bavaria, DE**		**Univ of Wisconsin Madison, US**		**Univ of Manitoba, CA**	
Start	**2009**			**2012**		**2014**		**2013**	
No. of farms	**12**			**3**		**9**		**20**	
Breeding roles	FB	RB	CB	FB	RB	FB	RB	FB	RB
Identify breeding goals	X	X	X	X	X	X	X	X	X
Select source germplasm	X	X	X	X	X	X	X	X	X
Pre-breeding		X			X		X		X
Early selection (F1–4)	X	X	X	X		X		X	
Advanced selection (F5–8)		X	X		X		X		X
Variety evaluation/testing			X		X		X		X
MAS		X	X		X				
Outcomes (Y/N):									
On-farm use	Y				N		N		Y
Commercialization	Y		Y[a]		N[b]		N		N
Seed network distribution			N		N		N		N

a First varieties are under registration trialling (2019).
b Promising clones are handed over to commercial breeders for further selection (2018).

The potato programs were usually initiated when researcher-breeders were approached by organic growers with an urgent call for action. As the late blight resistance genes that were derived from *S. demissum* are no longer effective, new resistance genes need to be introgressed from wild relatives, and the expertise of specialized pre-breeders from one of the universities or institutes is required. Most cultivated potato (*Solanum tuberosum* L.) is tetraploid, so introgressing new resistance traits from wild relatives needs an extra step as many of them are diploid. Many wild relatives do not produce tubers and need to be converted from short day types to long day types to match the northern long day growing conditions. After the introgression and pre-breeding phase of some 10 to sometimes 20 years, including several generations of backcrossing the wild relative with modern varieties with good agronomic properties, the scientist breeders can then produce commercial crosses and distribute seeds from relevant crosses to the farmers to select during several early field generations. Some breeders provide true seeds and others grow out first year seedling tubers for the growers. Usually, farmer breeders select over three to five years and then return the selected, promising clones to the researchers or breeding companies who organize testing across various locations in replicated trials. The number of seeds or seedling tubers that farmers select on a yearly basis differs; in many programs farmer breeders yearly receive a minimum of 200 seeds up to 3000 of two or more populations. They discard approximately 95–98% in the first three to four years.

As the F_1 progeny of potato crosses are vegetatively propagated, the populations do not segregate. This makes it relatively easy for growers to be involved in early stages of the program, visually selecting clones that perform well, with good and regular tuber shape, smooth skin, good storability, sufficient disease resistance, and other desirable traits.

As genotype-by-environment interaction is very large for potato, testing and selection over many years is needed to select a clone that is stable in performance across years and multiple locations. The programs described above are not yet quite in the stage that clones can be marketed (usually up to 10 years of selection after the initial cross). However, some farmer-breeders sell quality clones through their own farm sales, and do not pursue registration and commercialization (Table 5). Most projects aim at commercialization of the selected clones. It is custom in the Netherlands to register a potato variety on the names of both the involved farmer-breeder and commercial breeder, so that ownership is shared which is expressed in sharing the royalties on a 50-50% base (Almekinders et al. 2014).

Specific to late blight being very sensitive to mutations under high disease pressure, it is important to prevent breakdown of late blight resistance by stacking various resistance genes (Pacilly et al., 2019). The advantage for farmer breeders collaborating with universities is access to molecular markers for each source of late blight resistance which can be used to check whether the farmer's selected clones contain two or more resistance genes (Lammerts van Bueren et al., 2010).

For many modern farmers the skill of breeding has declined due to specialization. As a response, the Dutch project introduced a yearly training course for farmers or young breeders on potato breeding, and the course manual is published to make the practical potato breeding knowledge publicly available (Tiemens-Hulscher et al., 2013).

Case study of wheat

Bread wheat (*Triticum aestivum*) has a large number of published projects ranging from conference proceedings to peer reviewed journal articles. Projects exist in Europe (Berthet et al., 2020; Dawson et al,. 2010, 2011; Enjalbert et al., 2011; Goldringer et al., 2012, 2019; Rivière et al., 2013a, b; Rivière, 2014; Rivière et al. 2014, 2015; van Frank, 2018; van Frank et al., 2020; Vindras-Fouillet et al., 2016; Da Via et al., 2015; Malandrin and Dvortsin, 2013; Petitti et al., 2018), CA (Bauta Initiative, 2013; Entz et al., 2015, 2016, 2018; Kirk et al., 2015), and the US (Murphy et al., 2005, 2013; Darby et al., 2013; Kissing Kucek et al., 2015, 2016, 2017; Lazor, 2008) (Table 6). The large number of examples for bread wheat may be due to the existence of public plant breeding programs at many universities and research institutions. It may also be due to the strong genotype by environment interactions that are observed in small grains, meaning that varieties developed for other regions or other management systems may not perform well for farmers in another region or using a different management system.

The relative ease of logistics in managing participatory breeding projects with small grains is also likely a factor in the development of new projects.

Table 6. Farmer-breeders (FB), researcher-breeders (RB) and commercial-breeders (CB) roles in PPB in wheat

Project	**Manitoba, CA**		**Washington State, US**		**Northeast and Midwest US**		**France, EU**		**Italy, EU**	
Start	**2011**		**2002**		**2012**		**2006**		**2011**	
No. of farms	**8 (start)–75 (current)**		**1**		**4 (start)–8 (current)**		**1 (start)–80 (current)**		**1 (start)–4 (current)**	
Breeding roles	FB	RB	FB	RB	FB	RB	FB	RB	FB	RB
Identify breeding goals	X	X	X	X	X	X	X		X	
Select source germplasm	X	X	X	X		X	X	X	X	X
Pre-breeding		X		X		X	X	X	X	X
Early selection (F1–4)	X		X		X		X		X	
Advanced selection (F5–8)	X		X		X		X		X	
Variety evaluation/testing	X	X		X		X	X	X	X	X
Outcomes (Y/N):										
On-farm use	Y		Y				Y		Y	
Commercialization	Y	Y	Y	Y	Y	Y	Y		Y	
Seed network distribution							Y		Y	

The motivation for starting participatory breeding projects often comes from farmers who have been unable to find suitable varieties for their production. In most examples here (Table 6), farmers have been targeting a value-added market for artisanal bread and have not found varieties that are competitive in organic production with the high quality they need for artisanal bread making quality. Frequently crosses are made between higher yielding modern varieties that have been tested in organic systems and landraces or historic varieties known for artisanal bread-making quality, particularly those known to produce high quality bread at lower protein levels (i.e. around 10% vs. 12.5% for most conventional bread wheat). High protein percentage in winter bread wheat is often achieved either by growing in areas with less rainfall and lower yield potential such as the Mediterranean or the Great Plains and intermountain region of the US. Participatory breeding programs in areas with higher rainfall such as Northern

France and the northeastern and midwestern US have goals of increasing baking quality in winter wheat, which is preferred by growers because of its agronomic advantages but not by bakers due to its typically lower protein (Vindras- Fouillet et al., 2016; Dawson et al., 2011; Kissing-Kucek et al., 2015, 2016). In these climates, selection for resistance to Fusarium Head Blight (FHB, *Fusarium graminearum)* and resistance to pre-harvest sprouting is also critical, and these two traits are difficult to score on-farm. Participatory breeding projects in areas where bread wheat is typically grown often have goals of increasing yield under stressful conditions and lower inputs or organic systems while maintaining good artisanal bread-making quality.

The genotype by environment interactions seen in small grains often lead breeders and farmers to a decentralized model of selection to serve organic farmers in multiple ecological regions. There is also a lack of breeding in conventional systems for weed competitive ability or seed-borne disease resistance, which are major issues for organic farmers. Organic farmers frequently prefer lines that are taller with more tillering and biomass as long as lodging is minimal to compete with weeds during the season and to reduce the weed seedbank over the long term, as winter small grains are an excellent rotation crop to break up weed dynamics on organic farms that also grow row crops or vegetables. The desire for high biomass is also a trait that is more specific to organic farmers, who value the straw for soil building carbon or for livestock bedding or mulch. This is in contrast to goals of a high harvest index and a focus on grain yield in conventional systems.

In most cases, farmers approached the research team to initiate the project, often after trialling many modern and historic varieties which did not meet their needs. While there is a wide diversity of approaches to the details, there is a common breeding scheme that involves farmers proposing parental varieties to the research team, which makes the crosses in a greenhouse and then multiplies the first two generations on a research station or in a greenhouse without selection to get enough seed for farmers to plant in a small plot on their farm. In some cases such as France, the F_1 may be returned directly to the farmer who grows it in a protected plot (Dawson *et al.,* 2011). In some other cases, the lines may be more advanced before they are put on farmers' fields, due to difficulties in finding small scale equipment for on-farm trials.

For most projects, on-farm trials start with the F_3 generation and are managed in small plots with shared equipment, either from the research team or from a farmers' organization. As bread wheat is a self-pollinating species with the harvested grain also being the seed for the next cycle of selection, on farm management of multiple populations is primarily constrained by access to small plot scale equipment.

For the projects in this case study, selection is done on-farm within populations by using negative selection to eliminate plants that are undesirable and positive selection to choose spikes from plants that have the desired characteristics. Farmers also choose between populations that come from different crosses. The selected spikes are frequently given to the research team for threshing and measurement (grain filling, protein content etc.) and then returned to the farmer for planting. Farmers frequently also visit research station trials of lines developed in the participatory breeding program to observe and select among more lines than they can manage on-farm. Research station trials might include dozens of lines while on-farm trials typically have 5–10.

Projects vary in terms of how much selection is done on the research station to complement on-farm selection. All projects have on-farm selection and on-farm evaluations of more advanced lines involving more farmers. Some also add research station selection for certain traits. The project in France is based entirely on on-farm selection, with researchers measuring traits such as protein and thousand-kernel-weight on selected spikes to return information to farmers on the results of their selection (Dawson et al*.*, 2011; Rivière, 2014). The project in the Northeast region of the US uses a combination of on-farm selection for production traits and on-station selection for traits like FHB and pre-harvest sprouting resistance, which are difficult to rate on-farm and is much more reliably scored in an inoculated nursery for FHB and in greenhouse misting conditions for pre-harvest sprouting, which are labour intensive and not realistic for an on-farm trial (Kissing Kucek, 2017). Similarly, pre-harvest sprouting is scored by researchers using a specialized nursery and greenhouse misting to create the ideal conditions for sprouting (Kissing Kucek, 2017). The research team also usually does grain protein and quality measurements are also done by the research team with information returned to farmers (Rivière, 2014; Kissing Kucek, 2017). Researchers may also do their own selection, often with input from farmers attending field days and winter meetings and maintain researcher and farmer selections in parallel.

Longer running projects have more varieties that are in production and in the stages just prior to release. For any participatory selection process, a long-term commitment is required to see results, both because of how long it takes to get from a cross to a new variety and because selection involves a learning curve for many farmers without prior experience, just as it does for new breeders. It can be difficult for farmers who are new to on-farm breeding to select efficiently. This can lead to unwanted increases in height of plants for example, or a reduction in tillering, or an unintentional reduction of diversity in the population. Managing on-farm trials can also be tricky and some experience is needed to manage the trial in a way that allows selection primarily on genetic merit rather than micro-environmental differences. As everyone learns, selection becomes more efficient, and progress is clearer. Selection results after only a few years may not show much advantage to on-farm selection. However, after several years, projects in Manitoba, Washington, France, Italy and the northeastern US all showed that farmer developed varieties had equivalent yields to modern varieties with some of the important additional traits that farmers developed and frequently greater stability over time and space than pureline varieties. Varieties are in the release process in CA and the northeastern US and are in production in France and Italy with each farmer doing their own seed multiplication due to more restrictive regulations on the types of varieties that can be commercialized.

The main differences in programs in different geographic locations is in their ability to release lines from participatory projects as commercial varieties. Europe has the most restrictive seed regulations, and the varieties of the PPB program cannot go through the normal commercialization process. The farmers seed network that developed these varieties however is not interested in commercialization or royalties from other farmers using their varieties. They see these varieties as a shared resource among members of the network, which each member can multiply and produce them on their own farms. About ten varieties have been named and circulated among the farmer group (Rivière, personal communication). The Canadian system of registration is similar to the European one but is slightly more flexible and the fact that breeders participating in the projects have access to the registration trials and can put forward varieties developed with farmers means that these varieties may be commercialized and can also be grown by the farmers that developed them. In the northeastern US, many farmers are not interested in producing their own seed due to the risk of seed-borne diseases, and the formal variety release process allows for the release of heterogeneous varieties as long as they can be adequately described. The varieties developed could either be released with a plant variety protection (PVP) certificate with farmers named as co-developers, or through an alternate mechanism such as the Open Source Seed Initiative (https://osseeds.org). There are regional independent seed companies interested in commercializing such varieties for the organic market.

In terms of methodology, many of these programs are in close contact with one another to share best practices, and there are many similarities among the programs. In Europe, farmers are more self-sufficient in terms of plot scale equipment and the ability to manage trials with farmers organizations. This is in part due to the fact that they have to produce their own seed of unregistered varieties so they have had to gain the knowledge and equipment to do so. In the US, typically individual farmers work directly with the research team, and other organizations help with coordination, communication, and education, particularly in developing a market for the resulting varieties.

High-value markets for the varieties that result from participatory plant breeding are critical, and one of the reasons that farmers become involved in these projects. The farms working on these varieties typically are interested in value-added production by creating a short chain from the farm to the consumer. This involves building on-farm mills and bakeries or working closely with local mills and artisanal bakers. In Europe, farms tend to be smaller in size, and more diversified with other crops (grains and vegetables/fruit/dairy/livestock for example) and rely more on very local marketing. In the US and CA, projects and markets are organized on a regional scale, with larger farms (although still smaller and more diversified when compared to conventional farms growing wheat). The common thread among all these projects is the desire to create well-adapted varieties for specific environmental conditions and management systems with excellent baking quality for local consumers.

Discussion

The current study reinforces the premise that the formal seed sector leaves gaps in farmers' seed needs, but also reveals more complex motivations for PPB. Overall, the drivers of PPB can be divided into two primary groups. One is leveraging PPB to optimize genetic advancements through decentralization and the incorporation of farmer or other stakeholder preferences in selection. The second is a more philosophical or socio-political lens with PPB initiatives centred around farmers' rights to save seed and achieve autonomy or seed sovereignty, as well as preservation of biodiversity and upholding organic principles of health, ecology, fairness and care set forth by the International Federation of Organic Agriculture Movements (IFOAM International) (Chable et al., 2014). In practice PPB projects are dynamic in motivations and adaptive in methods employed over time. Coordination is commonly approached through an action learning model in which participants share roles in decision making and their goals and skills change over time. This reality, coupled with balancing farmers' benefits over scientific hypothesis testing, may be reasons that many PPB projects are not published in peer reviewed journals, but instead shared through informal publications, conferences or personal communications.

Participatory plant breeding and organic agriculture

The current study confirmed that there are clear synergies between PPB and organic agriculture as proposed by prior authors (Dawson, 2011; Chable et al., 2014; Shelton and Tracy, 2016; Ortolani et al., 2017). While the majority of projects reviewed were conducted in organic agriculture, the scope of implementation of PPB was not limited to organic systems exclusively as exemplified by the long-standing sweet potato program in the United States. Many projects stated the goal of improving adaptation to organic farming environments, but projects were also motivated by organic principles and values. The current study identified that projects commonly prioritized breeding goals of improving traits crucial to organic producers that are not a priority in conventional breeding programs, for example, the case of resistance to late blight (*Phytophthora infestans*) in potato (Keijzer et al., 2021) and seedling vigour in cool soil conditions in sweet maize (Shelton and Tracy, 2016).

The number of projects and geographical and institutional representation indicates growth in PPB in developed countries, but still represents a finite body of experience and only select cases demonstrate commercialization of new cultivars. This is not surprising as most PPB projects started within the last decade, so additional releases are anticipated in the future. It is promising that several projects include mechanisms for managing the testing and registry requirements for commercialization and even shared royalties with farmers breeders as in the case of potato in the Netherlands, sweet maize in the US, and future plans for wheat, oats and potato in CA and the US. As Desclaux (2008) states organic and low-input systems are characterized by a wide diversity of locations, farming and market systems and farmers' needs and thus require highly diverse seed options. It is unlikely that all needs will be met in the foreseeable future even with increases in organic cultivar options, and PPB will remain a viable compliment to the formal seed sector to fulfil gaps in access to suitable seed.

The impact on farmers' access to seed should not only be measured by cultivar releases. Many of the farmers involved are already bringing crops to market and engaging culinary professionals and other end users in the variety evaluation, thus developing future market demand. In many cases farmers are also sharing seed within farmer networks and coordinating with other farmers for multiplication and commercialization as in the case of the French seed cooperative, Réseau Semences Paysannes, the VASO project farmer network in Portugal, and the sweet potato breeding in North Carolina, US. While the number of institutions involved is limited, researchers, like farmers, exchange seed and in several cases a PPB cultivar developed in one location is shared and tested, and even selected in additional regions of the country and even internationally. For example, the case of a broccoli PPB project from the US shared some breeding populations with the organic seed and breeding company De Bolster in the Netherlands who selected for several generations and recently registered a new organic variety (Myers and Lammerts van Bueren, personal communication). As most

PPB projects are focused on open-pollinated varieties the ability to continue breeding with PPB cultivars is also possible as in the case of the recently released sweet maize cultivar, 'Sweet Kisses', selected out of the US commercialized PPB cultivar 'Who Gets Kissed?' (Shelton and Tracy, 2016; Open Source Seed Initiative, 2021). Researchers' engagement in organic, participatory breeding can also raise awareness of the importance of key traits that in a related, conventional breeding program might otherwise rank lower in priority. An example is the case of the late blight resistance breeding in the Dutch PPB potato programs stimulating commercial companies to place greater priority on resistance in their own selection program resulting in 29 resistant ('robust') varieties released by 2020 (Bionext, 2021). These varieties are now also used by conventional potato growers (Agrico, personal communications). Given these far reaching, but often unaccounted for ripple effects of PPB it is short-sighted to assess the agricultural impacts solely by the number of cultivars released from PPB projects alone.

Participatory plant breeding and agrobiodiversity

The emergence of PPB is attributed in part as a response to counter trends toward consolidation in the seed industry, narrowing crop genetic diversity and an emphasis of multinational corporations on breeding for major crops and large-scale agricultural regions (Pimbert, 2011). Emphasizing intra- and inter- specific genetic diversity is recognized as an important part of systems-based farm management in organic and low-input systems (Finckh, 2008; Pimbert, 2011; Dwivedi et al., 2017; Chable et al., 2020). Several projects in the current study focused on breeding for increased genetic diversity to counter inbreeding depression, and improve the crop's ability to adapt to environmental challenges (Murphy et al., 2005; Philips and Wolfe, 2005; Döring et al., 2011). Other cases strive to improve yield stability under heterogeneous environments by developing genetically diverse populations (Dawson et al., 2010). Evolutionary participatory breeding (EPB), a methodology described by Philips and Wolfe (2005) and employed in several PPB projects refers to breeding for local adaptation by creating highly genetically diverse populations and allowing several cycles of natural selection prior to trait selection, and also continued selection after release by repeated seed saving. The evolutionary potential of EPPB and PPB methods are argued as a means to cope with climate change (Ceccarelli, 2010; Murphy et al., 2013; Entz, 2015), but additional research to document evidence of responses to climate change would strengthen this breeding approach.

Efficiency and participatory plant breeding

Based on prior experience of PPB in the global South, there is evidence of improved efficiency in achieving breeding objectives through collaboration also in the North (Almekinders et al., 2014; Ceccarelli, 2015), and this premise was reinforced in several projects in the current study. Participation of multiple farms provides more sites and thus capacity for screening early generation material, testing late generation materials and enabling decentralized selection for regional adaptation, potentially improving the adaptation across a region rather than on a single farm site while conserving greater genetic diversity of the meta-population (Enjalbert et al., 1999; Goldringer et al., 2001; Porcher et al., 2004; Dawson et al., 2011; Enjalbert et al., 2011). A common approach to many PPB projects is to target specific adaptation, rather than minimizing genotype-by-location interaction as is practiced in most centralized breeding programs. These programs seek to buffer genotype-by-year interactions by creating genetically diverse, heterogeneous populations that may evolve specific adaptation through on-farm selection (Murphy et al., 2005; Petitti et al., 2021). All of the PPB wheat projects in the current case study highlighted the need to breed for specific adaptation not addressed by breeding programs that aim for broad adaptation.

Like the experience of PPB in the global South, there is evidence of improved efficiency in achieving breeding objectives through collaboration in the North (Almekinders et al., 2014; Ceccarelli, 2015) and this premise was reinforced in several projects in the current study. Participation of multiple farms provides more sites and thus capacity for screening in early generations testing in later generations. Participation enables selection for regional adaptation under decentralized locations, potentially improving the adaptation across a region rather than on a single farm site while conserving greater genetic diversity of the meta-population (Enjalbert et al., 1999; Goldringer et al., 2001; Porcher et al., 2004; Dawson et al., 2011; Enjalbert et al., 2011). Many researchers and farmers alike value the 'farmers' eye' in selection as farmers hold an intimate familiarity with their crop qualities and market demands as well as an ability to evaluate specific adaptation (Dawson et al., 2011; Almekinders et al., 2014). One of the Italian tomato project reviewed in the current case study found that farmers' selections resulted in improved local adaptation compared with the researcher selections (Campanelli et al., 2015).

Participatory plant breeding challenges and opportunities

In spite of the potential benefits of PPB, barriers clearly exist. The explicit objective of breeding for increased intra-cultivar genetic diversity creates a tension between the desire to retain genetic diversity and achieve adequate phenotypic uniformity to meet the Distinctness, Uniformity, and Stability (DUS) requirements of the official variety testing and registry systems within Europe and CA. Participatory plant breeding is thus influencing the broader regulatory system to accommodate and expand agrobiodiversity. Several of the researchers involved in projects in the current study have pushed for reform of the seed regulations and as a result the European Commission now accommodates a temporary experiment (2014–2021, COM2014/150/EU) to explore new ways of registering and marketing heterogeneous materials for four cereal crops (wheat, barley, oats and maize). The new EU regulation for organic farming (EC 2018/848) that will come into force in 2022, officially allows marketing of 'heterogeneous material'.

Market acceptance, however, is an important consideration in the adoption of new varieties or populations resulting from PPB projects. As an example, consumers and retailers are used to the names of potato varieties, it is not easy to enter the market with new, unknown resistant varieties that have an advantage for growers in the first place (Nuijten et al., 2018). Therefore, in the Netherlands a covenant was established in 2017 by the Dutch organic umbrella organization signed by all supermarkets to only sell late blight resistant ('robust') varieties for the organic potato segment by 2020, which was indeed achieved by 2020 (Raaijmakers, 2019; Bionext, 2021). Other programs in France, Italy, and Portugal similarly report collaboration with bakers and other culinarians supports the market development for PPB varieties (Chable, 2014; Powell, 2016). These experiences show that collaboration between farmers and breeders is important but when the market players further up in the value chain are not involved and committed it can limit or even block successful marketing of varieties.

There is a lack of research exploring financing models for PPB and consideration of the long-term sustainability of PPB projects. Many of the PPB projects reviewed were funded by large, collaborative research and education grants and operate through a project framework including the EU-funded projects Solibam, Diversifood and LiveSeed and the USDA-funded projects such as Northern Organic Vegetable Improvement Collaborative, and other USDA Organic Research and Extension Initiative projects in multiple crops, and the privately-funded Bauta Family Initiative on Canadian Seed Security (2020). While the public investments in PPB are encouraging given the potential for public benefit of expanded seed access and expansion of agrobiodiversity, it also raises the question if these projects could be supported by market driven returns on investments.

Finally, there is a need to support the education in participatory plant breeding at various levels (GAFF, 2020). Many modern farmers have lost the skills of breeding, and search for some background when getting involved in a breeding project, as was reported from the Dutch potato project. At universities there is also a need for education in PPB to train the plant breeders not only on technical issues but also on the social implications of making PPB with stakeholders a success (Lammerts van Bueren et al., 2020).

Participatory plant breeding and seed systems

Analysis of PPB necessitates a multi-disciplinary approach to fully understand the social, political and agroecological influences driving the emergence of projects in the global North and factors impacting implementation. The current study underscores that project goals and outcomes cannot be assessed through an agronomic lens alone. It is also clear that while the term PPB is broadly defined as a collaboration in breeding, each project is unique with a spectrum of scales of operations, methods employed and relationship dynamics between actors. Common themes that emerged include motivation to address gaps in seed needs that are not served by the formal breeding sector coupled with repairing a sense of loss of seed sovereignty and seed knowledge by farmers. The desire of farmers for seed autonomy and avoidance of hybrid varieties was a common motivating aspect of PPB in the current study across the maize, tomato and Brassica case studies underscoring the desire for restoring farmers' control of the seed in farming systems in the global North (Kloppenburg, 2010). It is clear from the current study that farmers in the North and South share the commonality that the dominant commercial seed sector's emphasis on breeding for major production regions and broad adaptation is not serving all farmers' needs to the extent that underserved farmers are motivated to take seed improvement into their own hands. What makes the PPB projects in the North different from those in the South might be the further developed specialization in the value chain in the North. Examples have shown that it is often important to engage not only farmers and breeders, but to also involve other actors including seed producers, processors, and retailers further up in the value chain for successful adoption of new PPB varieties (Nuijten et al., 2018). It is also clear that PPB projects are embedded in a broader seed system and that "system" varies from project to project. The success of projects additionally necessitates consideration of the broader regulatory, social and economic context in the planning and decision-making process in order to maximize intended outcomes and impacts.

References

Almekinders CJM, Mertens L, van Loon JP and Lammerts van Bueren ET (2014) Potato breeding in the Netherlands: a successful participatory model with collaboration between farmers and commercial breeders. *Food Security* **6**, 515–524.

Atlin GN, Cooper M and Bjornstad A (2001) A comparison of formal and participatory breeding approaches using selection theory. *Euphytica* **122**, 463–475.

Bauta Family Initiative on Canadian Seed Security (2013) Farmer Participatory Plant Breeding Newsletter, November 2013. Available at: http://www.seedsecurity.ca/doc/PPBNewsletterNov2013.pdf

Bauta Family Initiative on Canadian Seed Security (2020) Canadian Organic Vegetable Improvement Project. Available at: http://www.seedsecurity.ca/en/programs/creating-seed-diversity/302-canovi

Berthet ET, Bosshardt S, Malicet-Chebbah L, van Frank G, Weil, B, Segrestin B, Rivière, P, Bernard L, Baritaux E and Goldringer I (2020) Designing innovative management for cultivated biodiversity: lessons from a pioneering collaboration between French farmers, facilitators and researchers around participatory bread wheat breeding. *Sustainability* **12**, 605, 1–19.

Bionext (2021) Convenant robuuste aardappelteelt. Available at: https://bio-next.nl/thema-s/plantgezondheid/aardappel-convenant/

Brouwer B and Colley M (2016) Pacific Northwest Organic Plant Breeding Assessment of Needs, 2016. Port Townsend, WA, USA: Organic Seed Alliance. Available at: https://seedalliance.org/publications/pacific-north- west-plant- breeding-assessment-needs/

Campanelli G, Acciarri N, Campion B, Delvecchio S, Leteo F, Fusari F, Angelini P and Ceccarelli S (2015) Participatory tomato breeding for organic conditions in Italy. *Euphytica* **204**, 179–197.

Campanelli G, Sestili S, Acciarri N, Montemurro F, Palma D, Leteo F and Beretta M (2019) Multi-parental advances generation inter-cross population, to develop organic tomato genotypes by participatory plant breeding. *Agronomy* **9**(119), 1–13.

Casals J, Rull A, Segarra J, Schober P and Simó J (2019) Participatory plant breeding and the evolution of landraces: a case study in the organic farms of the Collserola natural park. *Agronomy* **9**, 486, 1–13.

Ceccarelli S (2015) Efficiency of plant breeding. *Crop Science* **55**, 87–97.

Ceccarelli S and Grando S (2019) Participatory plant breeding: who did it, who does it and where? *Experimental Agriculture* **56**, 1, 1–11.

Ceccarelli S, Grando S, Maatougui M, Michael M, Slash M, Haghparast R, Rahmanian M, Taheri A, Al-Yassin A, Benbelkacem A, Labdi M, Mimoun H and Nachit M (2010) Plant breeding and climate changes. *The Journal of Agricultural Science* **148**, 627–637.

Chable V, Conseil M, Serpolay E and Le Lagadec F (2008) Organic varieties for cauliflowers and cabbages in Brittany: from genetic resources to participatory plant breeding. *Euphytica* **164**, 521–529.

Chable V, Dawson J, Bocci R and Goldringer I (2014) Seeds for organic agriculture: development of participatory plant breeding and farmers' networks in France. In Bellon S and Penvern S (eds), Organic Farming Prototype for Sustainable Agriculture. Dordecht: Springer Science, pp. 384–400. https://doi.org/10.1007/978-94-007-7927-3_21

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

Chiffoleau Y and Desclaux D (2006) Participatory plant breeding: the best way to breed for sustainable agriculture? *International Journal of Agricultural Sustainability* **4**, 119–130.

Colley M, McCluskey C, Lammerts van Bueren ET and Tracy W (2021) The ripple effect of participatory plant breeding: a case study in us of organic sweet corn. In International Conference on Breeding and Seed Sector Innovations for Organic Food Systems by EUCARPIA Section Organic and Low Input Agriculture jointly with LIVESEED, BRESOV, ECOBREED, FLPP projects and ECO-PB, 8–10 March 2021. Latvia: Institute of Agricultural Resources and Economics, pp. 119–120. Available at https:// www.eucarpialiveseedconference2021.lv/abstract-e-book/

Darby H, Monahan S, Cummings E, Harwood H and Madden R (2013) 2012 Vermont On-Farm Spring Wheat Breeding Trials, Northwest Crops & Soils Program. University of Vermont. 214. Available at https://scholar-works.uvm.edu/cgi/viewcontent.cgi?article=1225&context=nwcsp

Da Via E (2015) Food sovereignty in the fields: seed exchange and participatory plant breeding of wheat landraces in Italy. In Trauger A (ed.), *Food Sovereignty in*

International Context: Discourse, Politics and Practice of Place. New York, NY: Taylor & Francis, pp. 198–211.

Dawson JC, Murphy KM and Jones SS (2008) Decentralized selection and participatory approaches in plant breeding for low-input systems. *Euphytica* **160**, 143–154.

Dawson JC, Rivière P, Galic N, Pin S, Serpolay E, Mercier F and Goldringer I (2010) On-farm conservation and farmer selection as a strategy for varietal development in organic agricultural systems. In Goldringer I, Dawson J, Rey F and Vettoretti A (eds), *Breeding for Resilience: A Strategy for Organic and Low-Input Farming Systems? Proceedings of EUCARPIA 2nd Conference of the "Organic and Low-Input Agriculture Section*. Paris, France: Eucarpia, pp. 123–126. Available at https://org-prints.org/id/eprint/18171/

Dawson JC, Rivière R, Berthellot JF, Mercier F, de Kochko P, Galic N and Pin S (2011) Collaborative plant breeding for organic agricultural systems in developed countries. *Sustainability* **3**, 1206–1223.

Dawson JC, Healy K and McCluskey C (2017) Organic Vegetable Trials and Plant Breeding Needs Assessment and Strategy for National Collaboration. Madison, WI, USA: University of Wisconsin-Madison. Available at: https://dawson.horticulture.wisc.edu/wp-content/uploads/sites/21/2018/02/ OVTSeedSummit_Needs-Assessment-Proceedings_30Aug2017-FINAL- digital.pdf (Accessed verified 1/30/2018).

Deppe CS (2021) Freelance plant breeding. *Plant Breeding Reviews* **44**, 113–186.

Desclaux D, Nolot JM, Chiffoleau Y, Gozé E and Leclerc C (2008) Changes in the concept of genotype×environment interactions to fit agriculture diversification and decentralized participatory plant breeding: pluridisciplinary point of view. *Euphytica* **163**, 533–546.

Döring, TF, Kovacs, G, Wolfe, MS and Murphy K (2011) Evolutionary plant breeding in cereals – into a new era. *Sustainability* **3**, 1944–1971.

Dwivedi SL, Lammerts van Bueren ET, Ceccarelli S, Grando S, Upadhyaya HD and Ortiz R (2017) Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends in Plant Science* **22**, 842–856.

Enjalbert J, Goldringer I, Paillard S and Brabant P (1999) Molecular mar- kers to study genetic drift and selection in wheat populations. *Journal of Experimental Botany* **50**, 283–290.

Enjalbert J, Dawson JC, Paillard S, Rhoné B, Rousselle Y, Thomas M and Goldringer I (2011) Dynamic management of crop diversity: from an experimental approach to on-farm conservation. *Comptes Rendus Biologies* **334**, 458–468.

Entz MH (2019) Participatory potato breeding program at the University of Manitoba (Canada). Available at: http://www.seedsecurity.ca/en/programs/ create/field-crops and http://www.umanitoba.ca/outreach/naturalagriculture/articles/ppb_potato.html

Entz MH, Kirk AP, Vaisman I, Fox SL, Fetch JM, Hobson D, Jensen HR and Rabinowicz J (2015) Farmer participation in plant breeding for Canadian organic crop production: implications for adaptation to climate uncertainty. *Procedia Environmental Sciences* **29**, 238–239.

Entz MH, Kirk AP, Jensen HR, Rabinowicz J and Dey A (2016) Development of a participatory plant breeding program for wheat, oat, and potatoes in Canada. In Davis K (ed.), *Organic Seed Growers Conference Proceedings,* February 4–6, 2016. Port Townsend, WA, USA: Organic Seed Alliance, pp. 42–46. Available at: https://seedalliance.org/publications/proceedings-8th-organic-seed-growers-conference/ (Accessed 22 April 2021).

Entz MH, Kirk AP, Carkner M, Vaisman I and Fox SL (2018) Evaluation of lines from a farmer participatory organic wheat breeding program. *Crop Science* **58**, 2433–2443.

Finckh MR (2008) Integration of breeding and technology into diversification strategies for disease control in modern agriculture. *European Journal of Plant Pathology* **121**, 399–409.

GAFF (2020) Shared Action Framework for Resilient Seed Systems. Global Alliance of the Future of Food. Available at: https://futureoffood.org/wp-content/uploads/2020/02/Resilient-Seed-Systems-Shared-Action-Framework-English.pdf.

Genger R (2018) Building Resilience and Flexibility into Midwest Organic Potato Production: Participatory Breeding and Seed Potato Production. Final project report, 2014–2018. University of Wisconsin-Madison, Wisconsin, USA. Available at: https://projects.sare.org/sare_project/lnc14- 358/

Goldringer I, Enjalbert J, David J, Paillard S, Pham JL and Brabant P (2001) Dynamic management of genetic resources: a 13-year experiment on wheat. In Cooper HD, Spillane C and Hodgkin T (eds), Broadening the Genetic Base of Crop Production. Rome, Italy: IPGRI/FAO, pp. 245–260. Goldringer I, Enjalbert J and Rivière P and Dawson J (2012) Recherche par- ticipative pour des variétés adaptées à une agriculture à faible niveau d'in- trants et moins sensibles aux variations climatiques. *POUR* **213**, 153–161.

Goldringer I, van Frank G, Bouvier d'Yvoire C, Forst E, Galic N, Garnault M, Locqueville J, Pin S, Bailly J, Baltassat R, Berthellot J-F, Caizergues F, Dalmasso C, de Kochko P, Gascuel J-S, Hyacinthe A, Lacanette J, Mercier F, Montaz H, Ronot B and Rivière P (2019) Agronomic evaluation of bread wheat varieties from participatory breeding: a combination of performance and robustness. *Sustainability* **12**, 128.

Healy GK and Dawson JC (2019) Participatory plant breeding and social change in the midwestern United States: perspectives from the seed to kitchen collaborative. *Agriculture and Human Values* **36**, 879–889.

Healy GK, Emerson BJ and Dawson JC (2017) Comparing tomato varieties for productivity and quality under organic hoop-house and open-field management. *Renewable Agriculture and Food Systems* **32**, 562–572.

Horneburg B (2010) Participation, utilization, and development of genetic resources in the organic outdoor tomato project. In Goldringer I, Dawson J, Rey F and Vettoretti A (eds), *Breeding for Resilience: A Strategy for Organic and Low-Input Farming Systems? Proceedings of EUCARPIA 2nd Conference of the "Organic and Low-Input Agriculture Section.* Paris, France: Eucarpia, pp. 139–142. Available at: https://orgprints.org/id/eprint/ 18171/

Horst M and Marion A (2018) Racial, ethnic, and gender inequities in farmland ownership and farming in the US. Agriculture and Human Values **36**, 1–16.

Hubbard K and Zystro J (2016) *State of Organic Seed*. Port Townsend, WA,

USA: Organic Seed Alliance. Available at: www.stateofroganicseed.org

Hultengren RL, Glos M and Mazourek M (2016) *Breeding, Research, and Education Needs Assessment for Organic Vegetable Growers in the Northeast.* Ithaca, NY, USA: Cornell University. Available at: https://ecom- mons.cornell.edu/handle/1813/44636 (Accessed 25 April 2021).

Keijzer P, Lammerts van Bueren ET, Engelen CJM and Hutten RCB (2021) Breeding late blight resistant potatoes for organic farming – a collaborative model of participatory plant breeding: the Bioimpuls project. *Potato Research*. Available at: https://doi.org/10.1007/s11540-021-09519-8

Kirk A, Vaisman I, Martens G and Entz M (2015) Field Performance of Farmer-Selected Wheat Populations in Western Canada. Winnipeg, Canada: University of Manitoba. Available at: http://www.seedsecurity.ca/ en/resources/onfarm-research

Kissing Kucek L (2017) *Participatory Breeding of Wheat for Organic Production* (PhD thesis), Cornell University, Ithaca, NY.

Kissing Kucek L and Sorrells ME (2016) Designing an organic wheat breeding program for the Northeast United States. In Davis K (ed.). *Organic Seed Growers Conference Proceedings*, February 4-6, 2016. Port Townsend, WA, USA: Organic Seed Alliance, pp. 32–36. Available at: https://seedalliance.org/ publications/proceedings-8th-organic-seed-growers-conference/

Kissing Kucek L, Darby HM, Mallory EB, Dawson JC, Davis M, Dyck E, Lazor J, O'Donnell S, Mudge S, Kimball M, Molloy T, Benscher D, Tanaka J, Cummings E

and Sorrells ME (2015) Participatory breeding of wheat for organic production. In Baker B (ed) *Organic Agriculture Research Symposium*. Organic Farming Research Foundation. Santa Cruz, CA: Organic Farming Research Foundation. Available at: http://eorganic. info/node/12972

Kloppenburg J (2010) Impeding dispossession, enabling repossession: bio- logical open source and the recovery of seed sovereignty. *Journal of Agrarian Change* **10**, 367–388.

Lammerts van Bueren ET, Tiemens-Hulscher M and Struik PC (2008) Cisgenesis does not solve the late blight problem of organic potato production: alternative breeding strategies. *Potato Research* **51**, 89–99.

Lammerts van Bueren ET, Østergård H, de Vriend H and Backes G (2010) Role of molecular markers and marker-assisted selection in breeding for organic and low-input agriculture. *Euphytica* **175**, 51–64.

Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C and Messmer MM (2011) The need to breed crop varieties suit- able for organic farming, using wheat, tomato and broccoli as examples: a review. *NJAS – Wageningen Journal of Life Sciences* **58**, 193–205.

Lammerts van Bueren ET, Almekinders CJM, Weltzien-Rattunde E, Chable V, Bocci R, Messmer M, Rattunde F and Van de Vijver CADM (2021) A postgraduate course on participatory plant breeding and resilient seed sys- tems: collaborative design, implementation, and resulting experiences. In *Abstract Book of the International Conference on Breeding and Seed Sector Innovations for Organic Food Systems by Eucarpia Section Organic and Low Input Agriculture Jointly with LIVESEED, BRESOV, ECOBREED, FLPP Projects and ECO-PB*, 8–10 March 2021. Latvia: Institute of Agricultural Resources and Economics. pp. 126–127. Available at: http// www.eucarpia.eu/images/publications/2021_EUCARPIA_LIVESEED_Abstract_ E-Book.pdf.

Lange J, Raj RP and Horneburg B (2018) Participatory breeding for improved Phytophthora-resistance in the organic outdoor tomato project. In Rahmann G, Andres

C, Yadav AK, Ardakani R, Babalad HB, Devakumar N, Goel SL, Olowe V, Ravisankar N, Saini JP and Soto G (eds), *Innovative Research for Organic 3.0-Volume 1: Proceedings of the Scientific Track at the Organic World Congress* 2017, November 9-11 in Delhi, India. Braunschweig, DE: Johann Heinrich von Thuner Institute, Thünen Report, pp. 348–351. Available at: https://www.cabdirect.org/cabdirect/abstract/20183331339

Lazor J (2008) A Vermont Farmers Breeding Club: Developing Varieties That Work For Us, Farmer Grant Report. Vermont, USA: Sustainable Agriculture Research and Education. Available at: https://projects.sare.org/ sare_project/fne07–613/

Lyon A, Silva E, Zystro J and Bell M (2015) Seed and plant breeding for Wisconsin's organic vegetable sector: understanding farmers' needs. *Agroecology and Sustainable Food Systems* **39**, 601–624.

Lyon A, Friedmann H and Wittman H (2021) Can public universities play a role in fostering seed sovereignty? Elementa **9**(1), 1–14.

Malandrin V and Dvortsin L (2013) Participatory processes of agroecological innovation in organic cereal breeding: a case study from Italy. *IV International Symposium Agrosym: Book of Proceedings*. Agrosym, pp. 719– 725. Available at: http://www2.agrosym.rs.ba/agrosym/agrosym_2013/index. html

Martin JH and Leonard WH (1967) *Principles of field crop production*. New York, NY: Macmillan.

McKenzie L (2013) *Breeding an Open-Pollinated Broccoli for Organic Production System Using Participatory Methods* (Ms thesis), Oregon State University, Corvallis, OR, USA. Available at: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/v692t940f?locale=en

Mendes-Moreira P (2006) Participatory maize breeding in Portugal. A case study. *Acta Agronomica Hungarica* **54**, 431–439.

Mendes-Moreira P and Pêgo SE (2012) On-farm conservation and participatory maize breeding in Portugal: an overview. In Maxted N, Dulloo ME, Ford-Lloyd BV, Frese L,

2

Iriondo JM and Pinheiro de Carvalho MAA (eds), *Agrobiodiversity Conservation: Securing the Diversity of Crop Wild Relatives and Landraces.* Wallingford, England: CAB International, pp. 131–136.

Mendes-Moreira P, Satovic Z, Mendes-Moreira J, Santos JP, Nina Santos JP, Pêgo S and Vaz Patto MC (2017) Maize participatory breeding in Portugal: comparison of farmer's and breeder's on-farm selection. *Plant Breeding* **136**, 861–871.

Mendum R and Glenna L (2010) Socioeconomic obstacles to establishing a participatory plant breeding program for organic growers in the United States. *Sustainability* **2**, 73–91.

Morris ML and Bellon M (2004) Participatory plant breeding research: oppor- tunities and challenges for international crop improvement system. *Euphytica* **136**, 21–35.

Murphy K, Lammer D, Lyon S, Carter B and Jones SS (2005) Breeding for organic and low-input farming systems: an evolutionary–participatory breeding method for inbred cereal grains. *Renewable Agriculture and Food Systems* **20**, 48–55.

Murphy KM, Campbell KG, Steven RL and Jones SS (2007) Evidence of varietal adaptation to organic farming systems. Field Crops Research **102**, 172–177.

Murphy KM, Carter AH and Jones SS (2013) Evolutionary breeding and climate change. In Kole C (ed.), *Genomics and Breeding for Climate-Resilient Crops.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 377–389. Available at https://doi.org/10.1007/978-3-642-37045-8_9

Myers JR, McKenzie L and Voorrips R (2012) Brassicas: breeding Cole crops for organic agriculture. In Lammerts van Bueren ET and Myers JR (eds), *Organic Crop Breeding*. Oxford, UK: Wiley-Blackwell, pp. 251–261.

Nuijten E, de Wit J, Janmaat L, Schmit A, Tamm L and Lammerts van Bueren ET (2018) Understanding obstacles and opportunities for successful market introduction of crop varieties with resistance against major diseases. *Organic Agriculture* **8**, 285–299.

Open Source Seed Initiative (2021) OSSI 'Freed' Seed: Sweet Kisses. Available at: https://osseeds.org/seeds/

Ortolani L, Bocci R, Paolo B, Salley H and Chable V (2017) Changes in knowledge management strategies can support emerging innovative actors in organic agriculture: the case of participatory plant breeding in Europe. *Organic Agriculture* **3**, 20–33.

Pacilly FCA, Hofstede GJ, Lammerts van Bueren ET and Groot J (2019) Analyzing social-ecological interactions in disease control: an agent-based model on farmers' decision making and potato late blight dynamics. *Environmental Modelling & Software* **119**, 354–373.

Pêgo S and Pilar Antunes M (1997) Resistance or tolerance? Philosophy, may be the answer. In *Proceedings of the XIX Conference of the International Working Group on Ostrinia*, pp. 303–341.

Petitti M, Bocci R, Bussi B, Ceccarelli S, McKeown P and Spillane C (2018) Evolutionary-participatory breeding generates wheat populations adapted for organic agriculture in Italy. In Baćanović-Šišić J, Dennenmoser D and Finckh MR (eds), *Proceedings of the Eucarpia Symposium on Breeding for Diversity. Witzenhausen, DE: Eucarpia,* pp. 39–41. Available at: https://www. uni-kassel.de/upress/online/OpenAccess/978-3-7376-0462-8.OpenAccess.pdf

Petitti M, De Santis G, Bocci R, Lo Fiego A, Di Luzio P, Cerbino D and Ceccarelli S (2021) Evolutionary participatory tomato breeding in Italy for organic agriculture. In *International Conference on Breeding and Seed Sector Innovations for Organic Food Systems by EUCARPIA Section Organic and Low Input Agriculture jointly with LIVESEED, BRESOV, ECOBREED, FLPP projects and ECO-PB*, 8-10 March 2021. Latvia: Institute of Agricultural Resources and Economics, pp. 44–45. Available at: https://www.eucarpialiveseedconference2021.lv/abstract-e-book/

Philips SL and Wolfe MS (2005) Evolutionary plant breeding for low input systems. *Journal of Agricultural Science* **143**, 245–254.

Pimbert M (2011) Participatory Research and On-Farm Management of Agrobiodiversity in Europe. London, UK: IIED. Available at: https://pubs.iied. org/sites/default/files/pdfs/migrate/14611IIED.pdf (Accessed 22 April 2021).

Porcher E, Giraud T, Goldringer I and Lavigne C (2004) Experimental demonstration of a causal relationship between heterogeneity of selection and genetic differentiation in quantitative traits. *Evolution* **58**, 1434–1445.

Powell JB (2016) White Maize to Pigarro: an actor-network analysis if improved crop variety in Northwest Portugal. *Journal of Ethnobotony* **36**, 45–65.

Raaijmakers M (2019) Doelstelling 100% robuuste aardappelrassen in 2020 gaan we halen. Biojournaal, 2 December 2019. Available at: https://www.biojournaal.nl/article/9168815/doelstelling-100-robuuste-aardappelrassen-in- 2020-gaan-we-halen/

Rivière P (2014) *Méthodologie de la sélection décentralisée et participative: un exemple sur le blé tendre* (PhD thesis). University Paris-Sud, Gif-Sur-Yvette, France.

Rivière P, Pin S, Galic N, de Oliveira Y, David O, Dawson JC, Wanner A, Heckmann R, Obbellianne S, Ronot B, Parizot S, Hyacinthe A, Dalmasso C, Baltassat R, Bochède A, Mailhe G, Cazeirgue F, Gascuel J-S, Gasnier R, Berthellot J-F, Baboulène J, Poilly C, Lavoyer R, Hernandez M-P, Coulbeaut J-M, Peloux F, Mouton A, Mercier F, Ranke O, Wittrish R, de Kochko P and Goldringer I (2013a) Mise en place d'une méthodologie de sélection participative sur le blé tendre en France. Innovations *Agronomiques* **32**, 427–441.

Rivière P, Goldringer I, Berthellot J-F, Galic N, Pin S, De Kochko P and Dawson JC (2013b) Response to farmer mass selection in early generation progeny of bread wheat landrace crosses. *Renewable Agriculture and Food Systems* **30**, 190–201.

Rivière P, Dawson JC, Goldringer I and David O (2014) Experimental design for PPB in farm network. In Chable V, Goldringer I, Howlett SA, Barberi P, Miko P, Mendes-Moreira PMR, Rakszegi M, Ostergard H, Brogen A, Finckh MR, Pedersen T and Bocci R (eds), *Diversity Strategies for Organic and Low Input Agricultures and Their Food Systems Book of Abstracts of Solibam Final Congress*, Nantes, France, 7–9 July 2014, pp. 17–18. Available at: https://www.researchgate.net/profile/Peter-Miko/publication/282864256_Diversity_strategies_for_organic_and_low_input_agricu ltures_and_ their_foodsystems/links/56d6cd8508aebabdb402df7e/Diversity-strategies-for- organic-and-low-input-agricultures-and-their-foodsystems.pdf

Rivière P, Dawson JC, Goldringer I and David O (2015) Hierarchical Bayesian modeling for flexible experiments in decentralized participatory plant breeding. *Crop Science* **55**, 1053–1067.

Rodriguez A, Koutis K, Annicchiarico P, Nuijten E and Messmer M (2020) LiveSeed: Deliverable 3.4 Report on breeding gaps and key factors for strengthening small breeding initiatives: Experiences on five crops. Liveseed. Available at: https://www.liveseed.eu/wp-content/uploads/2020/09/LIVESEED_D3.4.-strengthening-small-scale-breeding-initiatives_final_ revised.pdf

Sahamishirazi S, Moehring J, Zikeli S, Fleck M, Claupein W and Graeff-Hoenninger S (2018) Agronomic performance of new open- pollinated experimental lines of broccoli (Brassica oleracea L. var. italica) evaluated under organic farming. *PLoS One*, **13**, 1–13. e0196775.

Shelton AC and Tracy WF (2015) Recurrent selection and participatory plant breeding for improvement of two organic open-pollinated sweet maize (Zea mays L.) populations. *Sustainability*, **7**, 5139–5152.

Shelton AC and Tracy WF (2016) Participatory plant breeding and organic agriculture: a synergistic model for organic variety development in the United States. Elementa *Science of the Anthropocene* **4**, 1–12.

Sieber K, Forster GM, Diekmann K, Sprengel M, Kellermann A, Dehmer KJ and Hammann T (2018) Schlussbericht zum Thema Entwicklung von Phytophthora-resistentem Kartoffelzuchtmaterial fuer den oekologischen Landbau. Freising, Germany: Bayerische Landesanstalt fuer Landwirtschaft (LfL). Available at: https://orgprints.org/36354/5/36354-10OE121-lfl-keller- mann-2018-phytophthera-resistenz-zuchtmaterial.pdf

Tiemens-Hulscher M, Lammerts van Bueren ET and Hutten RCB (2012) Potato: improving organic cultivars including a participatory approach. In Lammerts van

Bueren ET and Myers JR (eds), *Organic Crop Breeding*. Hoboken, NJ, USA: Wiley-Blackwell, pp. 227–238.

Tiemens-Hulscher M, Delleman J, Eising J and Lammerts van Bueren ET (eds) (2013) *Potato Breeding – A Practical Manual for the Potato Chain. The Hague, The Netherlands*: Aardappelwereld BV, pp. 170.

van Frank G (2018) *Gestion participative de la diversité cultivée et création de mélanges diversifiés à la ferme* (PhD thesis). Université Paris-Sud, Gif-Sur-Yvette, France.

van Frank G, Rivièr P, Pin S, Baltassat R, Berthellot JF, Caizergues F, Dalmasso C, Gascuel, JS, Hyacinthe A, Mercier F, Montaz H, Ronot B and Goldringer I (2020) Genetic diversity and stability of performance of wheat population varieties developed by participatory breeding. *Sustainability* **12**, 384.

Vindras-Fouillet C, Rouellat V, Hyacinthe A and Chable V (2016) Empirical knowledge in participatory research: integration of the sensory quality of bread in the plant breeding process of wheat in France. *Universal Journal of Agricultural Research* **4**, 5–14.

Weltzien E, Smith ME, Meitzner LS and Sperling L (2003) *Technical and Institutional Issues in Participatory Plant Breeding-From the Perspective of Formal Plant Breeding: A Global Analysis of Issue, Results, and Current Experience*. Cali, Colombia: Centro International de Agricultura Tropical (CIAT), pp. 208.

Wolfe MS, Baresel JP, Desclaux D, Goldringer I, Hoad S, Kovacs G, Löschenberger F, Miedaner T, Østergård H and Lammerts van Bueren ET (2008) Developments in breeding cereals for organic agriculture. *Euphytica* **163**, 323–346.

Supplemental Materials

Supplemental materials are available at: https://doi.org/10.1017/S0021859621000782

Chapter 3

Carrot performance in organic and conventional management systems and implications for organic plant breeding

Authors:
Colley MR[1,2], Dawson JC[3], Zystro J[1], Hoagland L[4], Liou M[5], Myers JR[6], Silva EM[7], and Simon PW[8].
[1]Organic Seed Alliance
[2]Wageningen University, Plant Breeding
[3]University of Wisconsin-Madison, Department of Horticulture
[4]Purdue University, Department of Horticulture and Landscape Architecture
[5]University of Wisconsin-Madison, Department of Statistics
[6]Oregon State University, Department of Horticulture
[7]University of Wisconsin-Madison, Department of Plant Pathology
[8]University of Wisconsin-Madison/ United State Department of Agriculture/ Agricultural Research Service

Abstract

Organic carrot producers need varieties that are not only adapted to organic farming systems and local environments, but also hold qualities that address production challenges. Weed competition is challenge in organic carrot production as germination is slow and erratic resulting in slow canopy establishment compared with other horticultural crops. Organic producers rely on costly mechanical and hand weeding methods for weed management. To inform future plant breeding and testing strategies for improvement of carrot for organic systems the current study evaluated top growth measurements and yields in multi-environment trials in Wisconsin (WI) and Indiana (IN), across 4 years under organic and conventional management. Results revealed variation in genotypes for top height and width at 30 days after planting and 60 days after planting, as well as root and top weights at harvest demonstrating the potential to breed for improved crop establishment as well as yield. Results indicated that selection under conventional growing conditions would likely correlate to improved performance in organic conditions, however when possible genetic gains could be realized more quickly by selecting directly under organic management. A comparison of the ranking of variety performance and stability of performance across the range of growing environments also demonstrated that there are instances when varieties perform similarly across management systems while other genotypes exhibit a different response pattern in organic compared with conventional growing environments. A key implication is that differences in variety performance in organic versus conventional systems is highly complex with significant higher order interactions and contextual of the location, year and genotype.

Keywords: Organic plant breeding, organic seed, organic carrot production, adaptability, weed management, correlated response

Introduction

Organic farming is promoted for supporting environmental and human health as well as quality of life benefits (Bellon and Penvern, 2014; IFOAM, 2022). Organic agriculture, is however, frequently scrutinized for the ability to feed the worlds' growing population due to challenges in meeting nutrient availability and managing weeds, pests, and disease pressures (Conner, 2008; de Ponti et al., 2012). Several meta-data studies assessing the yield of organic versus conventional farming systems estimate lower yields in organic, but results are highly variable and there are clearly contextual differences depending on the crop, location, scale, and specific organic management practices employed (Badgley and Perfecto, 2007; Seufert et al., 2012, Smith et al., 2019). Along with growth in organic agriculture, researchers continue to strive to optimize the complex crop-ecological interactions in organic systems with the goal of improving yields while maximizing food quality and ecosystem services (Kristiansen et al., 2006). The role of plant breeding in addressing these goals is increasingly recognized as a potential leverage point to advance organic agricultural systems (Lammerts van Bueren and Myers, 2012; Dawson, 2008a; Abdelrazek et al., 2020a; Abdelrazek, 2020b).

There is evidence that varieties developed in and for conventional agriculture do not always perform optimally in organic systems (Murphy et al., 2007; Vlachostergios et al., 2008), and selection under organic management can improve yields relative to selection under conventional management (Kirk et al., 2012), yet organic farmers still frequently rely on conventionally bred varieties and seed sources (Hubbard et al., 2021, Solfarelli et al., 2021). Most studies comparing organic and conventional management are in grain crops (Murphy et al., 2007; Przystalski et al., 2008; Baresel et al., 2008; Löschenberger et al., 2008; Baenzinger et al., 2011; Kirk et al., 2012) with only select examples of horticultural crops such as onion (Lammerts van Bueren et al., 2012; Osman et al., 2008) and broccoli (Renaud et al., 2014). Organic vegetable farmers need organically available seed of varieties that are adapted to organic growing conditions and have market qualities demanded by organic consumers, yet most private breeding programs are focused on breeding for production regions and trait priorities of conventional agriculture. This raises the question of how best to breed vegetable crops for organic systems to address organic farmers' crop system needs and expand access to organic seed of suitable varieties. Organic farms are geographically distributed across locations and diversified in within-farm crop and variety type compared with conventional agriculture, thus there is also a need to consider efficient and effective breeding strategies. The current study explores how carrot can be improved for organic farming systems.

Carrot improvement for organic agriculture

Despite challenges in variety and seed choices, organic agriculture continues to expand with sales in the US tripling between 2008 and 2019 (USDA/NASS, 2020). Vegetables and fruits comprise the largest organic sales category representing 58% of total organic crop sales with carrots ranking in the top five among vegetable crops (USDA/ NASS, 2020; Redman, 2020). Carrots are a nutritionally and economically important vegetable for the organic sector with annual sales at $132 million USD representing a 49% increase from 2016-2019 and accounting for 25% of total carrot sales (USDA/NASS, 2020). Organic carrot producers rely on an integrated management approach with an emphasis on selection of crop varieties that work synergistically with cultural methods including use of cover crops, organic amendments, crop rotations, mechanical weed management, site selection, and timing of planting (Simon et al., 2017; Seaman, 2016; Finckh et al., 2015).

Carrot production challenges overlap between organic and conventional systems including major pests and disease, but the management practices and prioritization of variety traits often differs between the two systems. Recent reports assessing organic plant breeding priorities in the US identified flavor, weed competitiveness, Alternaria resistance, cavity spot resistance, and nematode resistance as top breeding priorities in carrots (Brouwer and Colley, 2016; Hultengren et al., 2016; Dawson et al., 2017; Simon et al., 2017; Colley, 2020). Public and private carrot breeding programs striving to develop varieties to address organic carrot growers' needs are often challenged by limited capacity to breed entirely within and for organic systems. As such assessment of the environmental influence of conventional versus organic managment on carrot performance may aid in developing efficient and effective breeding and testing strategies. No previous studies to our knowledge have assessed the interaction between genotype, environment, and management system for carrot root and shoot yields under organic and conventional production.

An understanding of the environmental influence of different locations and management systems on the heritability and selection potential of targeted traits in different carrot genotypes may also aid in developing effective participatory breeding strategies. The biennial nature of carrots presents a unique opportunity compared to annual crops to evaluate and select diverse varieties in a given location with seed regeneration in a separate location the following year. Carrot seed production can be challenging in certain environments where high temperatures, humidity, disease pressure and risks of outcrossing with wild carrot limit seed quality. For this reason, a participatory network that facilitates collaboration of farmers across locations including targeted environments for genotypic advancement in the root production phase and optimum environments for the seed production phase, presents an opportunity to address this challenge. At the same time the ability to select across multiple farms in a participatory approach presents the opportunity for decentralized selection across environments, collectively potentially aiding in development of more broadly or regionally adapted varieties.

To better understand if varieties perform differently across organic and conventional management systems and to explore the implications of selecting carrots under organic or conventional management when breeding for regional, organic farming systems in the Midwest Region of the US, we conducted multi-environment trials of diverse carrot genotypes under organic and conventional management in Indiana (IN) and Wisconsin (WI) across four years. For the results to inform a range of carrot breeding initiatives we included a wide diversity of genotypic entries including orange- and novel-colored types (red, purple and yellow) of landraces, open-pollinated varieties, F1 hybrid varieties and breeding lines from the United States Department of Agriculture (USDA). This study was undertaken as part of the Carrot Improvement for Organic Agriculture (CIOA) project funded by the USDA Organic Research and Education Initiative. The overall goals of CIOA are to improve the understanding of genotypic, environmental and management influences on carrot performance in organic systems, to develop and disseminate new varieties that serve the needs of organic farmers and establish decentralized participatory networks to advance organic carrot breeding, seed production and testing on organic farms in the US (for more information see: https://eorganic.info/carrotimprovement).

Addressing organic carrot production challenges

Supplying sufficient nutrients for optimum yields is a key production challenge in organic systems attributing to potential gaps in yield between organic and conventional production (Seufert et al., 2012). Organic is often considered a low-input system with reduced nutrient accessibility (Dawson et al., 2008b; Lammerts van Bueren et al., 2011). However high value horticultural crops, including carrot, are often carefully managed organically to optimize nutrient availability through the use of cover crops, crop rotations, and organic fertilizers (Eddy, 2008). Recent research also determined that carrot genotypes differ in their potential to alter the composition and activity of microbiomes that cycle organic materials in soil, thereby potentially increasing nitrogen (N) use efficiency in organic carrot production (Triviño, 2020). Bender et al. (2020), found organic carrots out yielded conventional in marketable quantity and quality when N was maintained at similar levels to conventional through the application of organic manure and compost. In a previous study by Bender et al. (2015), not maintaining N through use of manure produced yields were 8% lower than conventional systems, but conventional carrot showed more pesticides and nitrates in the harvested roots. Comparing organic and conventional management of carrot production in multi-environment trials with lifecycle impact assessment, Kowalczyk and Cupial (2020), also identified a lower environmental cost in organic production.

Weed management in carrot is particularly critical in organic production as herbicides are not allowed and growers rely on cultural methods including variety choice, mechanical cultivation, and hand weeding. In national surveys of US organic producers conducted by Organic Seed Alliance in 2010, 2014, and 2020, producers were asked to rank the most important crops and traits to breed for in organic systems (Dillon and Hubbard, 2011; Hubbard and Zystro, 2016; Hubbard et al., 2022). In all three surveys, organic carrot growers ranked breeding for weed competition and flavor as top priorities in carrot improvement. Carrot is notoriously slow in germination and canopy establishment extending the critical period of weed management compared with other horticultural crops (van Heemst, 1985; Peruzzi et al., 2007; Seaman, 2016; Colquhoun et al., 2017). This results in significant potential economic impacts of weed management in organic carrot production (Eddy, 2008). Calquhoun et al. (2018), noted the potential to breed for improved weed tolerance or weed competitiveness based on identification of differences in the ability of varieties to suppress weeds through rapid emergence and early establishment of the crop canopy. Previous studies also identified significant genetic variation in carrot shoot growth and morphology demonstrating the potential of breeding for improved weed tolerance and/or weed suppression (Turner, 2017). Carrot shoot morphology is influenced by both genetic and environmental effects, thus, understanding the genotype by environment interaction is key in developing breeding strategies (Grahn et al., 2018).

Disease management in organic carrot production is critical as growers rely on cultural practices such as variety resistance since application of synthetic crop protection chemicals is not allowed. Genetic differences in resistance are well documented for pathogenic nematodes as well as carrot leaf blight (caused by *Alternaria dauci*), a key foliar pathogen in organic carrot production (Simon and Strandberg, 1998; Gugino et al., 2007; Parsons et al., 2015; Que et al., 2019). Organic carrot producers in the US ranked carrot leaf blight as a top production challenge and breeding priority (Simon et al., 2017). *A. dauci* is widespread throughout the US and Europe, most prevalent on older leaves, and occurs in regions with high humidity in mid to late summer (Davis and Raid, 2002). It is the most common leaf blight in carrot in the Midwest region of the US where two of the environments in the current study are located. Microbiome research conducted under the CIOA project indicates that carrot genotypes that differ in resistance to *A. dauci* and pathogenic nematodes host different microbiomes (Abdelrazek et al., 2020a; Abdelrazek et al., 2020b; Meija, 2020). Abdelrazek et al. also demonstrated that carrot genotypes differ in tolerance to *A. dauci* when inoculated with individual microbial isolates that can produce antifungal compounds against this pathogen (Abdelrazek et al., 2020a).

Orange carrots for fresh market and processing comprise most of the market, but sales of novel-colored carrots (purple, red, yellow, and multi-colored) is on the rise as organic consumers seek unique, visually attractive, and nutritious varieties. The genetic background of these types however often lacks adaptation to US environments as the centers of origin and development are in other regions of the world. Assessing the environmental influence on performance and genetic variance of novel-colored carrot types may aid in improving adaptation of these novel types for production in the US.

Goals of the current study

The aim of the current study is to explore the role of genetic and environmental influences on carrot performance to inform classical and participatory breeding strategies for improving carrot performance for organic systems. To achieve this research objective, we analyzed multi-environment trials, comparing total root yield and top growth traits for a wide range of genotypes under organic and conventional management systems in two states, Indiana (IN) and Wisconsin (WI), from 2012-2015. This study addressed key research questions including (i) do carrot varieties perform differently under organic and conventional management systems or under different locations in the Midwest US, (ii) does the ranking of varieties differ between organic and conventional conditions, (iii) does the heritability for root yield or top growth differ under organic and conventional conditions or between locations, (iv) do varieties differ in stability and adaptation to high or low yielding environments?

Materials and methods

Plant materials

Entries of thirty-six carrot genotypes including commercially available F1-hybrid varieties, open-pollinated (OP) varieties, and breeding lines from the United States Department of Agriculture/ Agricultural Research Service (USDA/ARS) carrot breeding program (see Table 1.) were evaluated in field trials. The term “variety” is used to describe each genotype throughout this study, however entries included commercially available varieties as well as non-released, un-named breeding lines from the USDA. USDA lines are indicated by letters and numbers in table 1. Entries included orange, red, purple and yellow phenotypes. Entries were selected to represent a wide diversity of genotypes and origins including different market classes such as Danvers, Nantes, Imperator, and Chantenay types. In three instances, different varieties were used in years 1 and 2 and then changed for varieties with a similar class, color and ideotype in years 3 and 4 due to seed shortages. In these cases, the names of entries are indicated under variety name in Table 1, separated with a forward slash (/). Consistent seed lots were included in all trial sites and years by variety.

Table 1. Genotypes included in multi-environment trials of carrot conducted in Indiana and Wisconsin from 2012-2015 managed under organic and conventional practices.

Entry number	Variety Name	Type[1]	Primary Color	Market class	Seed Source[2]
1	B 0114	USDA	Purple	Danvers	USDA
2	B 0191	USDA	Purple	Danvers	USDA
3	B 0252	USDA	Purple	Danvers	USDA
4	Karotan	OP	Orange	Danvers	USDA
5	B 1129	USDA	Purple	Danvers/Imperator	USDA
6	B 6220	USDA	Red	Nantes	USDA
7	B 6306	USDA	Purple	Danvers	USDA
8	B 6637	USDA	Red	Nantes	USDA
9	B 8519	USDA	Yellow	Imperator	USDA
10	B 9244	USDA	Yellow	Nantes	USDA
11	B 3999	USDA	Orange	Nantes	USDA
12	B 4001	USDA	Orange	Imperator	USDA
13	B 4002	USDA	Orange	Imperator	USDA
14	B 8483	USDA	Orange	Nantes	USDA
15	B 8503	USDA	Orange	Imperator	USDA
16	B 8524	USDA	Orange	Imperator	Nunhems
17	B 8542	USDA	Orange	Imperator	USDA
18	GKX / Purple Haze	OP	Purple	Imperator	unknown
19	Gold King	OP	Orange	Chantenay	Rogers/Northrup King
20	Homs	OP	Purple	Danvers	USDA
21	Ping Ding	OP	Purple	Chantenay	USDA
22	Scarlet Fancy X Favourite	OP	Orange	Nantes	USDA
23	Brasilia	OP	Orange	Nantes	Embrapa
24	Red Core Chantenay	OP	Orange	Chantenay	OSA

25	Rumba	OP	Orange	Nantes	OSA
26	Midori Yellow / Yellowstone	OP	Yellow	Imperator	OSA
27	Synthetic 11/ Creampak	F1	Yellow	Imperator	OSA
28	Hilmar	OP	Orange	Nantes	OSA
29	Spring Market	OP	Orange	Nantes	OSA
30	Bolero	F1	Orange	Nantes	OSA
31	UpperCut	F1	Orange	Imperator	Nunhems
32	Sun 255	F1	Orange	Imperator	Nunhems
33	SugarSnax	F1	Orange	Imperator	Nunhems
34	Napoli	F1	Orange	Nantes	Bejo
35	Nelson	F1	Orange	Nantes	Bejo
36	Western Red	OP	Orange	Imperator	OSA

[1]F1 indicates a hybrid (F1) variety, OP indicates an open-pollinated variety, and USDA indicates a breeding line from the USDA/ ARS carrot breeding program at University of Wisconsin-Madison.
[2]OSA = Organic Seed Alliance

Market classes refer to the shape of the carrot and are developed for different market uses (Geoffriau, 2021). Nantes types are cylindrical with a blunt tip and commonly marketed fresh as bunching carrots (tops collected in a bunch). Imperator types are long and cylindrical, bred for fresh market grocery sales in cellophane (cello) packs or for cut and peel “baby” carrot market. Danvers are bred for processing as a diced carrot and have a broader shoulder gradually tapering to the tip. Chantenay is a relatively large carrot and even broader shouldered than Danvers. It is bred for early season fresh eating and for processing.

Field trial locations and management

Trial locations included paired organic and conventional fields in Wisconsin (WI) and Indiana (IN) conducted across four years (2012-2015). Researchers at each location identified organic and conventional trial sites within consistent conditions, including soil types to aid in comparison of the influence of organic and conventional management and to minimize the underlying variations in soil type or microclimatic differences in specific field locations. Weather patterns in both locations resulted in extreme drought in 2012 followed by relatively “normal” annual precipitation and temperatures in 2013-2015. Supplemental irrigation was provided by drip tape in both locations as needed. In both locations annual trials were planted at the end of May to early June and harvested the second or third week of September resulting in approximately 105-115 days from seed to harvest.

All trials in IN were conducted at Purdue's Meigs Horticultural Research Farm (40.28917°N, 86.88389°), located approximately 10 miles south of Lafayette, IN. Soil at this site is classified as a Toronto-Millbrook complex, 0-2% slope with a fine, silty texture and 3-5% organic matter. The mean annual precipitation at this site is 1,008 mm, and summer temperatures range from 21.1 to 26.7°C. The research farm includes fields using either organic or conventional farming practices since 2001. In both systems fertilizers were applied to achieve a target rate of 134.5, 180 and 224 kg ha-1 of N, P and K respectively. In the organic plots, this consisted of Re-vita Pro Compost (Ohio Earth Foods, Hartville, OH), applied at a rate of 5,380 kg ha-1 to meet fertility needs, assuming 50% of the nutrients would be available for plant uptake in the year of application. In the conventional plots, diammonium phosphate (18- 46-0) and potash (0-0-60) were applied to meet fertility needs. In the conventionally managed system, a pre-emergent herbicide (Prowl H2O, BASF Corporation) was applied immediately after planting. In the organically managed system, plots were hand weeded as needed. No additional pesticides were applied in either crop management system after emergence. The previous year's crop rotation in organic field was various cover crop mixes. The previous crop in conventional each year was soybean with winter fallow. In 2013 an accidental herbicide spray on the conventional field resulted in loss of root and top growth harvestable yield. Early and mid-season top growth measurements were recorded prior to the incident, but root and top weights at harvest were not included in the data set due to unrepresentative harvest yields.

All trials in WI were conducted at the USDA-ARS West Madison Vegetable Crop Research Unit (43.03422°N- 89.31541°W, approximately 10 miles west of Madison, WI. Soil at the organic field of this site is classified as Kegonsa Silt Loam and at the conventional field site Plano Silt Loam. Mean precipitation is 914mm and average summer temperatures range from 22 to 28°C. The organic fields at this site were first certified organic in 2008. They are managed as a mixed vegetable rotation with cover crops between vegetable crops. Fertilizer was applied as 3300-3700 kg ha-1 composted poultry manure and no pesticides were applied. Weed management included hand cultivation with stirrup hoes and hand weeding. The conventional field site was managed as a rotation between vegetable crops and corn with each carrot trial following corn in the previous year. Fertility applications included mineral fertilizers applied as 9-23-30 at 450kg ha-1; urea at 243kg ha-1; K2O at 347kg ha-1 (2013), urea 290 kg ha-1; 9-23-30 at 121kg ha-1 (2014), and 46-0-0 at 364kg ha-1; 9-23-30 at 295kg ha-1; and 0-0-60 at 353kg ha-1 (2015). Information on fertility inputs in 2012 was not available but assumed to be like other years. Herbicide application for weed management included linuron pre- and post-emergence at 1.7L ha-1 (59 oz /ha). Pesticides applied included Linex 4L at 2.3L ha-1 and Poast at 1.8L ha-1 post-emergence (2013), Prowl 2.3L ha-1 pre-emergence; Lorox 1.2kg ha-1 post-emergence (2014), and Prowl at 2.3L ha-1 pre-emerge; Lorox DF at 1.0kg ha-1 and Poast at 1.8L ha-1 post-emergence (2015). Irrigation in both systems was applied by drip tape.

Experimental design

Field trials included 36 carrot varieties arranged in a randomized complete block design with three replications in each experimental field site. Trials were conducted annually from 2012-2015 at trial sites that included locations in IN and WI. Each location included two trials per year, one managed with organic practices and one managed with conventional practices. Individual treatment plots were planted on raised beds, 1.8 m apart on center. Each plot was 1 m long and 1 m wide with four rows across the bed. The inside two rows consisted of trial entries (varieties) with the two outer rows planted to a standard variety across the field as boarder rows to minimize edge effects. To minimize foliar competition with the border rows the varieties Mokum or Napoli were planted as they typically have relatively average to short tops. In each plot, seeds were direct sown to provide approximately 60 plants m^{-1} per sub-plot to assure appropriate germination rates. Seeds were sown to a depth of 1 cm.

Data collection

Foliar measurements: The foliar height of each plot was taken at 35 days and 60 days after sowing and at harvest with a meter stick of three plants per plot in centimeters (cm). The three measurements per plot were taken on plants representative of the normal range of variation present within the plot. If plants or areas within the plot were abnormally large or stunted, these plants were not used for the measurements. Plant height measurements included carrot tops from soil to canopy height at three spots within the plot capturing the normal range of variation.

Harvest data collection: The week prior to harvest a count of the number of bolted plants was recorded and any bolted plants were removed from plots. At the time of harvest roots and tops were harvested with a digging fork. Each plot was photographed and then roots over 6 cm diameter were counted and recorded. The foliar tops were then snapped from the roots of counted carrots and the combined roots, and combined tops, for each plot and were weighed in grams separately on a per plot basis.

Soil analysis

Soil collection for analysis consisted of composite samples taken from 10-15 locations across each replication of the trial for a total of 3 samples per sampling event. Samples were collected on each of four sample dates: preplant (sample 1), approximately 30 days after sowing (sample 2), 60 days after sowing (sample 3) and at harvest (sample 4). On each of the four collection dates samples for analysis of abiotic properties were collected at a depth of 20 cm, dried and then shipped to Purdue University for analysis. On the 30-day sample period a second sample an additional second collected to a depth of 10 cm, immediately placed in a cooler, and shipped overnight with dry ice for analysis of biological properties. The preplant soil sample was subject to several assays associated with a standard soil fertility test according to common methods used in this region (Brown, 1998). Briefly, total soil organic matter (OM) was determined using loss of weight on ignition; available phosphorous (P) was extracted as Weak Bray (readily available P) and Strong Bray (potentially available P) and analyzed calorimetrically; exchangeable potassium (K), calcium (Ca), and magnesium (Mg) were extracted with neutral ammonium acetate (1 N) and quantified by inductively coupled argon plasma–mass spectrometry detection; and base saturation and cation exchange capacity [mmol (+)·kg−1] were estimated from the results of exchangeable minerals. Ammonium- (NH4+ -N) and nitrate/nitrite- (NOx-N) N concentration of all soil samples collected at preplant, 30day and 60days after sowing and harvest were determined calorimetrically after KCl extraction. Concentrations of NH4+ -N and NOx-N were combined and expressed as plant available N. Finally, the sample collected for biological properties was lyophilized and stored at −20, before subjecting the soils to a phospholipid fatty acid analysis (PLFA) using methods described in (Buyer and Sasser, 2012). An overview of the soil characteristics is given in Table 2.

Table 2. Biotic and abiotic soil characteristics from conventionally and organically managed research sites in Indiana and Wisconsin used to conduct carrot variety trials.

Location-Year	System	pH	P (ppm)	K (ppm)	Ca (ppm	Mg (ppm)	%OM	Total Microbial Biomass (mg/kg soil)	Microbial Diversity Index
IN-2012	Org	6.4	32/46	166	1940	326	2.27	1729	1.42
	Conv	6.0	27/50	174	1935	322	2.43	1761	1.21
IN-2013	Org	6.7	56/88	246	1721	269	2.27	1827	1.48
	Conv	5.7	49/76	214	1812	302	2.43	2001	1.49
IN-2014	Org	5.9	82/82	427	1909	308	2.80	1833	1.40
	Conv	5.6	96/204	360	2121	356	2.93	1656	1.38
IN-2015	Org	5.6	34/68	230	2790	426	3.07	2433	1.31
	Conv	6.0	71/81	256	1991	336	2.23	1588	1.29
WI-2012	Org	6.4	133/147	423	1870	497	3.6	2249	1.44
	Conv	7.2	107/140	367	1801	476	3.6	2802	1.40
WI-2013	Org	6.1	58/82	364	1847	511	3.17	2462	1.45
	Conv	6.1	62/77	299	1884	518	3.10	3079	1.59
WI-2014	Org	6.0	107/137	410	2070	552	3.63	3301	1.54
	Conv	7.3	66/90	308	2098	598	3.403.4	3942	1.63
WI-2015	Org	7.1	65/107	291	2100	547	3.20	2651	1.45
	Conv	6.8	120/116	401	1906	507	3.63	1853	1.27

N Availability

In Fig. 1 the total plant-available nitrogen (NH4+ + NOx) across growing season sampled at various time points in the carrot trials are presented.

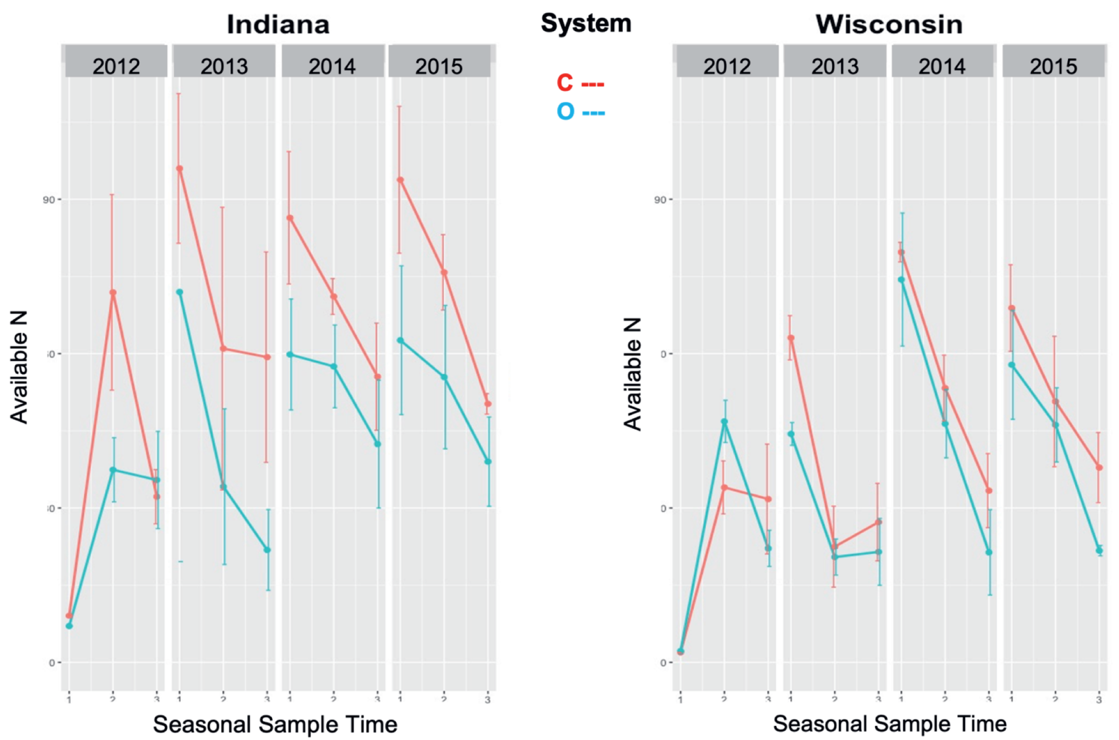


Figure 1. Total plant-available nitrogen (NH4+ + NOx-) across growing season sampled at preplant (sample time 1), post emergence, ~ 30 days after planting (sample time 2), and at harvest (sample time 4) in carrot trials in 16 environments including 2 locations (Indiana and Wisconsin), 4 years (2012-2015) and 2 management systems (organic and conventional).

Statistical analysis

All statistical analysis was conducted in the statistical environment and language R (R core team, 2021). Various analyzes involving linear mixed models used R packages lmerTest (Kuznetsova et al., 2017) and lme4 (Bates et al., 2015) in R. We first prepared the data by applying a linear model of the fitted data and residuals to identify and eliminate outliers greater than 3 times the inter-quartile range using the R package lme4.

A mixed model analysis of variance (ANOVA) was applied to assess variation in traits within and across environments. The informal model formula may be written as:

$$\begin{aligned} Response = {} & genotype + environment \\ & + genotype\ by\ environment\ interaction \\ & + replicate\ within\ environment + error \end{aligned}$$

The formal model is written as:

$$y_{ijk} = G_i + E_j + GE_{ij} + R_k(E_j) + e_{eijk}$$

where G_i = effect of genotype i, E = effect of environment j, R = effect of block k, and e_{ijk} = error

The environment term included year (Y), location (L), and management system (S) depending on the analysis with the most general model for analysis as,

$E_j = Y_k + L_l + S_m + Y_k \times L_l + Y_k \times S_m + L_l \times S_m + Y_k \times L_l \times S_m$ and $G_i \times E_j = G_i \times Y_k + G_i \times L_l + G_i \times S_m + G_i \times Y_k \times L_l + G_i \times Y_k \times S_m + G_i \times L_l \times S_m + G_i \times Y_k \times L_l \times S_m$

where G_i = effect of genotype i, E_j = effect of environment j, Y_k = effect of year k, L_l = effect of location l and S_m = effect of system m.

Where L is the effect of location, (IN and WI). Y is the effect of year (2012, 2013, 2014, and 2015. S is the effect of system (organic management and conventional management). The combination of L, Y and S defined individual trial fields with 16 trials total included in the analysis.

All random terms included in the analysis were assumed to be normally distributed with a common variance. To assess the main effects of G, Y, L, S and all two-way and higher-level interactions, we conducted a mixed model analysis of variance (ANOVA) with all terms as fixed effects and block as a random effect. Random effects are assumed as needed for calculating coefficient of variation. To aid in interpretation of analysis of variance and compare among traits, we additionally reported variance components as coefficients of variation, calculated as the standard deviation as a percentage of the trait mean. ANOVA and %CV used lme4 and LmerTest in R. This approach is similar to Renaud et al. (2014), and Lorenzana and Bernardo (2008), in comparing organic and conventional management systems in multi-environment trials. We assessed coefficients of variation within the location and management system separately with genotype and year as random effects in the model. The formula is expressed as:

$$\%CV = 100\sqrt{V}/\mu$$

Where V is the variance for a particular model term and μ is the trait mean.

We visually explored the relationship and interactions of genotypes, locations, and years by conducting analysis of additive main effects and multiplicative interactions (AMMI) using the R package Metan designed for evaluation of multi-environment trials (Olivoto, 2020).

To assess the potential for genetic gains from selection of various traits under different locations and systems we calculated the repeatability of traits (analogous to broad sense heritability [H^2] for unrelated genotypes) from the variance components. Broad sense heritability (H^2) is expressed as:

$$H^2 = V_G/(V_G + V_{GY}/nY + V_e/(n_Y \cdot n_R)$$

Where V_G = genetic variance, V_{GY} = genotype x year interaction, V_e = error variance, and n_Y and n_R = number of years and replications, respectively.

To compare direct and indirect selection strategies for organic production systems we assessed the correlated response between organic and conventional management systems within each region across years. In other words, we wanted to determine if selection under conventional management may be as effective or more effective than selection within organic management systems for the targeted traits when the goal is to breed for improved performance in organic systems. A correlated response ratio of less than 1 indicates that it is preferable to select within organic conditions for improved performance in organic systems than selecting in conventional conditions for organic systems. The theory and statistical procedures are described by Falconer and Mackay (1996). Correlated Response (CR) is expressed as:

$$CR/DR = r_G(h_C/h_O)$$

Where r_G = the genetic correlation between organic and conventional and H_C and H_O are the ratio of the square roots of conventional and organic broad sense heritability (H^2).

We calculated genotypic means for each management system by location combination across years to compare the differences in response. Means were calculated using the lsmeans package in R (Lenth, 2016).

To assess the correlations of responses between organic and conventional systems we conducted Spearman's rank correlations for each location-year combination, as well as for each location across years. In addition, we analyzed the rank correlation of subsets of genotypes (cultivars) by cultivar type including F1 hybrids, open-pollinated cultivars (OP's) and USDA breeding lines.

Spearman's rank correlation coefficient (R_S) was calculated using the following equation:

$$\rho = 1 - \frac{6\sum d_i^2}{n\left(n^2 - 1\right)}$$

where d^2 is the difference in rank change of each genotype squared and summed for all 35 genotypes and n is the number of genotypes. Statistical significance was assessed at the alpha=0.05 probability level unless otherwise stated.

To study the stability (or adaptability) of varieties for each response trait across environments (years and locations) we conducted a regression of each variety against an environmental index calculated as the mean of all varieties in all environments as described by Finlay and Wilkinson (1963). The resulting slope is calculated as the regression coefficient β and interpreted on the scale of the environmental index.

The linear model is as follows:

$$Y_{ijk} = \mu + G_i + (1 + \beta)\hat{E}_j + \varepsilon_{ijk}$$

where y_{ijk} denotes the response variable, for the i^{th} genotype, j^{th} environment, and k^{th} replicate in the environment, G_i is the i^{th} genotype (variety) studied, and $\hat{E}_j$ is the j^{th} environment, for example, a combination of year, location and system of management.

To study the stability (or adaptability) of varieties for each response trait across environments (years and locations) we conducted a regression of each variety against an environmental index calculated as the mean of all varieties in all environments as described by Finlay and Wilkinson (1963). The resulting slope β is interpreted on the scale of the environmental index. Interpretation of the slope varies in the literature, intermixing stability and adaptability (Lyon et al., 2019). Hypothesis tests calculate p-values as two-sided tests with the null hypothesis of $\beta=1$. A slope near 0 indicates a lack of response to environment and consistent performance across environments, defined as "stable" by Finlay and Wilkinson (1963). A slope of 1 indicates the variety performs like the average performance across the environmental index in terms of presenting higher response rates in more favorable environments and lower response rates in less favorable environments, for example favorable nutrient, water, and temperature conditions. In the current study we are interested in better understanding the potential to breed for organic environments, which are often characterized as lower yielding. As such we interpret the slope, as described by other researchers with similar goals (Hildebrand and Russel, 1996; Lyon et al., 2019; Ceccarelli and Grando, 2022), with the aim of assessing the specific adaptation to high or low yielding environments. It this case, in addition to identifying broad adaptation as varieties that respond similar the mean performance across environments (slope = 1) we explore if slopes are significantly different than 1, indicating potential adaptation to high or low yielding environments. In cases of specific adaptation, the slope may be greater than or less than 1 depending on the relation to the environmental index and targeted environment for breeding (Hildebrand and Russel, 1996; Ceccarelli and Grando, 2022).

Results

Analysis of variance

Table 3. Analysis of variance for horticultural traits of carrot genotypes in two regions (WI and IN) in two management systems (organic and conventional) across four years (2012-2015). F-values, and levels of significance are reported.

	Harvest Root weight (g)	Harvest Top weight (g)	Early top height (cm)	Early top width (cm)	Mid-season top height (cm)	Mid-season top width (cm)	Harvest top height (cm)	Harvest top width (cm)
Year	2.21 ns	1.93 ns	15.97 *	2.60 ns	17.71 ns	32.84 *	4.50 ns	2.24 ns
Location	5.98 ns	0.08 ns	17.40 *	6.23 ns	2.42 ns	8.50 ns	7.40 ns	0.00 ns
System	0.91 ns	0.24 ns	1.54 ns	0.22 ns	3.35 ns	10.88 ns	0.83 ns	0.01 ns
Genotype	43.88 ***	62.86 ***	21.85 ***	18.99 ***	21.94 ***	23.32 ***	32.66 ***	30.83 ***
Year x Location	3.44 ns	0.14 ns	14.62 *	6.71 ns	15.01 ns	43.65 *	2.08 ns	0.08 ns
Year x System	1.05 ns	1.09 ns	2.15 ns	0.51 ns	5.77 ns	18.37 ns	1.45 ns	0.60 ns
Location x System	5.26 ns	3.49 ns	1.13 ns	0.09 ns	1.23 ns	14.03 ns	1.71 ns	0.73 ns
Year x Genotype	3.87 ***	4.11 ***	2.73 ***	2.74 ***	3.20 ***	2.79 ***	3.28 ***	3.25 ***
Location x Genotype	2.18 ***	2.31 ***	1.08 ns	1.83 **	2.10 ns	2.33 ***	2.85 ***	1.33 ns
System X Genotype	1.36 ns	0.97 ns	1.53 *	1.31 ns	1.70 **	1.88 **	0.92	0.88 ns
Year x Location x Genotype	1.90 ***	1.91 ***	1.78 ***	1.52 **	1.29 ns	1.51 **	1.94 ***	1.20 ns
Year x System Genotype	1.36 *	1.73 ***	1.51 **	1.03 ns	1.64 ***	1.67 ***	0.98 ns	1.06 ns
Location x System x Genotype	1.86 **	2.77 ***	1.43 ns	2.14 ***	1.19 ns	2.13 ***	2.08 ***	1.70 **

*, **, *** Significance levels are indicated as p ≤ 0.05, 0.01, 0.001, respectively. No significance is indicated as ns.

The analysis, shown in Table 3, identified highly significant genotypic main effects ($p < 0.001$) and genotype by year interactions for all traits including harvest root and top weights as well as top height and width measured early season (~30 days after sowing), mid-season (60 days after sowing) and at time of harvest. Significant genotype by location interactions were identified for root weight and top weight as well as mid-season and harvest top height and early season and mid-season top width ($p \leq 0.01$). Genotype by system interactions were only identified for early season top height, mid-season top height, and mid-season top-width. Higher order, three-way interactions that were significant included year × system × genotype for the traits root weight, top weight, early season top height, and mid-season top height and width. Significant interactions for location × system × genotype were identified for root weight, top weight, early-season, mid-season and harvest top width as well as harvest top height.

3

Coefficient of Variation

Table 4. Partitioning of variance components presented as coefficients of variance (%) for horticultural traits of 36 carrot varieties grown in two regions (WI and IN) and 2 paired management systems (organic and conventional) across four years (2012-2015).

	Wisconsin									
	Organic					Conventional				
	Year (Y)	Genotype (G)	Y × G	Y × Rep (R)	Res-idual	Year (Y)	Genotype (G)	Y × G	Y × Rep (R)	Res-idual
Root weight (g)	17	35	18	11	29	31	41	24	12	34
Top weight (g)	42	53	40	7	34	17	66	35	22	47
30-day top height (cm)	80	7	9	8	16	48	13	9	6	19
30-day top width (cm)	60	8	2	6	22	43	17	13	4	16
60-day top height (cm)	47	9	7	4	10	46	11	8	4	12
60-day top width (cm)	53	16	13	6	19	38	14	10	5	16
Harvest top height (cm)	21	14	8	3	15	13	16	15	13	16
Harvest top width (cm)	28	13	12	6	16	10	19	12	10	18
	Indiana									
	Organic					Conventional				
	Year (Y)	Genotype (G)	Y × G	Y × Rep (R)	Resi-dual	Year (Y)	Genotype (G)	Y × G	Y × Rep (R)	Res-idual
Root weight per plot (g)	50	58	47	35	69	35	34	29	10	5
Top weight (g)	82	115	91	40	124	44	61	55	22	53
30-day top height (cm)	13	16	9	10	21	4	12	12	9	27
30-day top width (cm)	13	19	13	10	24	13	13	10	9	23
60-day top height (cm)	10	13	6	9	18	28	11	8	8	13
60-day top width (cm)	24	18	8	11	22	27	17	12	9	22
Harvest top height (cm)	28	18	7	4	21	19	14	0	4	20
Harvest top width (cm)	40	23	11	5	28	22	18	9	2	22

Genetic variability seems to dominate root weight and top weight, while yearly variability seems to dominate top width/height traits, with a larger separation in the Wisconsin environments (Table 4). In nearly all locations and management systems root weight and top weight genotypic coefficient of variation was greater than the coefficient for variation by year or genotype by year interactions. The only exception was for root weight in conventional management in IN where year was higher than genotype by a narrow margin of 35% and 34% respectively. Top growth measured 30 and 60 days after planting showed very low variability across all locations/systems (%CV < 25). Response of top height and width at 30 days and 60 days in WI were 2-4 times greater for year than for genotype in both organic and conventional systems. Differences in coefficients for variation were variable and less pronounced between year and genotype in IN for these same response measurements with a range between 4% and 27% across response variables and systems. The coefficients for variation in the height of top growth and width at harvest were higher for year than genotype in IN, but in WI year was greater than genotype for organic, but genotype was greater than year for conventional.

Broad Sense Heritability and Correlated Response

Table 5. Broad sense heritability of organic and conventional management systems for various traits of carrot within two regions (Wisconsin and Indiana) followed by correlated response (CR) of selection in conventional for organic (C/O) and selection in organic for conventional (O/C).

	Wisconsin		Indiana	
	Organic	Conventional	Organic	Conventional
Harvest Root weight (g)	0.89	0.87	0.78	0.82
CR	C/O = 0.91	O/C = 0.92	C/O = 0.92	O/C = 0.87
Harvest Top weight (g)	0.93	0.95	0.90	0.87
CR	C/O = 0.97	O/C = 0.96	C/O = 0.89	O/C = 0.92
30-day top height (cm)	0.56	0.79	0.81	0.67
CR	C/O = 0.83	O/C = 0.59	C/O = 0.82	O/C = 0.94
30-day top width (cm)	0.58	0.82	0.80	0.70
CR	C/O = 0.87	O/C = 0.61	C/O = 0.78	O/C = 0.90
60-day top height (cm)	0.82	0.80	0.82	0.80
CR	C/O = 0.83	O/C = 0.85	C/O = 0.81	O/C = 0.83
60-day top width (cm)	0.78	0.81	0.85	0.80
CR	C/O = 0.82	O/C = 0.79	C/O = 0.79	O/C = 0.84
Harvest top height (cm)	0.81	0.78	0.90	0.89
CR	C/O = 0.79	O/C = 0.85	C/O = 0.87	O/C = 0.88
Harvest top width (cm)	0.75	0.86	0.85	0.84
CR	C/O = 0.86	O/C = 0.80	C/O = 0.88	O/C = 0.89

Broad sense heritability for all responses was relatively high (≥ 0.75) demonstrating a high potential for genetic gains through selection (Table 5). The exceptions included 30-day top height and width in WI under organic management, 0.56 and 0.58, respectively, and 30-day top height and width in IN under conventional management, 0.67 and 0.70, respectively. In all instances, including the responses for top height and width, the correlated response between organic and conventional was relatively high (≥ 0.75), though none were above 1.00. The converse also held true as the correlated response for selection in organic for conventional was similarly high with rates 0.80 and above except for 30-day top height and width in WI under organic management which was 0.59 and 0.61 respectively.

Management Systems Comparison of Response Means

Table 6. Means for horticultural traits for 36 carrot genotypes compared between organic and conventional management systems in 2 locations (Wisconsin and Indiana), assessed across 4 years.

Harvested root weight per plot (g)		
Location	System	Mean
Wisconsin	Organic	1813.63 a[1]
	Conventional	1305.21 b
Indiana	Organic	1106.17 a
	Conventional	1337.17 a

Harvested top weight per plot (g)		
Location	System	Mean
Wisconsin	Organic	633.01 a
	Conventional	398.20 b
Indiana	Organic	438.41 a
	Conventional	493.39 a

Average top height at harvest (cm)		
Location	System	Mean
Wisconsin	Organic	38.16 a
	Conventional	32.15 b
Indiana	Organic	41.93 a
	Conventional	42.00 a

Average top width at harvest (cm)		
Location	System	Mean
Wisconsin	Organic	49.97 a
	Conventional	44.09 a
Indiana	Organic	46.43 a
	Conventional	48.40 a

Average top height at ~ 30 days after planting (cm)		
Location	System	Mean
Wisconsin	Organic	22.24 a
	Conventional	18.57 b
Indiana	Organic	14.06 a
	Conventional	13.70 a

Average top width at ~ 30 days after planting (cm)		
Location	System	Mean
Wisconsin	Organic	16.17 a
	Conventional	15.62 a
Indiana	Organic	11.43 a
	Conventional	10.83 a

Average top height at ~ 60 days after planting (cm)		
Location	System	Mean
Wisconsin	Organic	31.21 a
	Conventional	31.09 a
Indiana	Organic	34.25 a
	Conventional	31.39 a

Average top width at ~ 60 days after planting (cm)		
Location	System	Mean
Wisconsin	Organic	32.88 a
	Conventional	30.54 b
Indiana	Organic	27.75 a
	Conventional	27.76 a

[1]Means separations are indicated as different letters at p-values ≤ 0.05

Overall, the mean response across years for root weight, top weight, 30-day top height, 60-day top width, and harvest top height were significantly different ($p \leq 0.05$) between organic and conventional management in WI with organic out-yielding conventional (Table 6). No differences were observed for 60-day top height or harvest top width in WI between systems. In IN, no differences in means for all response traits were observed between organic and conventional.

Spearman's Rank Correlation

Table 7. Spearman's rank correlation (RS) for carrot horticultural traits for crops grown under organic and conventional sites in Indiana (IN) and Wisconsin (WI) across four years (2012-2015).

	Harvest Root weight	Harvest Top weight	Early top height	Early top width	Mid-season top height	Mid-season top width	Harvest top height	Harvest top width
IN	0.90***	0.92***	0.86***	0.83***	0.85***	0.81***	0.86***	0.87***
WI	0.92***	0.94***	0.80***	0.73***	0.87***	0.81***	0.83***	0.83***

*** Significant at $P \leq 0.001$.

Table 8. Spearman's rank correlation (RS) for horticultural trait response 36 carrot genotypes (varieties) under organic and conventional management in Indiana (IN) and Wisconsin (WI) by year (2012-2015).

	Harvest Root weight	Harvest Top weight	Early top height	Early top width	Mid-season top height	Mid-season top width	Harvest top height	Harvest top width
IN 2012	0.85***	0.82***	0.66***	0.74***	0.79***	0.82***	0.77***	0.76***
IN 2013	NA	NA	0.28	0.36	0.16	0.37*	NA	NA
IN 2014	0.72***	0.79***	0.71***	0.74***	0.74***	0.68***	0.68***	0.60***
IN 2015	0.65***	0.79***	0.80***	0.62***	0.75***	0.58***	0.72***	0.74***
WI 2012	0.72***	0.72***	0.71***	0.76***	0.92***	0.86***	0.59***	0.38*
WI 2013	0.76***	0.78***	0.64***	NA[1]	NA	NA	0.63***	0.53***
WI 2014	0.86***	0.82***	0.69***	0.76***	0.79***	0.84***	0.47**	0.62***
WI 2015	0.88***	0.95***	0.18	0.27	0.29	0.34*	0.83***	0.87***

*, **, *** Significant at $P \leq 0.05$, 0.01, 0.001, respectively.

Positive genotypic rank correlations ($p \leq 0.001$) were found between organic and conventional in all regions when evaluated across all years by region (Table 7). We analyzed the rank correlations by year to better understand if there were differences by year (Table 8). Positive and significant rank correlations were found for most traits across years when analyzed by region and year ($p \leq 0.05$). The exceptions where significant rank correlations were not identified in the analysis for IN in 2013 for early top height, early top width, and mid-season top height. There were many instances however of differences in ranking of individual genotypes (varieties) between management systems within a location and year. For example, Figure 2 demonstrates rank changes for root weight in IN in 2012, a year and location in which environments were significantly correlated as indicated by Spearman's rank correlation (RS).

It is common in similar studies comparing the ranking of variety performance in organic and conventional systems to focus on the rank of the top 5-10 varieties to see if there are rank changes among the highest yielding. However, in the current study due to the wide diversity of genotypes and market classes there are likely greater yield differences due to market class, such as differences between a long imperator or a shorter Nantes, that are not indicative of optimum yield within market class since the two classes are bred for a different ideotype. Furthermore, there is a wide range of within-variety genetic diversity and previous selection intensity. For this reason, we assessed the different types (subclasses) including F1, OP and USDA lines as the information

3

provided would be more relevant about correlations between organic and conventional environments for the intent of informing breeding efforts. We therefore assessed the rank correlation by class category (F1, OP, and USDA) presented in Tables 9-11.

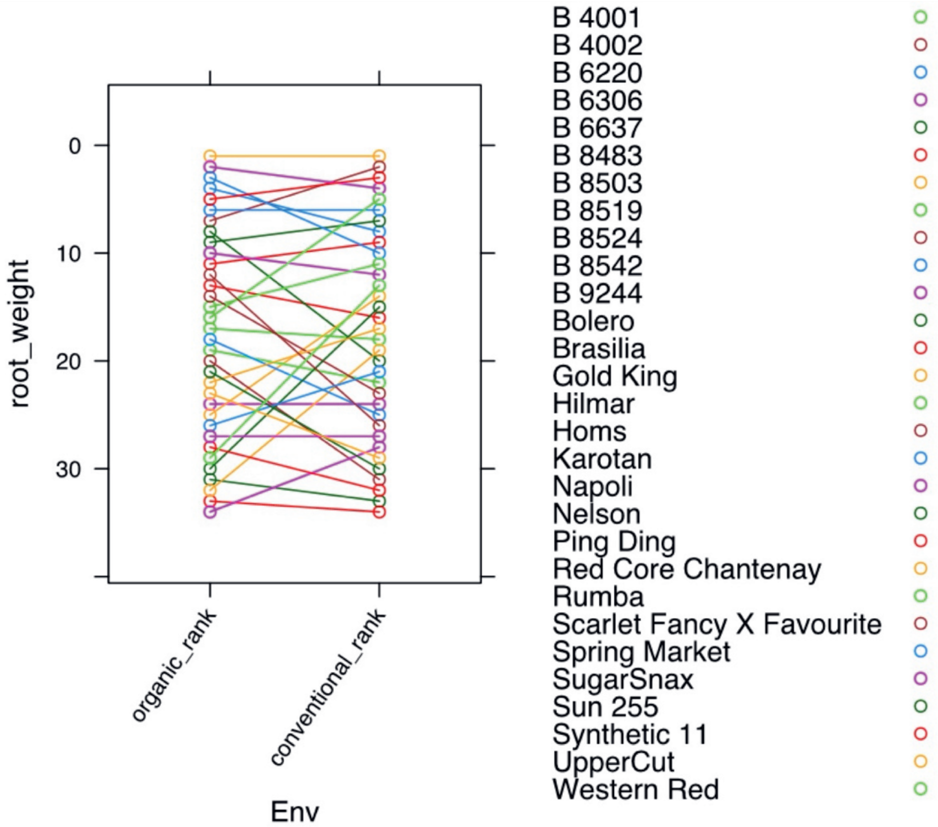


Figure 2. Ranking of carrot genotypes (varieties) for root weight (g) in organic and conventional management system environments (Env) in Indiana, 2012.

Table 9. Spearman's rank correlation (RS) for horticultural trait response of seven F1 hybrid carrot varieties grown under organic and conventional management in Indiana (IN) and Wisconsin (WI) across 4 years (2012-2015).

	Harvest Root weight	Harvest Top weight	Early top height	Early top width	Mid-season top height	Mid-season top width	Harvest top height	Harvest top width
IN 2012	0.77	0.89*	0.37	0.94**	0.46	0.71	0.83*	(0.11)
IN 2013	NA	NA	0.54	0.94**	0.31	0.71	NA	NA
IN 2014	0.60	0.77	0.52	(0.26)	0.90*	0.60	0.71	0.60
IN 2015	0.89*	0.94**	0.43	0.60	0.54	0.43	0.60	0.89*
WI 2012	(0.14)	0.83*	0.77	0.49	0.89	0.94**	0.03	-0.03

WI 2013	0.60	0.61	0.02	NA	NA	NA	0.77	-0.14
WI 2014	0.37	0.83*	0.38	0.77	0.66	0.77	0.84*	0.49
WI 2015	0.37	0.94**	(0.14)	0.26	0.84*	(0.60)	0.54	0.94**

*, **, *** Significant at P ≤ 0.05, 0.01, 0.001, respectively. Negative RS are indicated with parenthesis.

Analysis of F1 hybrid varieties reveals production systems were not correlated for most traits and years. Root weight was only correlated in one year in IN (RS 0.89, p ≤ 0.01). Although top weight was correlated in all years and locations except for IN 2014 and WI 2013. Early top height was not correlated in any years or locations and even has a negative RS (-0.14) in WI 2015. For top growth measurements significant correlations were identified in select years and locations, but were only significant in 9 out of 46 combinations of years × location including early top width in IN 2012 and 2013 (RS 0.94 and 0.94 respectively, p ≤ 0.001), mid-season top height in IN 2014 and WI 2015 (RS 0.90 and 0.84 respectively, p ≤ 0.05), mid-season top width WI 2012 (RS 0.94, p ≤ 0.01), harvest top height IN 2012 and WI 2014 (RS 0.83 and 0.84 respectively, p ≤ 0.05), and harvest top width IN 2015 and WI 2015 (RS 0.89 and 0.94 respectively, p ≤ 0.05 and 0.01 respectively). None of these instances of significant correlation between organic and conventional for top growth responses present clear patterns in terms of the consistency of significance for the given year and location (trial event), i.e. responses were identified for select traits, but not all traits in the same trial year × location.

Table 10. Spearman's rank correlation (RS) for horticultural trait response of thirteen open-pollinated (OP) carrot varieties grown under organic and conventional management in Indiana (IN) and Wisconsin (WI) across 4 years (2012-2015).

	Harvest Root weight	Harvest Top weight	Early top height	Early top width	Mid-season top height	Mid-season top width	Harvest top height	Harvest top width
IN 2012	0.82***	0.73**	0.63*	0.76**	(0.89)***	0.76**	0.61*	0.83***
IN 2013	NA	NA	0.42	0.15	(0.03)	0.55*	NA	NA
IN 2014	0.82***	0.93***	0.80***	0.89***	0.69**	0.78***	0.56	0.33
IN 2015	0.35	0.87***	0.75**	0.51	0.75**	0.55*	0.67**	0.77**
WI 2012	0.38	0.36	0.50	0.61*	0.79**	0.83***	0.66*	0.03
WI 2013	0.70*	0.87***	0.50	NA	NA	NA	0.80***	0.36
WI 2014	0.69*	0.85***	0.65*	0.54	0.86***	0.74**	0.55*	0.58*
WI 2015	0.87***	0.94**	0.02	(0.01)	0.56*	0.60*	0.92***	0.91***

*, **, *** Significant at P ≤ 0.05, 0.01, 0.001, respectively. Negative RS are indicated with parenthesis.

In comparison with the results of correlations for F1 hybrid varieties (Table 9), open-pollinated (OP) varieties presented more instances of correlation between management systems in given locations and years (Table 10), though results varied by year and location across all response traits. Significant correlations were found in IN 2012 for all responses, yet in IN 2013 top growth measurements for early top height and width and mid-season top height were not correlated, as reflected in the overall correlations of all genotypes across years and locations (Table 8). As both locations experienced drought in 2012 it is interesting to note that the highly significant correlations for root weight and top weight between management systems in IN was not observed in WI where no correlations were identified for either root weight or top weight.

Table 11. Spearman's rank correlation (RS) for horticultural trait response of sixteen USDA carrot varieties (breeding lines) grown under organic and conventional management in Indiana (IN) and Wisconsin (WI) across 4 years (2012-2015).

	Harvest Root weight	Harvest Top weight	Early top height	Early top width	Mid-season top height	Mid-season top width	Harvest top height	Harvest top width
IN 2012	0.74**	0.74**	0.76***	0.67**	0.70**	0.67**	0.86***	0.75***
IN 2013	NA	NA	(0.70)	0.26	0.06	0.15	NA	NA
IN 2014	0.19	0.55*	0.75***	0.80***	0.84***	0.62*	0.77***	0.74**
IN 2015	0.60*	0.67**	0.82***	0.61*	0.75***	0.79***	0.79***	0.71**
WI 2012	0.80***	0.84***	0.88***	0.86***	0.95***	0.83***	0.68**	0.71**
WI 2013	0.71**	0.69**	0.77***	NA	NA	NA	0.61*	0.71**
WI 2014	0.71**	0.78***	0.80***	0.86***	0.79***	0.90***	0.44	0.73**
WI 2015	0.68**	0.93***	0.23	0.39	0.16	0.53*	0.65**	0.69**

*, **, *** Significant at $P \leq 0.05, 0.01, 0.001$, respectively. Negative RS are indicated with parenthesis.

Analysis of the USDA breeding lines presents significant correlations between management systems for most response traits in most years, (Table 11). The lack of correlation in IN 2013 for top growth traits again reflects the lack of correlation for this year and location across all genotypes (Table 8). The other instances of a lack of correlation are limited to IN 2014 for root weight, WI 2014 harvest top height, and WI 2015 early top height, early top width, and mid-season top height.

Stability Analysis

The stability analysis provided insights into the relative stability or adaptability of 36 carrot genotypes (varieties) across environments. Figures 3a and 3b provide a visual of the performance of harvest root weight (g) and harvest top weight (g) in organic and conventional systems compared with the environmental index of all varieties across all environments. Figures of additional horticultural traits are presented in supplemental materials. In the case of response of root weight and top weight some varieties demonstrated consistent performance along the environmental index in both organic and conventional systems, while other varieties presented slopes significantly different from 1 in either or both management systems.

Red Core Chantenay and Western Red demonstrated adaptation to high yielding environments for root weight (g) (β=2.26, $p \leq 0.01$ and β=2.06, $p \leq 0.05$, respectively) and top weight (g) (β=3.28, $p \leq 0.001$ and β=2.80, $p \leq 0.05$, respectively) under conventional management, but not organic. Midori Yellow demonstrated significant adaptation to high yielding environments for root weight in conventional (β=1.83, $p \leq 0.05$), but not organic, and top weight in organic (β = 2.8, $p \leq 0.05$). Karotan and Synthetic 11, on the other hand, demonstrated significance for top weight adaptation under organic management, but not conventional (β=1.92, $p \leq 0.001$ and β = 1.89, $p \leq 0.05$, respectively). Bolero, a standard variety of organic producers, developed in and for conventional systems, performed consistently above the mean and was stable for root weight in both systems and was close to the mean for top weight in both systems demonstrating relatively broad adaptation to both systems.

Several USDA breeding lines had response slopes significantly less than one for root weight and top weight and yields below the average variety performance as indicated by the positioning of slope relative to the slope of the environmental index. Those with lower root weights and slopes included B6220 in conventional (β=0.53, $p \leq 0.05$, B6306 in conventional (β=0.45 $p \leq 0.01$) and organic (β=0.40 $p \leq 0.01$) , B8483 in conventional (β=0.48, $p \leq 0.05$), B3999 in conventional (β=0.39, $p \leq 0.001$) and B4001 in conventional (β=0.32, $p \leq 0.01$) and organic (β=0.57, $p \leq 0.01$) as well as Homs, a historic variety frequently used in the USDA breeding program, in conventional (β=0.01., $p \leq 0.001$) and organic (β=0.50, $p \leq 0.05$). Low yields and significantly lower slopes were found for top weight in both organic and conventional USDA lines including B0114 (conventional β=0.38, $p \leq 0.01$, organic β=0.50, $p \leq 0.05$), B0252 (conventional β=0.63, p ≤ 0.05; organic β=0.20, p ≤ 0.001), B3999 (conventional β=0.54, p ≤ 0.001; organic β=0.29, p ≤ 0.001), B8483 (conventional β=0.32, p ≤ 0.001; organic β=0.56, p ≤ 0.001) and B8542 (conventional β=0.34, p ≤ 0.001; organic β=0.42, p ≤ 0.001). The low yields in these genotypes, and low response to favorable environments may reflect that the USDA program has selected each line for specific traits of value, such as disease resistance or flavor for example, but not for overall yield performance.

Top growth responses across the season demonstrated variable adaptability of genotypes to high and low yielding environments. Several varieties presented positive slopes in organic systems for early top height including Red Core Chantenay, Midori Yellow, Synthetic 11, B8519 and B0191 with slopes of β=1.34, 1.21, 1.29, 1.22 and 1.20, respectively (p≤0.05). Bolero had a negative slope in organic (β-0.84, p≤0.05) that was above the environmental mean in low yielding environments and below the mean in high yielding environments with a slope above the mean across environments in conventional. Brasilia, performed above the mean environmental index in both systems with a positive slope in conventional (β=1.33, p≤0.01). Differences between genotypes was less pronounced for early top width with most genotypes tracking across the environmental mean in both systems. The exceptions included several varieties with slopes less than 1 in conventional including B1129, B6306, B8483, B9244 and Scarlet Fancy Favorite (β=0.68, 0.72, 0.69, 0.62, 0.67 respectively, p≤0.05). In conventional systems, Ping Ding, Brasilia, Bolero, and Synthetic 11 presented yields above the mean across environments while GKX had yield performance below the mean in low yielding environments and above the mean in high yielding environments (β=1.60, p≤0.001).

Mid-season top growth responses (height and width) tended to track the mean for most varieties. For mid-season top height only a few had slopes significantly different than zero with cross over between management systems including slopes lower than 1 for B6637 and B8483 (β=0.57 and 0.75, respectively, ≤0.05) and positive slopes in conventional for Synthetic 11 and Western Red (β=1.29 and 1.46, respectively, ≤0.05). Mid-season top width demonstrated a cross over between organic and conventional systems for several varieties including B0114, B0191, B0252, B8483, B3999, GKX, Homs, Uppercut, and Western Red indicating differential adaptation patterns between the two management systems. Response of both harvest top height and width presented consistently below the mean for several USDA varieties in both systems including B3999, B4001, B8483, and B8542. Several varieties demonstrated a cross over effect between organic and conventional systems with conventional yields lower than organic in low yielding environments and higher in high yielding environments for B6637, B3999, GKX, Homs, Ping Ding, Scarlet Fancy Favorite and Western Red. The opposite cross over pattern (i.e. organic mean above conventional in high yielding environments) was seen for Gold King, Brasilia, Red Core Chantenay, and Synthetic 11.

The following pages present figures of results of for adaptability analysis (Finlay Wilkinson linear regression) for root weight and top weight. Figures presenting results for additional horticultural traits are presented in supplemental materials at the end of this chapter.

Figure 3. (*Presented on following page*) Finlay Wilkinson linear regression of mean root weight of 36 varieties (genotypes) (G) of carrot in organic and conventional systems plotted against the environmental index of mean response across all genotypes under across 16 environments (E) including four years (2012-2015), two locations (IN and WI) and 2 management systems (organic and conventional). A slope of 1 is indicated by the dashed line. Genotypes with slopes significantly different than 1 are indicated in the sub-plots of the figure as organic (Org) or conventional (Conv) followed by slope and significance level. Significance levels are indicated as *, **, *** $p \leq 0.05, 0.01, 0.001$, respectively

Figure 4. (*Presented on page after next*) Finlay Wilkinson linear regression of mean top weight of 36 genotypes (G) of carrot in organic and conventional systems plotted against the environmental index of mean response across all genotypes under across 16 environments (E) including four years (2012-2015), two locations (Indiana and Wisconsin) and 2 management systems (organic and conventional). Genotypes with slopes significantly different than 1 are indicated in the sub-plots of the figure as organic (Org) or conventional (Conv) followed by slope and significance level. Significance levels are indicated as *, **, *** $p \leq 0.05, 0.01, 0.001$, respectively.

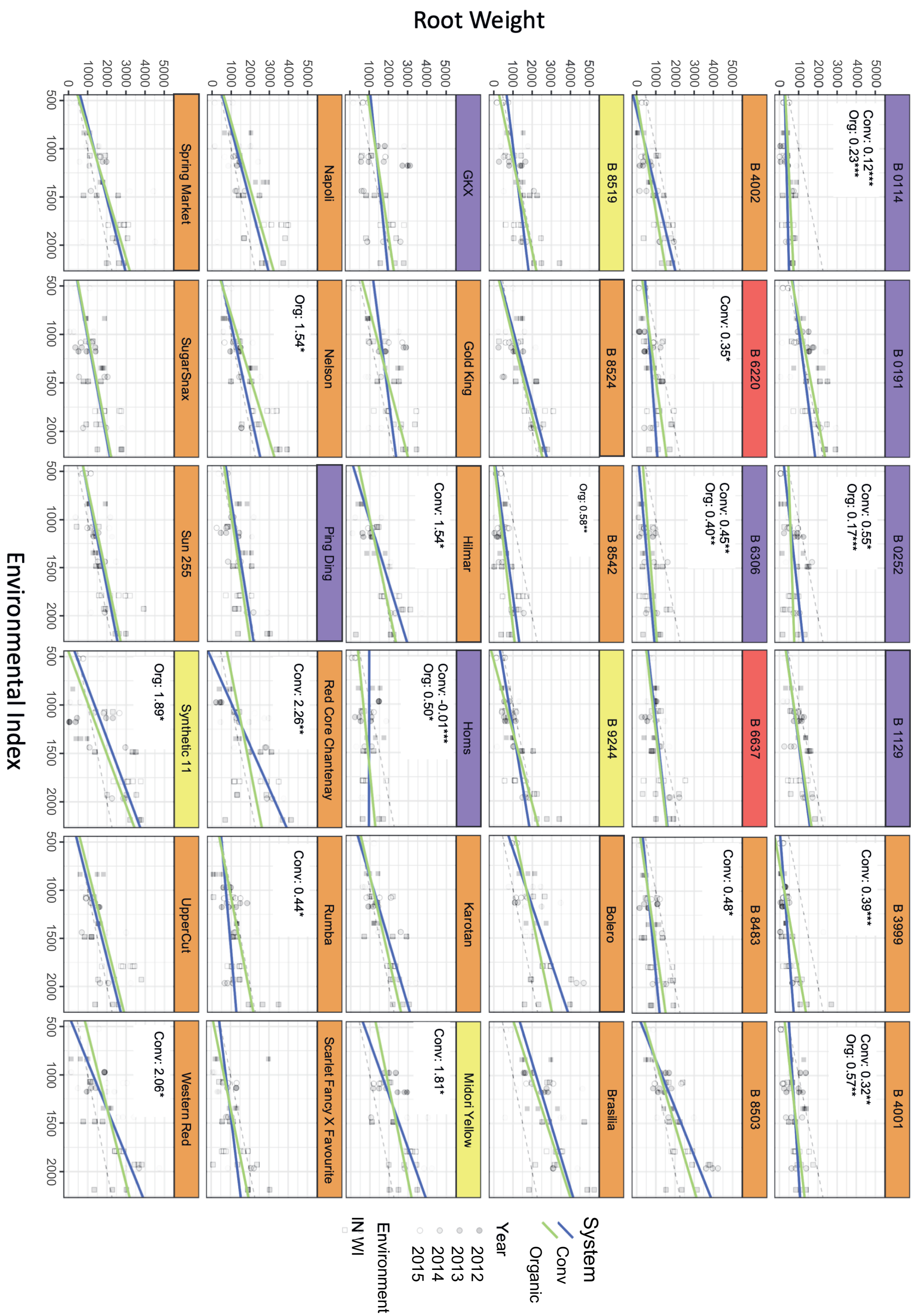


Figure 3. Finlay Wilkinson linear regression of mean root weight *(full description on previous page)*

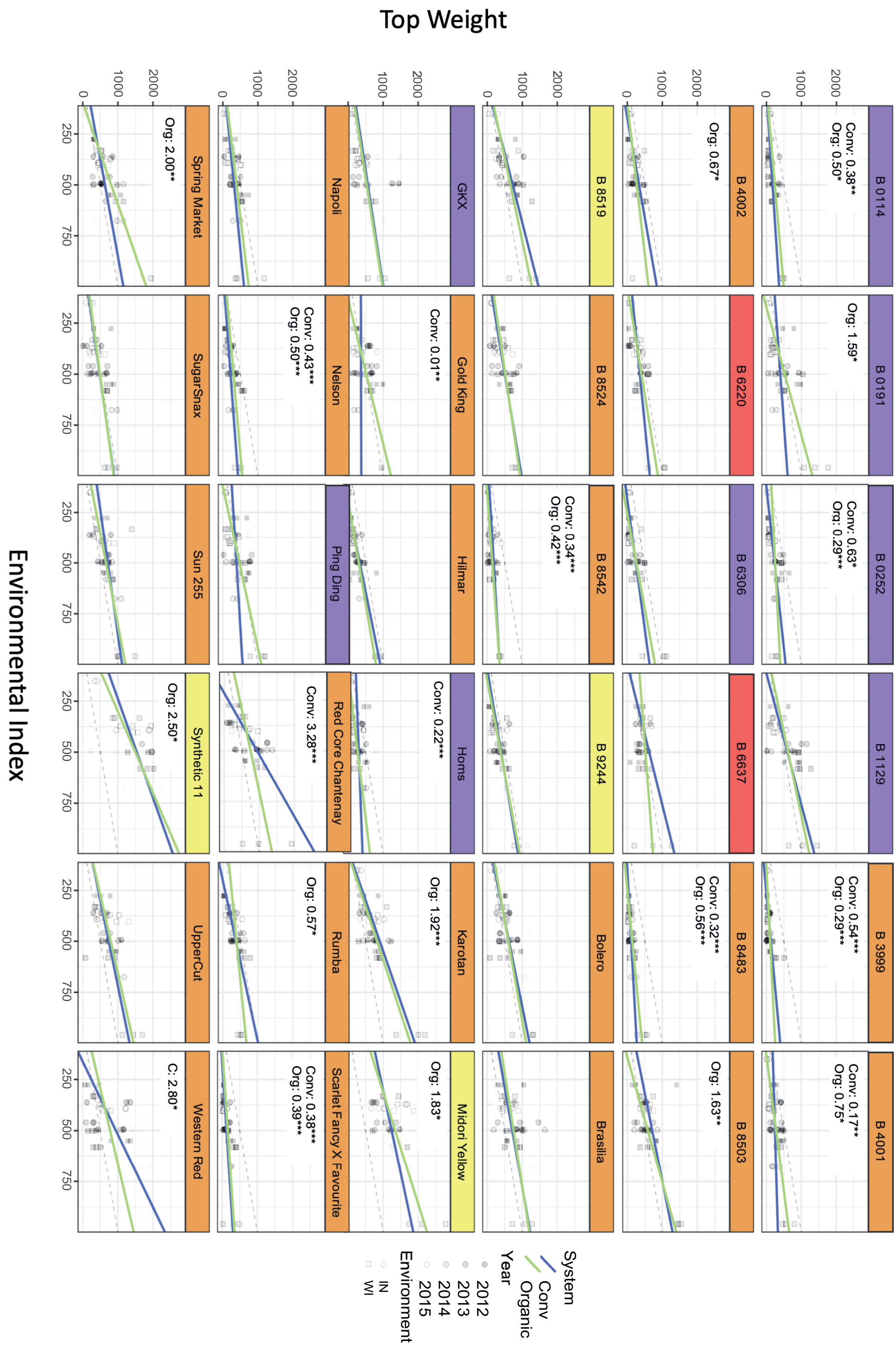


Figure 4. Finlay Wilkinson linear regression of mean top weight. (full described on page before previous page)

AMMI Analysis:

AMMI analysis provided a visual representation of the patterns of response for genotypes (G) and environments (E). AMMI analysis is commonly applied to multi-environment trials as the large number of genotype by environment interactions over years and locations can be challenging to interpret (Lyon et al., 2019). Results are presented in Figures 5(a, b), 6(a, b), 7(a, b), and 8(a, b) as AMMI2 biplot (PC1 vs PC2) for carrot horticultural traits of 36 genotypes (varieties) and 16 environments (E), 2 locations (IN and WI), 4 years (2012-2015) and 2 systems (organic and conventional).

Carrot genotypes are numbered as: 1=B0114, 2=B0191, 3=B0252, 4=Karotan, 5=B1129, 6=B6220, 7=B6306, 8=B6637, 9=B8519, 10=B92244A, 11=B3999, 12=B4001, 13=B4002, 14=B8483, 15=B8503, 16=B8524, 17=B8542, 18=GKX/Purple Haze, 19=Gold King, 20=Homs, 21=Ping Ding, 22=Scarlet Fancy Favorite, 23=Brasilia, 24=Red Core Chantenay, 25=Rumba, 26=Midori Yellow/ Yellowstone, 27=Synthetic 11/Creampak, 28=Hilmar, 29=Spring Market, 30=Bolero, 31=Upper Cut, 32=Sun 55, 33=Sugar Snax, 34=Napoli, 35=Nelson, 36=Western Red.

Figure 5A (Root Weight). AMMI biplot (PC1 vs PC2) for carrot root weight (g) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

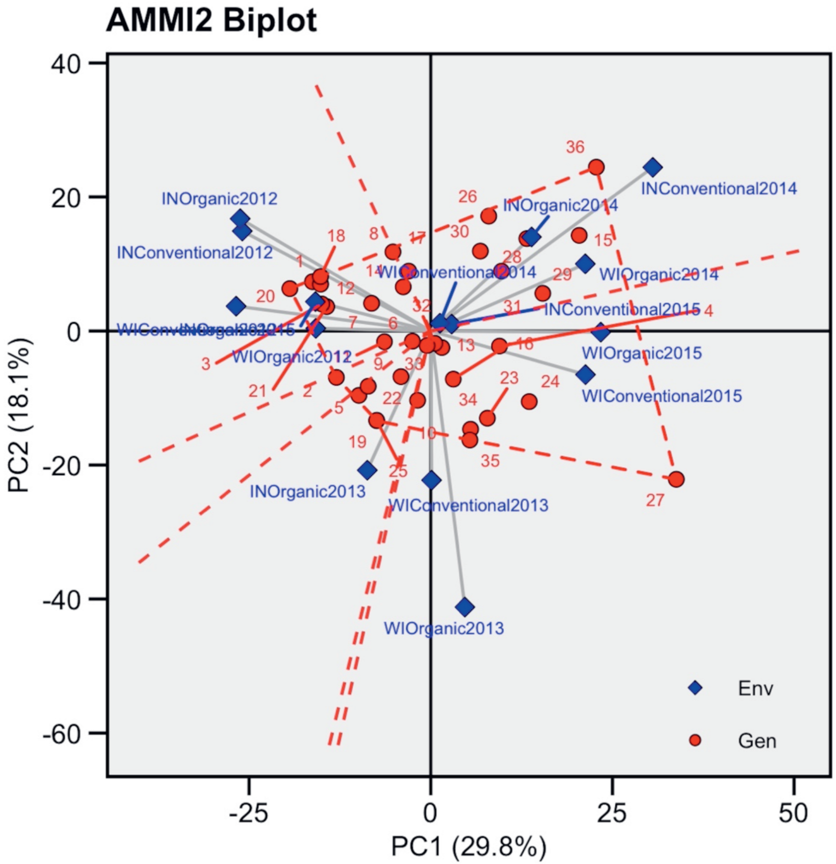


Figure 5B (Top Weight). AMMI biplot (PC1 vs PC2) for carrot top weight (g) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

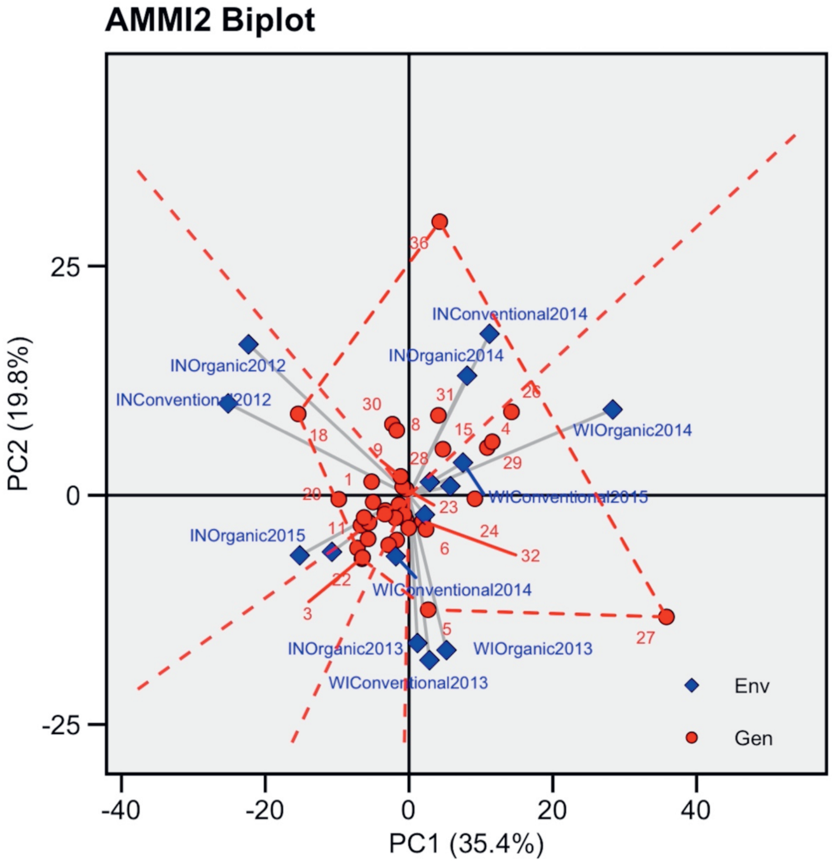


Figure 6A (Early Top Height). AMMI biplot (PC1 vs PC2) for carrot early top height (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

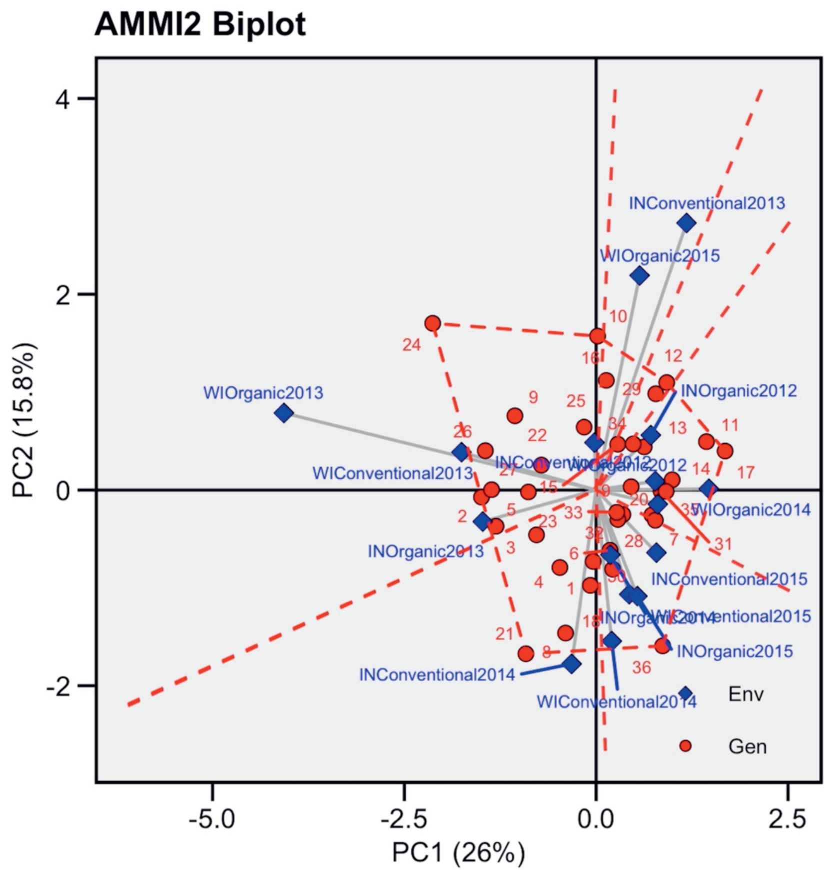


Figure 6B (Early Top Width). AMMI biplot (PC1 vs PC2) for carrot early top width (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

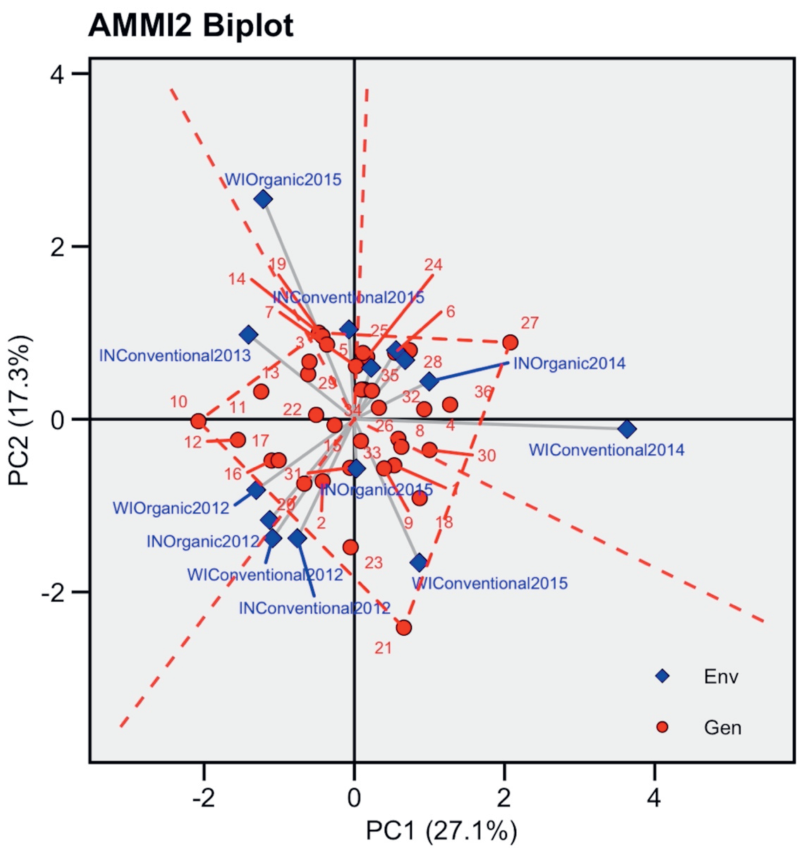


Figure 7A (Mid Top Height). AMMI biplot (PC1 vs PC2) for carrot mid top height (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

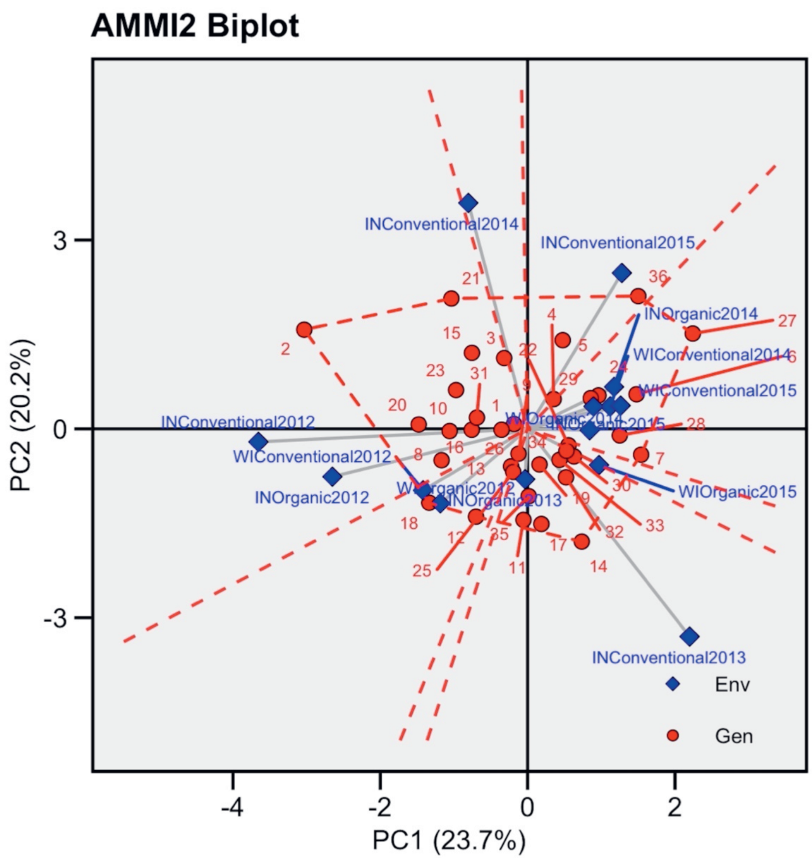


Figure 7B (Mid Top Width). AMMI biplot (PC1 vs PC2) for carrot mid top width (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

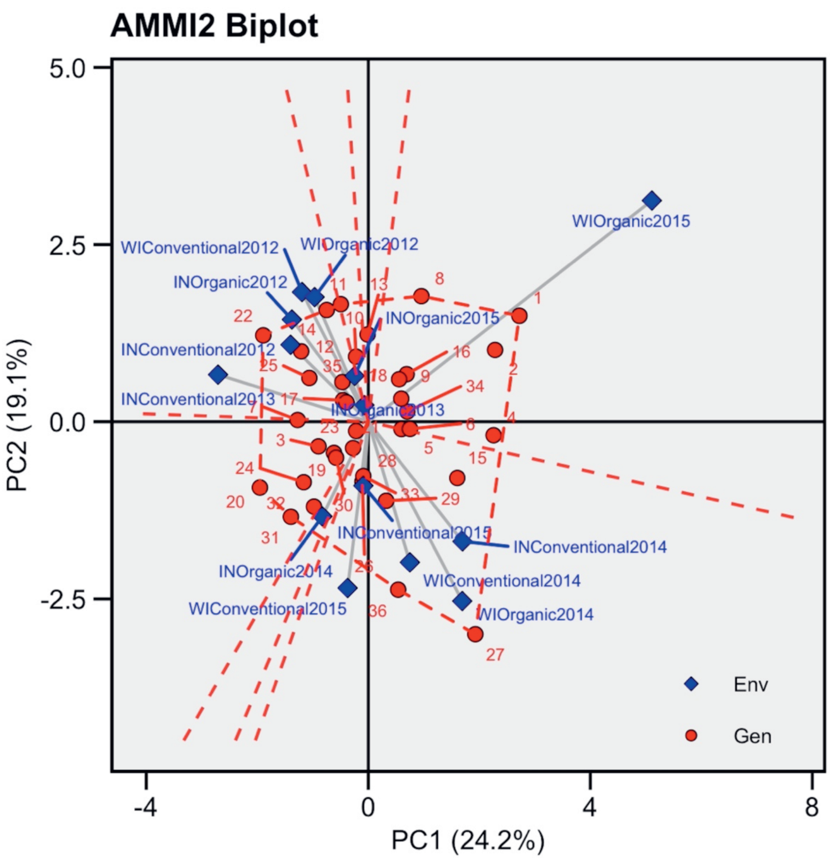


Figure 8A (Harvest Top Height). AMMI biplot (PC1 vs PC2) for carrot harvest top height (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.

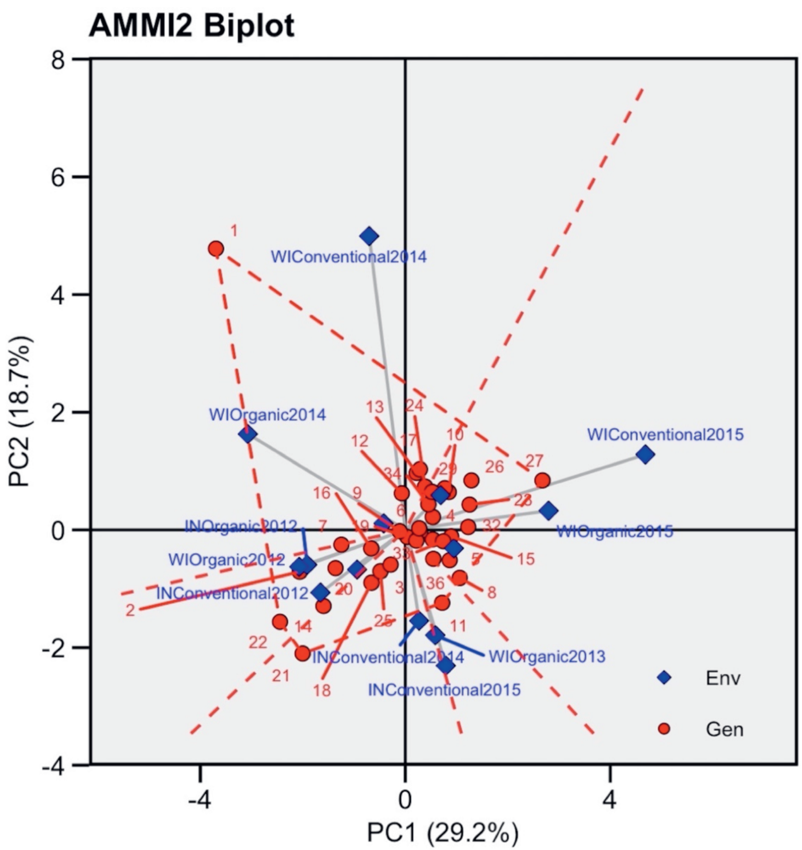
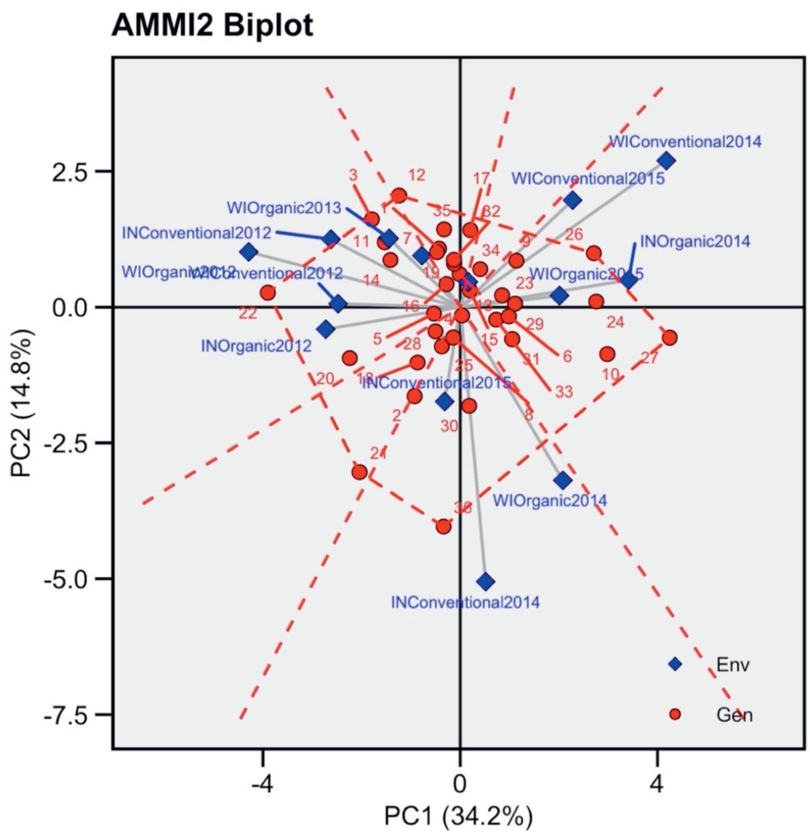


Figure 8B (Harvest Top Width). AMMI biplot (PC1 vs PC2) for carrot harvest top width (cm) of 36 genotypes and 16 environments (2 locations (IN and WI), 4 years (2012-2015), and 2 systems (organic and conventional)). Genotypes are numbered and code provided on previous page under heading AMMI Analysis.



The AMMI analysis does not present any clear patterns for management system or location but reflects the highly significant effect of year in G × E interactions. The first and second principle components only explain a range of total variance from 41.8% for early top height to 55.2% for harvest top weight. For all responses 2012 tended to be along the opposite axis from 2014 and 2015, which are clustered together. This effect is most pronounced for top height at all three time points (~ 30 days after sowing, ~60 days after sowing and at harvest). The response of genotypes for top growth in 2012 may reflect the fact that both locations experienced drought in 2012 and precipitation in 2014 and 2015 reflected the regional averages. Root weight genotypes presented spread across environmental vectors while top weight presented clustered genotypes closer to the origin indicating greater stability of performance across environments. Early and mid-season top height and width presented genotypes spread across environmental axis. Varieties Synthetic 11 (entry 27) and Western Red (entry 36) represented extreme points for root weight and top weight which correspond to these varieties performing above the environmental mean in the Finlay-Wilkinson analysis (Figures 3 and 4).

Discussion

Influence of management system, location, and years on carrot genotype performance

The results of the current study indicate that there are significant interactions between genotype and crop management system, but the relative influence of organic and conventional management is highly contextual and varied by year, trait, and genotype. While results did not identify main effect for system there were two-way interactions of genotype by system for early top height and mid-season top height and width, key traits associated with weed competitiveness, a priority for crop improvement of organic systems. Significant three-way interactions with genotype, management system and year or location also demonstrate the complexity of the various environmental influences on carrot variety performance. The complexity of the interactions is also reflected in the AMMI analysis as describing no more than 55% of total variation for all traits. These results reflect the findings of Renaud et al. (2014), in broccoli, another vegetable crop where two-way interactions were not present, but higher order interactions were significant indicating complexity in variation in management system response. The strong influence of year as demonstrated in the ANOVA (Table 3), coefficient of variation (Table 5) and AMMI analysis (Figures 5-8) underscores the importance of conducting multi-year trials in variety testing and research programs. It also highlights the need to breed for yield stability across seasons in each location particularly as climate change continues to impact the year-to-year variability within locations. Development of flexible varieties with yield stability in environments with lower yield potential due to environmental stress is increasingly an important consideration for organic and conventional breeding programs alike.

One of the reasons for a lack of significant management system by genotype interaction for root weight and top weight is likely that the soil nutrient availability and soil organic matter were maintained at similar levels between the systems. In fact, in WI organic root and top yields were significantly higher in organic than conventional and comparable in IN (Table 6). This reinforces similar findings of Bender et al. (2020), that experienced higher yield and quality in organic carrot than conventional when N levels between the two systems were maintained at equal levels. Carrot does not require high N levels for yield maximization, and it is a good N scavenging crop (Nunez, 2020; Triviño, 2020), which may help explain why even in WI where soil N levels were slightly higher in conventional but comparable between the systems organic yields were still higher, and in IN where N levels were higher in conventional than organic at some points in the seasons yields were still comparable. While the current study cannot determine the cause of the higher yields in organic, there is evidence that soil microbial communities in organic systems can positively influence disease resistance and N accessibility in carrot via root-microbial interactions that can vary by carrot genotype (Abdelrazek et al., 2020b; Triviño, 2020). Future research is needed to better understand the complex environmental influences of carrot genotypic performance in organic systems. Since carrot is a high value crop, it is generally managed for yield optimization including application of fertilizers, crop rotations, and weed management in organic systems. The current study applied standard organic and conventional horticultural practices, including fertilizer and weed management, so the organic environment was not reflective of a low-input system. This contrasts with results of many studies in grains where organic, as well as conventional, cropping systems are commonly low-input and cases of genotype by management systems influences exist (Murphy et al., 2007; Dawson et al., 2008a, 2008b; Kirk et al., 2012).

Influence of selection environment

As breeding programs strive to allocate limited resources to serve the needs of both organic and conventional farmers, understanding the potential to make gains from selection in the non-target environment is an important consideration (Lorenzana and Bernardo, 2008; Vlachostergios et al., 2008; Renaud et al., 2014). Our findings indicate that in most cases, based on correlated responses close to one, genetic gains for organic systems can be achieved by selecting in conventional systems (Table 5). We also found the opposite to be true, that selection in organic would similarly result in improved performance in conventional systems. The fact that none of the correlated response rates was greater than one also indicates that, while the difference may be small, there is potential to make gains more rapidly for organic systems by testing and selecting in organic environments when possible. High levels of broad sense heritability were identified, ≥ (0.75) for all responses with levels between the two systems very close, except for early top height and width in organic in WI and conventional in IN, ≥ 0.56. This indicates that there is potential for crop improvement for yield and top growth characteristics in carrot by selection in either system. The lower repeatability for early top height were due to lower genetic variance in organic in WI and in conventional in IN. These results are in alignment with Renaud et al. (2014), that found broad sense heritability measures similar or higher in organic for yield responses in broccoli. As Renaud et al. reflects, this is in contrast with the other findings that heritability in organic systems is commonly lower due to higher variation in microenvironments, because of variable within-field conditions such as nutrient limitations, weed competition, and pest pressures in organic fields (Ceccarelli, 1994).

These results must be interpreted with care because the current study included a wide range of genotypes and the correlated response calculations were derived from estimates of broad sense heritability. As such the results do not reflect the additive gene effects that would be measured with inbred lines or by parent-offspring regression. We would expect that additive genetic variance would be somewhat lower. Thus, narrow-sense heritability would be smaller, but how much so is impossible to know from this study.

The current study also focused on yield and growth traits, but not quality characteristics. Additional studies are needed to better understand the variation in heritability for different genotypes and for achieving objectives of breeding for quality traits such as flavor, nutrition, and visual appearance, priorities for organic carrot producers.

Ranking and adaptability of variety performance

The highly significant rank correlations of variety performance across organic and conventional systems when considering all genotypes in our trials reflects that there is no unifying pattern of differences in performance between the two systems (Tables 7-8). Differences in ranking of individual varieties were still evident (Fig. 2). The variability in correlations when analyzing different variety types (F1, OP and USDA lines) indicates that there is genotypic variation in response to management systems (Tables 9-11). Przystalski et al. (2008) similarly found in wheat that high genetic correlations between organic and conventional systems did not necessarily mean that there was high correlation in the ranking of varieties between the two systems. These results suggest that testing in organic systems for varieties suitable in organic systems is important as testing in conventional alone may not reveal varieties that perform more optimally in organic systems. Variation in patterns of adaptability to the spectrum of environments further reflects differences between varieties in performance in organic and conventional systems.

Analysis of adaptability to high and low yielding environments revealed variable patterns in adaptation between varieties. This suggests that the potential to select varieties specifically for target environments depends on the anticipated environmental conditions. It also implies that further improvement for adaptation to environments with low yield potential is possible as well as for varieties that respond optimally in organic environments when conditions are favorable. Several varieties bred for productivity in conventional systems demonstrated strong potential for root weight yield in favorable environments with lower root weight yield in low-yielding environments in conventional trials compared to organic including Red Core Chantenay, Western Red, and Bolero (Fig. 3). This may reflect the focus on breeding programs for response to selection in high input systems, although in each instance the response under organic management to high yielding environments was also above the environmental mean for these varieties.

Implications for organic plant breeding programs

In conclusion, from our study there is evidence that management system has a significant influence on variety performance in carrot, but there are no clear trends that apply across all genotypes or environments. The results of this study indicate that previous genetic improvements in conventional systems have and can continue to deliver improved varieties for organic systems. If selection is not justified in organic for a breeding program, then at least testing in organic systems is highly recommended to ensure the variety assortment reflects optimum performance in organic systems. Our results also indicate that breeding holds good potential to address key organic production challenges related to slow early crop development and resulting impacts of weed competition. Furthermore, to fully optimize adaptation to organic systems, testing and selection is best performed under organic management whenever possible.

References

Abdelrazek S, Choudhari S, Thimmapuram Y, Simon P, Colley M, Mengiste T and Hoagland L (2020a) Changes in the core endophytic mycobiome of carrot taproots in response to crop management and genotype. *Scientific Reports.* doi.org/10.1038/s41598-020-70683-x

Abdelrazek S, Simon P, Colley M, Mengiste T and Hoagland L (2020b) Crop management system and carrot genotype affect endophyte composition and Alternaria dauci suppression. *PLOSOne.* doi.org/10.1371/journal.pone.0233783

Badgley C and Perfecto I (2007) Can Organic Agriculture Feed the World? *Renewable Agriculture and Food Systems* **22** (2), 80–85.

Bates D, Mächler M, Bolker B, and Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4 *Journal of Statistical Software* **67**(1). 1–48. https://.doi.org/10.18637/jss.

Baenziger PS, Salah I, Little RS, Santra DK, Regassa T and Wang MY (2011) Structuring an Efficient Organic Wheat Breeding Program. *Sustainability* **3** (8), 1190–1205. https://doi.org/10.3390/su3081190.

Baresel JP, Zimmerman G and Reents HJ (2008) Effects of genotype and environment on N uptake and N partition in organically grown winter wheat (*Triticum aestivum* L.) in Germany. *Euphytica* **163**, 347-354.

Bellon S and Penvern S (eds) (2014) Organic Farming, Prototype for Sustainable Agricultures. *Dordrecht: Springer* https://doi.org/10.1007/978-94-007-7927-3.

Bender I, Moor U and Luik A (2015) The effect of growing system on the quality of carrots. *Research for Rural Development* **1,** 118-123

Bender I, Edesi L, Hiiesalu I, Ingver A, Kaart T, Kaldmäe H, Talve T, Tamm I and Luik A (2020) Organic Carrot (*Daucus carota* L.) Production Has an Advantage over Conventional in Quantity as Well as in Quality. *Agronomy* **10**(9), 1420. https://doi.org/10.3390/agronomy10091420

Boiteux LS, Belter JG, Roberts PA and Simon PW (2000) RAPD linkage map of the genomic region encompassing the root-knot nematode (*Meloidogyne javanica*) resistance locus in carrot. *Theoretical and Applied Genetics* **100**, 439-446.

Brown JR (1998) *Recommended chemical soil test procedures for North Central Region*. Missouri Agricultural Experiment Station, University of Missouri-Columbia.

Buyer JS and Sasser M (2012) High Throughput phospholipid fatty acid analysis of soils. *Applied Soil Ecology* **61**, 127-130.

Brouwer B and Colley M (2016) Pacific Northwest Organic Plant Breeding Assessment of Needs. *Organic Seed Alliance* (Accessed November 2018) Available at: https://seedalliance.org/publications/pacific-northwest-plant-breeding-assessment-needs/

Ceccarelli S (1994) Specific Adaptation and Breeding for Marginal Conditions. *Euphytica* **77**, 205-219.

Ceccarelli S and Grando S (2019) Participatory Plant Breeding: Who Did It, Who Does It and Where? *Experimental Agriculture* **56**(1), 1–11. Available at: https://doi.org/10.1017/S0014479719000127.

Ceccarelli S and Grando S (2022) Return to Agrobiodiversity: Participatory Plant Breeding. *Diversity* **14** (2), 126. https://doi.org/10.3390/d14020126.

Chiffoleau Y and Desclaux D (2011) Participatory Plant Breeding: The Best Way to Breed for Sustainable Agriculture? *International Journal of Agricultural Sustainabilit*y **4**, 119–130. Available at: https://doi.org/10.1080/14735903.2006.9684795

Colley MR, Dawson JC, McCluskey C, Myers JR, Tracy WF and Lammerts van Bueren E T (2021) Exploring the Emergence of Participatory Plant Breeding in Countries of the Global North – a Review. *The Journal of Agricultural Science* **159** (5–6), 320–38. https://doi.org/10.1017/S0021859621000782

Colley M (2020) Organic Carrot Production. In: *Carrots and Related Apiaceae Crops*, edited by Geoffriau Emmanuel and W. Simon Philipp, 2nd ed., 197–215. Wallingford: CABI. https://doi.org/10.1079/9781789240955.0197

Colquhoun J, Rittmeyer BA and Heider DJ (2017) Tolerance and Suppression of Weeds Varies among Carrot Varieties. *Weed Technology* **31**(06), 1-6.

Colquhoun JB, Rittmeyer BA and Heider DJ (2018) Integrated weed management without linuron herbicide in carrot. In: *Proceedings from the 39th International Carrot Conference. Madison, Wisconsin, USA*. pp.9. Available at: https://vcru.wisc.edu/simonlab/carrotconference/39th%20International%20Carrot%20Conference%20Program.pdf).

Connor DJ (2008) Organic Agriculture Cannot Feed the World. *Field Crops Research* **106** (2), 187–90. https://doi.org/10.1016/j.fcr.2007.11.010.

Davis R.M and Raid RN (2002) *Compendium of Umbelliferous Crop Diseases* American Phytopathological Society, St. Paul, MN, 75 pp.

Dawson JC, Kevin MM and Jones SS (2008a) Decentralized Selection and Participatory Approaches in Plant Breeding for Low-Input Systems. *Euphytica* **160** (2), 143–54. https://doi.org/10.1007/s10681-007-9533-0.

Dawson JC, Huggins DR and Jones SS (2008b) Characterizing Nitrogen Use Efficiency in Natural and Agricultural Ecosystems to Improve the Performance of Cereal Crops in Low-Input and Organic Agricultural Systems. *Field Crops Research* **107** (2), 89–101. https://doi.org/10.1016/j.fcr.2008.01.001.

Dawson J, Healy K and McCluskey M (2017) Organic Vegetable Trials and Plant Breeding Needs Assessment and Strategy for National Collaboration. University of Wisconsin-Madison, USA. Available at: https://dawson.horticulture.wisc.edu/wp-content/uploads/sites/21/2018/03/OVTSeedSummit_Needs-Assessment-Proceedings_30Aug2017-FINAL-digital.pdf

de Ponti T, Bert R and van Ittersum MK (2012) The Crop Yield Gap between Organic and Conventional Agriculture. *Agricultural Systems* **108**, 1-9.

Dillon M and Hubbard K (2011) *State of Organic Seed Report*; Organic Seed Alliance: Port Townsend, WA, USA. Available at: https://seedalliance.org/publications/state-of-organic-seed-report/

Eddy D (2008) Organic Explosion. *American Vegetable Grower*; Willoughby. **56** (1), 8-9.

Falconer and Mackay (1996) *Introduction to Quantitative Genetics*. 4th Edition, Prentice Hall, Essex.

Finckh MR, van Bruggen HC and Tamm L (eds) (2015) Plant Diseases and Their Management. In: *Organic Agriculture,* APS Press, St. Paul, Minnesota.

Finlay KW and Wilkinson GN (1963) The analysis of adaptation in a plant-breeding programme. *Crop and Pasture Science* **14**, 742-754.

Geoffriau E (2020) Genetic Diversity and Main Carrot Types. In: Geoffriau E and Simon PW (eds) *Carrots and Related Apiaceae Crops*, 2nd ed., 197–215. Wallingford: CABI. https://doi.org/10.1079/9781789240955.0197.

Grahn C, Silva E, Ellison S and Simon P (2018) Mapping QTL for carrot shoot traits in diverse management systems. In: *Proceedings from the 39th International Carrot Conference* Madison, Wisconsin, USA. pp.9. Available at: https://vcru.wisc.edu/simonlab/carrotconference/39th%20International%20Carrot%20 Conference%20Program.pdf)

Gugino BK, Carroll JE, Widmer TL, Chen P and Abawi GS (2007) Field evaluation of carrot varieties for susceptibility to fungal leaf blight diseases in New York. *Crop Protection* **26**(5), 709-714.

Hildebrand PE and Russell JT (1996) *Adaptability Analysis: A Method for the Design, Analysis, and Interpretation of On-Farm Research-Extension*. 1st ed. Ames: Iowa State University Press.

Hubbard K and Zystro J (2016) *State of Organic Seed, 2016.* Organic Seed Alliance Available at: https://stateoforganicseed.org

Hubbard K, Wood L and Zystro J (2021) *State of Organic Seed, 2022.* Organic Seed Alliance. Port Townsend, WA, USA Available at: www.stateoforganicseed.org

Hultengren R, Glos M and Mazourek M (2016) *Breeding, Research, and Education Needs Assessment for Organic Vegetable Growers in the Northeast*. Cornell University eCommons. *USA.* Available at: https://ecommons.cornell.edu/handle/1813/44636

IFOAM (2022) International Federation of Organic Agriculture Movements. Available at: https://www.ifoam.bio

Kirk AP, Fox SL and Entz M (2012) Comparison of Organic and Conventional Selection Environments for Spring Wheat. *Plant Breeding* **131** (6), 687–94. https://doi.org/10.1111/j.1439-0523.2012.02006.x.

Kowalczyk Z and Cupiał M (2020) Environmental Analysis of the Conventional and Organic Production of Carrot in Poland. *Journal of Cleaner Production* **269** (October): 122169. https://doi.org/10.1016/j.jclepro.2020.122169.

Kristiansen P, Acram T and Reganold P (2006) *Organic Agriculture: A Global Perspective. Collingwood*, Vic.: *CSIRO Pub*.

Kuznetsova A, Brockhoff PB and Christensen RHB (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software* **82**(13), 1–26. https:doi.org/10.18637/jss.v082.i13.

Lammerts van Bueren ET (2006) Organic plant breeding and seed production: ecological and ethical aspects. In: *Organic Agriculture: A Global Perspective*. Kristiansen P, Taji A and Reganold J (eds.) CSIRO Publishing, Collingwood / CABI, Wallingford / Cornell University Press, Ithaca / Manaaki Whenua Press, Lincoln, Australia.

Lammerts van Bueren ET and Myers JR (2012) *Organic Crop Breeding.* Chichester, West Sussex: Wiley-Blackwell. ISBN: 978-0-470-95858

Lammerts van Bueren E, Osman AM, Tiemens-Hulscher M, Struik PC, Burgers SLGE, and van den Broek RCFM (2012) Are Specific Testing Protocols Required for Organic Onion Varieties? Analysis of Onion Variety Testing Under Conventional and Organic Growing Conditions. *Euphytica* **184** (2), 181–93.

Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C and Messmer MM (2011) The Need to Breed Crop Varieties Suitable for Organic Farming, Using Wheat, Tomato and Broccoli as Examples: A Review. *NJAS - Wageningen Journal of Life Sciences* **58** (3–4), 193–205. https://doi.org/10.1016/j.njas.2010.04.001.

Lenth RV (2016) Least-Squares Means: The R Package lsmeans. *Journal of Statistical Software* **69**(1), 1-33. doi:10.18637/jss.v069.i01

Lorenzana RE and Bernardo R (2008) Genetic Correlation between Corn Performance in Organic and Conventional Production Systems. *Crop Science* **48**(3), 903-910.

Löschenberger F, Fleck A, Grausgruber H, Hetzendorfer H, Hof G, Lafferty J, Marn M, Neumayer A, Pfaffinger G and Birschitzky J (2008). Breeding for organic agriculture: the example of winter wheat in Austria. *Euphytica* **163**, 469-480.

Lyon A, Tracy WF, Colley M, Culbert P, Mazourek M, Myers J, Zystro J and Silva EM (2019) Trial of Organic Vegetable Crops. *Renewable Agriculture and Food Systems* **17**.

Meija, L (2020) *Carrot genotype and nitrogen stress alter plant soil feedbacks and susceptibly to pathogenic nematodes*. Caldas University Columbia Senior Thesis. 49 pp.

Murphy KM, Campbell KG, Lyon SR and Jones SS (2007) Evidence of Varietal Adaptation to Organic Farming Systems. *Field Crops Research* **102** (3), 172–77. https://doi.org/10.1016/j.fcr.2007.03.011.

Nunez (2020) Carrot Production Practices In: Simon PW and Geoffriau E (eds.) *Carrots and Related Apiacea Crops second edition*. CABI, Oxfordshire, UK.

Olivoto T and L'ucio AD (2020) metan: an R package for multi-environment trial analysis. *Methods in Ecology and Evolution* **11**(6), 783-789. https://doi.org/10.1111/2041-210X.13384.

Osman AM (2014) *Towards an Improved Variety Assortment for the Dutch Organic Sector: Case Studies on Onion and Spring Wheat.* A PhD thesis, Wageningen: Wageningen University. Available at: https://edepot.wur.nl/312216

Parsons J, Matthews W, Iorizzo M, Roberts P and Simon P (2015). *Meloidogyne incognita* nematode resistance QTL in carrot. *Molecular breeding* **35** (5), 1-11.

Peruzzi A, Ginanni M, Fontanelli M, Raffaelli M and Barberi P (2007) Innovative strategies for on-farm weed management in organic carrot. *Renewable Agriculture and Food Systems* **22** (4), 246–259.

Przystalski M, Osman A, Thiemt EM, Rolland B, Ericson L, Østergård H and Levy L (2008) Comparing the Performance of Cereal Varieties in Organic and Non-Organic Cropping Systems in Different European Countries. *Euphytica* **163** (3), 417–33. https://doi.org/10.1007/s10681-008-9715-4.

Que F, Hou XL, Wang GL, Xu ZS, Tan GF, Li T, Wang YH, Khadr A and Xiong AS (2019) Advances in research on the carrot, an important root vegetable in the Apiaceae family. *Horticulture research* **6**.

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/.

Redman R (2020) Organic Produce Sales Higher than Normal Amid Coronavirus Outbreak. *Supermarket News.* New York. USA. Available at: https://www.proquest.com/docview/2395187065?accountid=27871

Renaud ENC, Lammerts van Bueren ET, Paulo MJ, van Eeuwijk FA, Juvik JA, Hutton MG and Myers JR (2014) Broccoli Variety Performance under Organic and Conventional Management Systems and Implications for Crop Improvement. *Crop Science* **54** (4), 1539–54. https://doi.org/10.2135/cropsci2013.09.0596.

Seaman A (ed) (2016) *Organic Production and IPM guide for carrots*. Cornell University, New York State Department of Agriculture and Markets. NYS Publication No. 133. Available at: https://ecommons.cornell.edu/bitstream/handle/1813/42892/2016-org-carrots-NYSIPM.pdf?sequence=5

Seufert V, Ramankutty N and Foley JA (2012) Comparing the Yields of Organic and Conventional Agriculture. *Nature* **485** (7397), 229–32. https://doi.org/10.1038/nature11069.

Shelton AC and Tracy WF (2016) Participatory Plant Breeding and Organic Agriculture: A Synergistic Model for Organic Variety Development in the United States. *Elementa Science of the Anthropocene* **4**, 1-12. https://doi.org/10.12952/journal.elementa.000143

Simon PW and Strandberg JO (1998) Diallel Analysis of Resistance in Carrot to Alternaria Leaf Blight. *Journal of the American Society for Horticultural Science* **123**, 412-415.

Simon PW, Navazio JP, Colley M, McCluskey C, Zystro J, Hoagland L and Roberts PA (2017) The CIOA (Carrot Improvement for Organic Agriculture) Project: Location, Cropping System and Genetic Background Influence Carrot Performance

Including Top Height and Flavour. *Acta Hort* **1153**, 1–8. https://doi.org/10.17660/ActaHortic.2017.1153.1

Smith OM, Cohen AL, Rieser CJ, Davis AG, Taylor JM, Adesanya AW and Jones MS et al (2019) Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis. *Frontiers in Sustainable Food Systems* **3**(82). https://doi.org/10.3389/fsufs.2019.00082.

Solfanelli F, Orsini S, Zanoli R and Schaefer F (2021). *The State of Organic Seed In Europe.* Petiti M, Ortolani L and Schaefer F (eds.) *LiveSeed*. Available at: https://www.liveseed.eu/wp-content/uploads/2021/03/Booklet2-LIVESEED_2021_web.pdf.

Triviño NJ (2020) *Characterizing carrot microbiomes and their potential role in soil organic matter decomposition.* A PhD Thesis, Purdue University Graduate School. https://doi.org/10.25394/PGS.12246014.v1

Turner S (2017) *Genetic influences on shoot architecture in carrot (Daucus carota).* A PhD Thesis, University of Wisconsin–Madison. Available at: https://search.library.wisc.edu/catalog/9912724632302121

USDA/NASS (2020) Census of Organic Agriculture: highlights from the 2019 survey. Available at: https://www.nass.usda.gov/Publications/Highlights/2020/census-organics.pdf

van Heemst HDJ (1985) The influence of weed competition on crop growth. *Agric Syst*. **18**, 81-93. https://doi.org/10.1016/0308-521X(85)90047-2

Vlachostergios DN and Roupakias DG (2008) Response to Conventional and Organic Environment of Thirty-Six Lentil (Lens Culinaris Medik.) Varieties. *Euphytica* **163** (3), 449–57. https://doi.org/10.1007/s10681-008-9712-7.

Wilbois K-P and Schmidt JE (2019) Reframing the Debate Surrounding the Yield Gap between Organic and Conventional Farming. *Agronomy* **9** (82). https://doi.org/100.3390/agronomy9020082

Supplemental Materials

The following figures (9-14) present graphs of Finlay-Wilkinson linear regression of mean for early top height, early top width, mid-season top height, mid-season top width, harvest top height, and harvest top width of 36 genotypes (G) of carrot in organic and conventional systems plotted against the environmental index of mean response across all genotypes under across 16 environments (E) including four years (2012-2015), two locations (Indiana and Wisconsin) and 2 management systems (organic and conventional). Genotypes with slopes significantly different than 1 are indicated in the sub-plots of the figure as organic (Org) or conventional (Conv) followed by slope and significance level. Significance levels are indicated as *, **, *** $p \leq 0.05, 0.01, 0.001$, respectively.

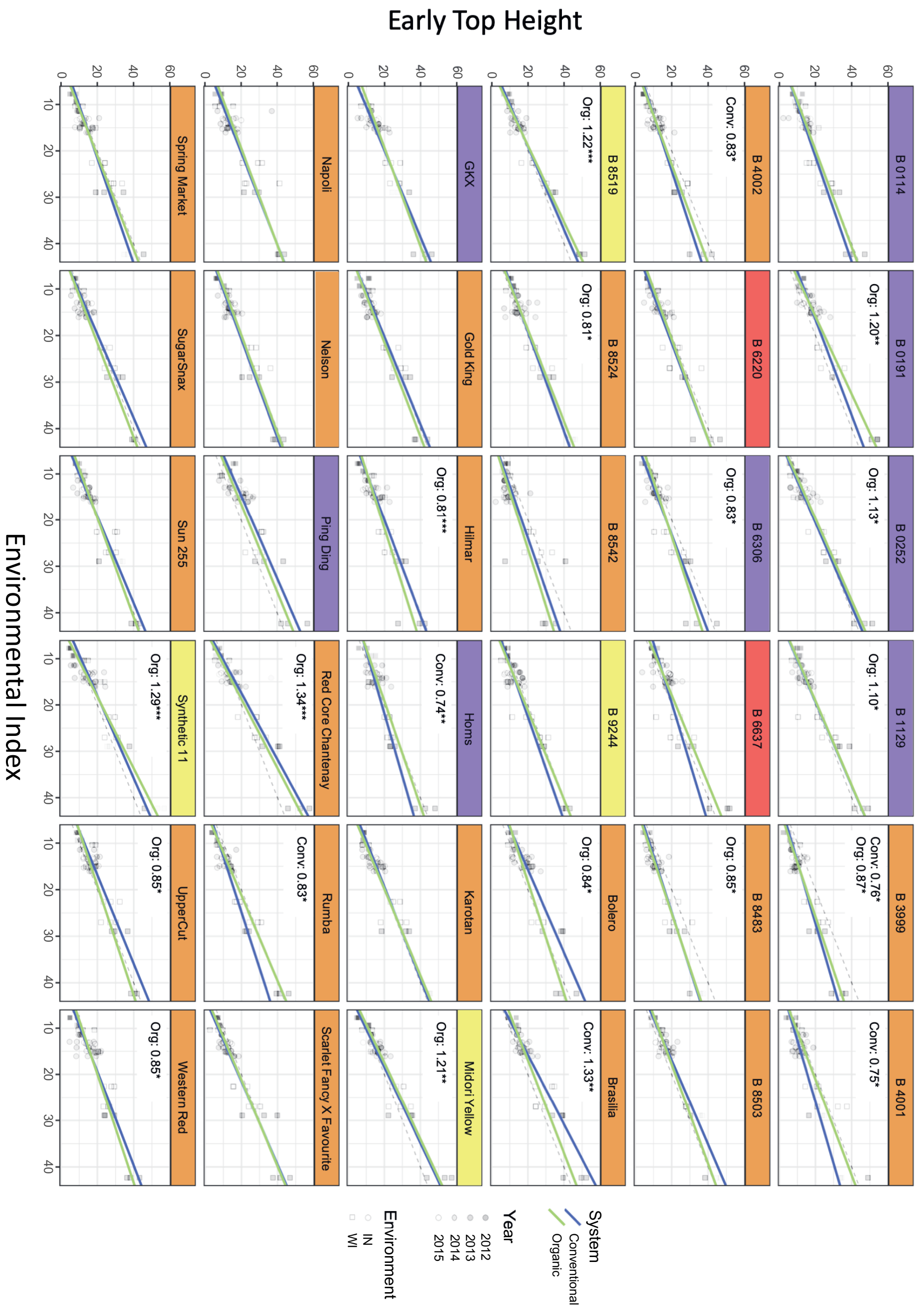


Figure 9. Finlay Wilkinson regression for early top height (cm) (full description under heading Supplemental materials)

. **Figure 10.** Finlay Wilkinson regression for early top width (cm) (full description under heading Supplemental Materials).

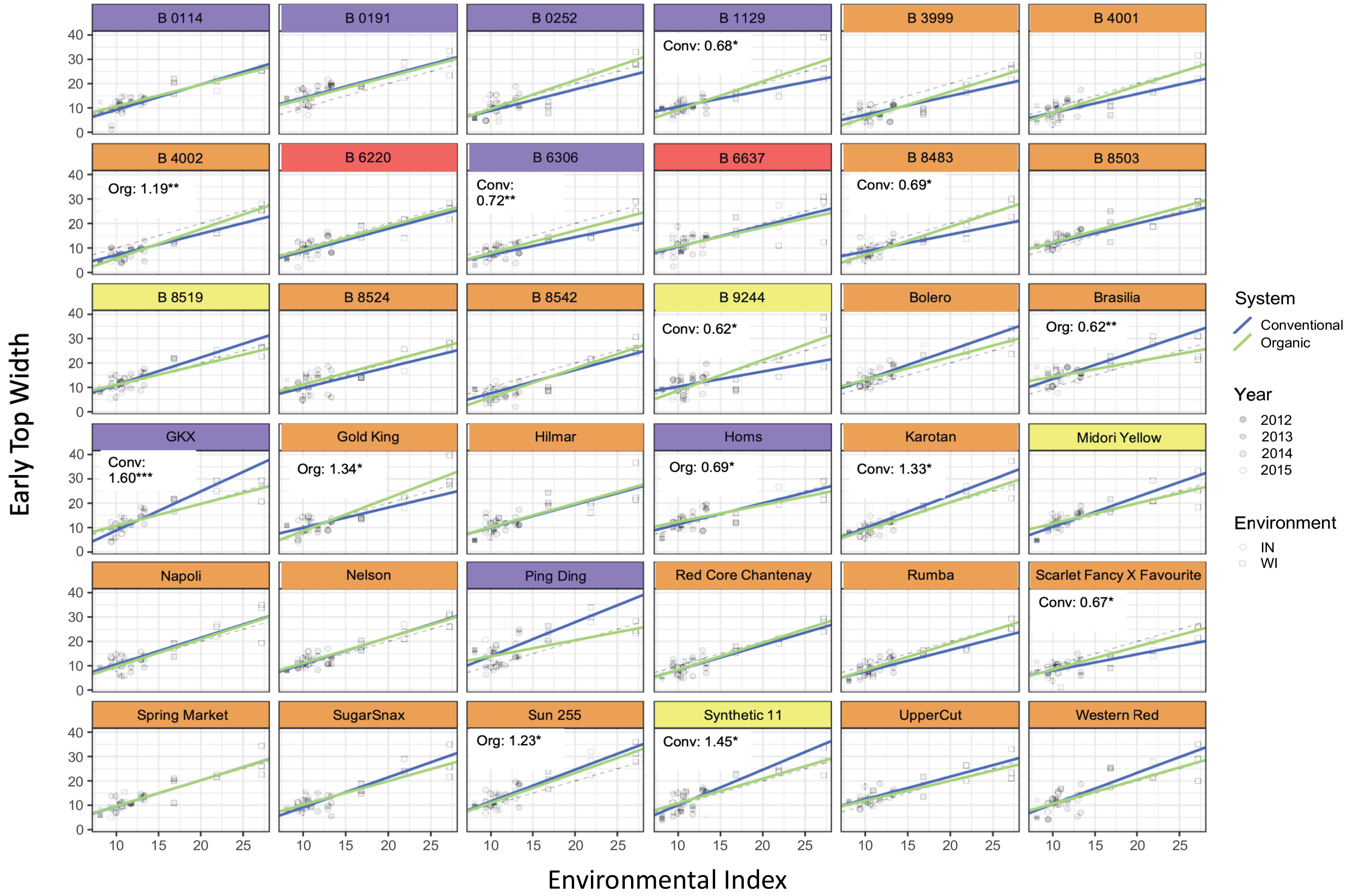


Figure 11. Finlay Wilkinson regression for mid-season top height (cm) (full description under heading Supplemental Materials).

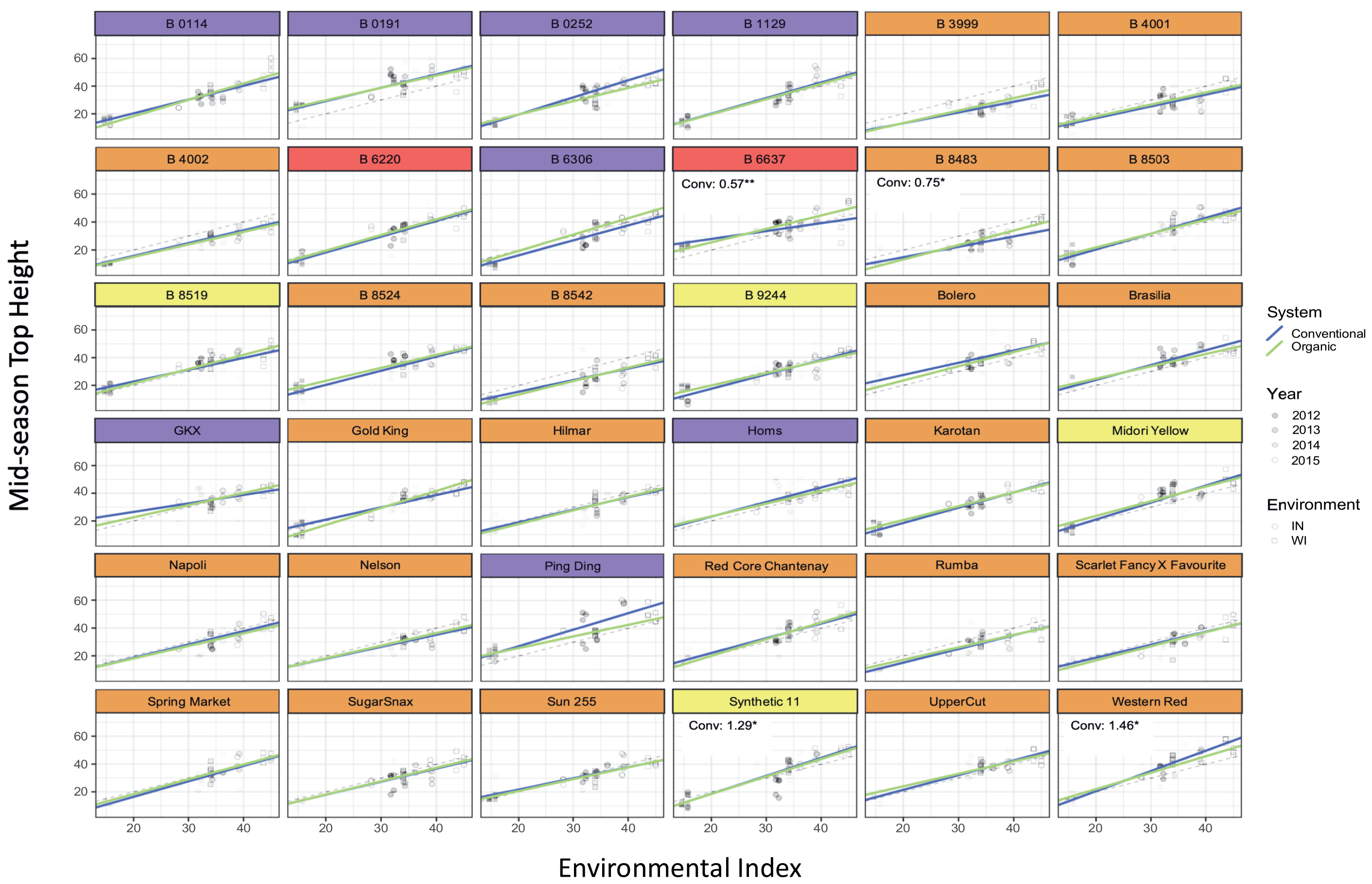


Figure 12. Finlay Wilkinson regression for mid-season top width (cm) (full description under heading Supplemental Materials).

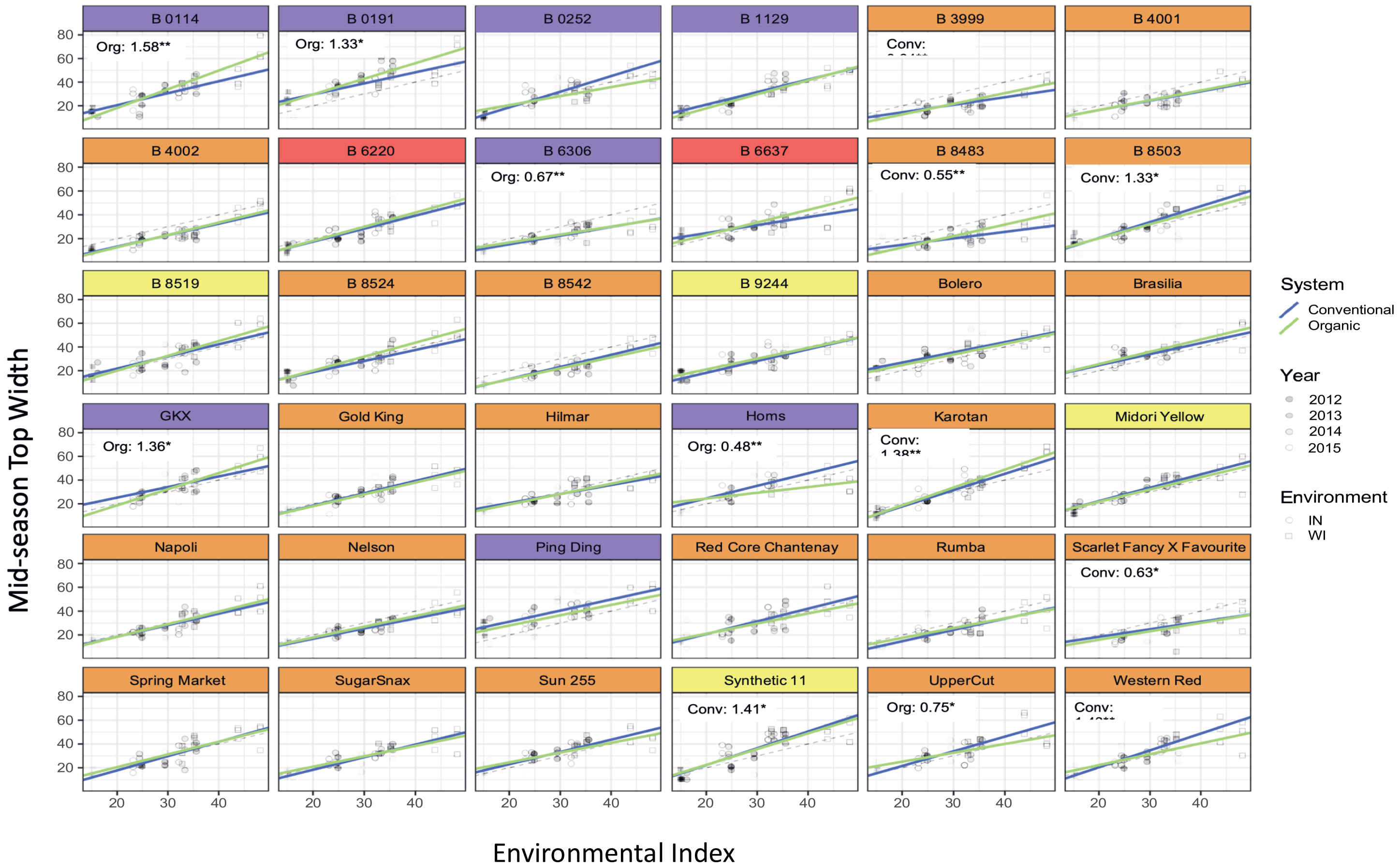


Figure 13. Finlay Wilkinson regression for harvest top height (cm) (Full description under heading Supplemental Materials).

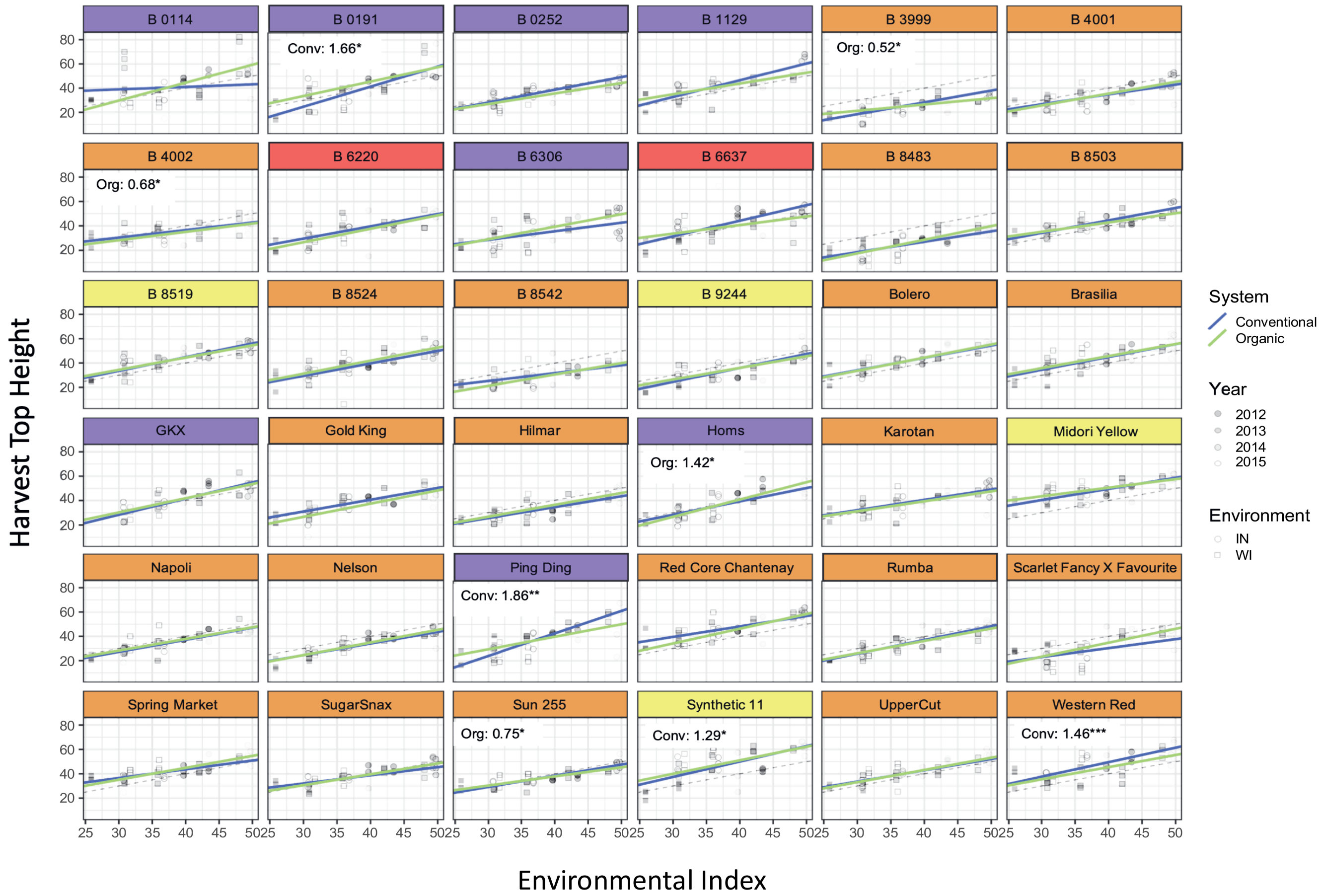
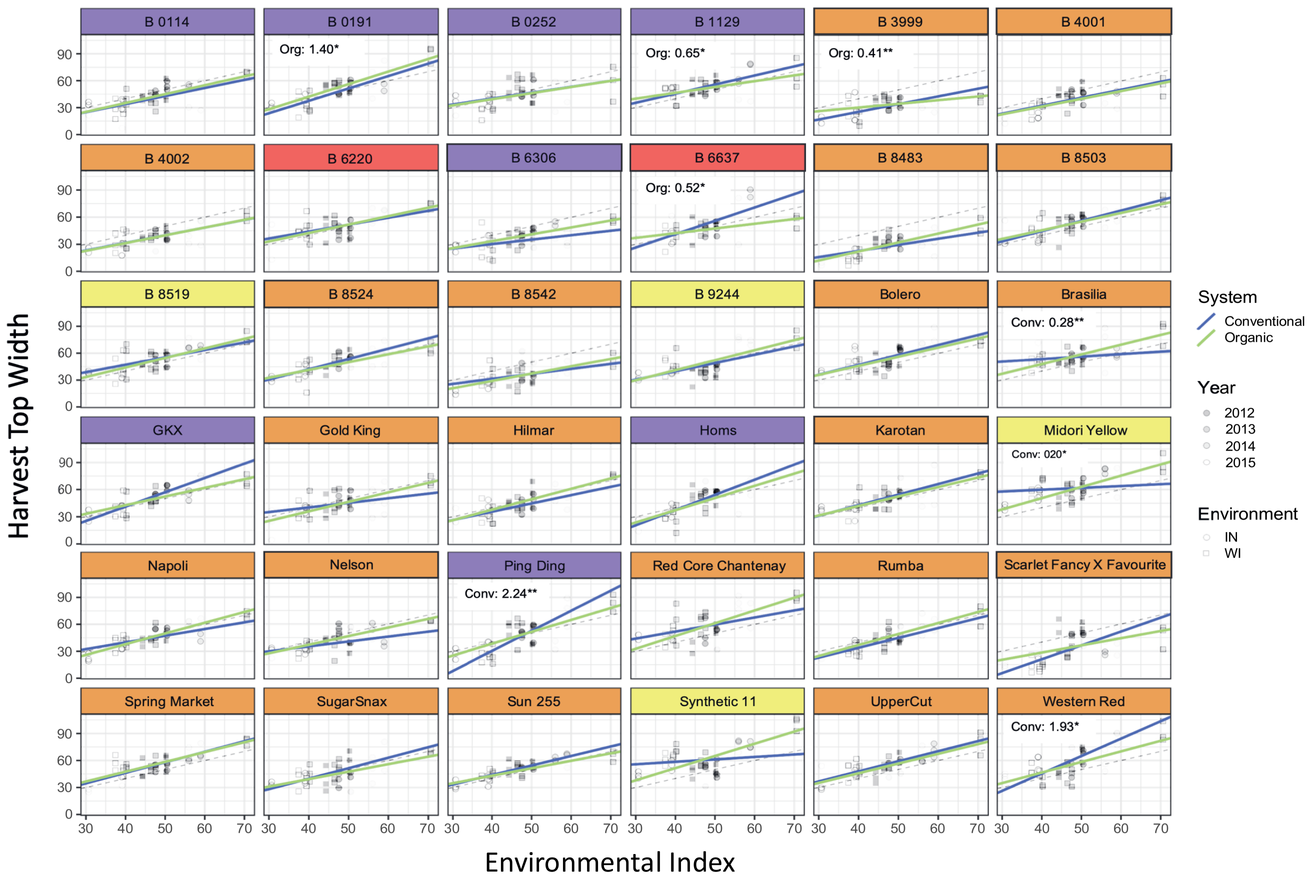


Figure 14. Finlay Wilkinson regression for harvest top width (cm) (full description under heading Supplemental Materials)



Chapter 4

Suitability of a network model to facilitate testing and increase adoption of organic seed: reflections from 12 years of the Northern Organic Vegetable Improvement Collaborative (NOVIC)

Authors:
Colley MR[1,7], Dawson JC[2], Selman L[3], Loria K[4], Tracy WF[5], Silva EM[6], McKenzie L[1], Lammerts van Bueren ET[7], Almekinders CJM[8], Myers JR[3].
[1]Organic Seed Alliance
[2]University of Wisconsin-Madison, Department of Horticulture
[3]Oregon State University, Department of Horticulture
[4]Cornell University, Integrative Plant Science
[5]University of Wisconsin-Madison, Department of Agronomy
[6]University of Wisconsin-Madison, Department of Plant Pathology
[7]Wageningen University, Plant Breeding
[8]Wageningen University, Knowledge, Technology, and Innovation

Abstract

Access to seed of adapted varieties that meets agronomic, and market needs of organic farms is essential to the optimization of organic agriculture. Organic farms in the Global North are however commonly smaller scale, decentralized and highly diversified in crop type and markets and thus centralized research station trials may not represent the range of on-farm environments and desired crop ideotypes. This presents challenges in efficiently and effectively testing the agronomic and market suitability of organically available varieties. For these reasons farmer-participatory network approaches are proposed to improve representation of trial results across the range of farm environments, in addition to enhancing farmer-researcher knowledge exchange, and increasing adoption of suitable organic varieties. The Northern Organic Vegetable Improvement Collaborative (NOVIC) in the USA sustained a participatory variety testing network over the span of 12 years with the aim of achieving these goals. The current study analyzes reflections from own and participant experience collected through surveys and interviews. It presents outcomes, lessons learned and recommendations for future trial networks. The network facilitated farmer adoption of suitable varieties of organic seed and expanded market access. Researchers and farmers alike however struggled with capacity limitations, narrow evaluation windows of vegetable crop and evaluator consistency impacting quality of on-farm data. Knowledge exchange, relationship building, and expanded awareness of crop qualities, market access, and insights into seed system dynamics emerged as project highlights among network participants. Decision making dynamics shifted across the 12-year span toward expanded farmer consultation in trial objectives and regional autonomy in choice of crops and trial goals reflecting the dynamic regional nature of organic farms. Positive impacts and sustained engagement for over a decade are attributed to adaptability in management informed by iterative participant reflections during the project.

Keywords: Breeding and seed systems, participatory plant breeding, participatory variety selection, organic plant breeding, organic vegetable seeds

Introduction

Organic vegetable sales in the United States (US) continues to rise with 29% growth in sales from 2016-2019 worth more than 2 billion USD annually (USDA/ NASS, 2019). Organic vegetable farmers rely on agroecological approaches to manage biotic and abiotic production challenges as organic methods prohibit the use of synthetic forms of nutrition and crop protection inputs. This makes the availability of suitable seeds of adapted varieties a crucial component in organic agricultural production systems.

Choice of crop variety is a critical management strategy in organic agricultural systems to mitigate crop stresses including pests, disease and weed competition while optimizing nutrient acquisition (Lammerts van Bueren et al., 2011a; Lammerts van Bueren and Myers, 2012; Van Bruggen et al., 2016). Organic markets also drive variety selection as organic consumers value diversity, flavour and nutrition (Bonti-Ankomah and Yiridoe, 2006; Rahman et al., 2021). In addition to suitability of organic varieties, organic farmers are compelled to use organic seed sources to comply with US (7 CFR § 205.204) and European Union (EU) (EU 2018/848) regulations requiring farmers to use certified organic seed when available in suitable form (NOP, 2002; EU, 2022). Yet despite these regulations, most organic farmers still rely on conventional seed for at least a portion of their production. On average organic farms in the US produce 79% of their organic vegetables using organic vegetable seed. However, an inverse relationship exists between the size of the farm and the quantity of organic seed used, with only 25% organic seed planted on average on farms over 480 acres according to a national survey of US organic producers reported in the State of Organic Seed Report (Hubbard et al., 2022). The fact that still most crop varieties are bred in and for conventional agriculture brings to light that conventionally bred varieties are not always optimum for organic systems (Murphy et al., 2007; Singh, 2011; Lammerts van Bueren et al. 2011ab; Lammerts van Bueren and Myers, 2012; Entz et al., 2015).

To address organic famers need for suitable varieties available as certified organic seed, public and private research initiatives are striving to test existing varieties for suitability in organic systems, identify gaps in priority traits and breed new varieties to better suit organic farmers needs and build the supply of organic seed (Lammerts van

Bueren and Myers, 2012; Hubbard et al., 2022; Rivière et al., 2021). However, organic farms represent highly diverse environments, often serving local or regional markets with diversified cropping systems so testing is less straightforward than for a highly concentrated and uniform crop production system often characterizing the industrial and conventional agricultural systems with high input levels to mitigate crop stress. The majority of organic variety trials reported in scientific literature to date are in cereal crops (Murphy et al., 2007; Darby et al., 2013; Entz et al., 2018, Goldringer et al., 2019, Costanzo, 2021), leaving gaps in assessment of vegetable variety performance in organic systems, though recent studies are expanding organic vegetable trials of select crops (Chable et al. 2008; Lammerts van Bueren et al., 2012; Renaud et al., 2014). Compared with grain and commodity crops, such as field corn, vegetable crops on diversified farms are subject to greater variation in production practices, variable timing in maturity between varieties, narrow harvest windows, and high variability between environments, presenting greater challenges in consistency in evaluations (Dawson, 2011; Lyon et al., 2019). Grain crops are generally more straightforward in evaluations of yield and quality as they are harvested after maturation and can be stored or held post-harvest, allowing for flexibility in the timing of collecting data on a busy farm. All these factors present challenges in evaluating organic vegetable crops and underscores the importance of communication and clarity between researchers and farmers when establishing trial protocols and expectations.

Despite the challenges researchers broadly recognize that advancing organic seed systems necessitates testing varieties and breeding populations under organic conditions and soliciting input from organic farmers familiar with their production environment and market demands (Chable et al., 2014; Ortolani et al., 2017; Lyon et al., 2019; Rivière et al., 2021). To address the previously stated challenges decentralized networks and participatory methods are commonly employed to account for the heterogeneity of environments within and across farms and diverse variety needs (Dawson et al., 2008; Chable et al., 2008, Chable et al., 2014; Colley et al., 2021). Participatory on-farm variety testing and selection approaches also provide an opportunity to define relevant traits for organic breeding and to evaluate performance of developing and new varieties directly under the conditions of intended use applying organic farm management practices (Chiffoleau and Desclaux, 2006; Dawson et al., 2011). Effectively designing and managing decentralized, participatory trial networks necessitates consideration of not only research and data collection strategies, but also social and financial implications of facilitating a dynamic network of farmers and other stakeholders (de Buck et al., 2021; Rivière et al., 2021).

With dwindling numbers of public plant breeders and even fewer specifically addressing the needs of organic agriculture and with far less public investment in organic plant breeding research than conventional breeding, collaborative networks and participatory strategies are considered valuable to leverage plant breeders' capacity and address the challenges that researchers encounter in breeding for scattered and highly diverse environments and markets (Chiffoleaux and Desclaux, 2006; Dawson et al., 2008; Hubbard et al., 2021). Organic vegetable farmers additionally value crop diversity and novelty, seeking to extend the season for high value crops and differentiate their products by introducing varieties with novel traits and unique or superior culinary qualities (Lyon et al., 2015; Brouwer and Colley, 2016; Hultengren et al., 2016; Healy et al., 2017; Healy and Dawson, 2019). These factors underscore the need to involve organic farmers as collaborators in the objective setting and evaluation of trials.

Acquiring statistical significance from on-farm trials can be challenging for many participatory projects due to irregularities in experimental design and wide-ranging environmental conditions (Rivière et al., 2015; Lyon et al., 2019). The high cost of farming, particularly for horticultural crops, can limit the capacity for large population sizes and the number of replications on-farm necessary for statistical accuracy (Lyon et al., 2019). While there are clear potential benefits to conducting on-farm trials from both agronomic and social perspectives, there is a need to refine and streamline trial methods to ensure the maximum value is achieved given the type of crop, trial feasibility, and goals of the breeder and farmer. While many practitioners of participatory agricultural research are entrenched in the tacit benefits of the participatory approach, such as leveraging farmer's crop expertise, and facilitating variety adoption, it is essential to continually evaluate experiences to refine participatory methodologies (Sperling, 2001). Clarity of priorities and awareness of the limitations of participatory trials, based on experiences, can help inform strategies and establish realistic goals (de Buck et al., 2021; Rivière et al., 2021).

The current study analyzes the experience of a farmer-participatory organic variety trial network in the US coordinated as the Northern Organic Vegetable Improvement Collaborative (NOVIC) (https://eorganic.info/novic/about). The collective experience of the farmers and researchers over the course of the three phases of the project serves as a prime opportunity to assess the outcomes and lessons learned to inform future projects. It also serves as an opportunity to assess the suitability of a network-model for making suitable seeds of adapted varieties available for organic farmers, involving the participatory research methodologies employed.

Background: The Northern Organic Vegetable Improvement Collaborative

The overall goals of the NOVIC project, launched in 2010 with federal funds administered through the USDA Organic Research and Extension Initiative (OREI), aimed to expand organic farmer's awareness and access to varieties that address their needs, expand access to and use of organic seed sources and develop and release improved varieties. To help achieve this goal, the researchers associated with three land-grant universities (Oregon State University, University of Wisconsin-Madison, and Cornell University, along with a non-profit organization Organic Seed Alliance (OSA)) developed the participatory trial network with the objectives of capturing both on-farm and on-station (research farms) data of adequate quality to inform farmers' seed purchasing decisions, direct breeding efforts and facilitate the adoption of organic seed sources. The NOVIC project involved collaborators located in four states in the northern tier of the US, Oregon (OR), Washington (WA), Wisconsin (WI), and New York (NY). Collaborators included university and non-profit plant breeders, variety trial coordinators, organic farmers, seed companies and independent breeders. Project activities included plant breeding, participatory variety trials, and training farmers and graduate students in organic variety testing and plant breeding. Three cycles of four-year funding periods supported NOVIC over the span of 12-years.

Each of the four collaborating institutions conducted plant breeding efforts on one to three crops during each four-year project period, resulting in 10 crops being advanced with 18 new varieties released to date and many more in advanced stages of breeding and testing. The collaborating institutions also served as hubs for facilitating on-station and on-farm variety trials to evaluate performance of commercially available varieties and breeding populations across the four states. The project intended to utilize multi-environment trials to assess broad and specific adaptation and test the suitability of varieties for regional environments and markets. Farmer involvement leveraged the dual purpose of providing representative testing environments to evaluate new breeding lines and facilitating farmer adoption of organically available varieties.

The project employed a mother-daughter variety trial design as first described by Snapp (1999) to test maize populations across villages in Malawi with each farm location testing a subset of entries across large numbers of farm sites representing the regional range of environments (Snapp, 1999; Snapp, 2002). With the approach of NOVIC, researchers evaluated crops in replicated trials with three replications at each research station and single plots of the full set of varieties on at least three farms per crop per region with each farm environment representing blocks as a replicated complete block design (RCBD) for conducting an analysis of variance. All four regions evaluated all crops involved in breeding activities (5-7 crops per 4-year project period) each year and the farmers within each region identified additional crops for trials based on regional farmer priorities (Table 1). In annual planning meetings, participating farmers, researchers and organic seed companies collectively identified varieties for inclusion in the trials including a farmer-identified “check” variety that was a reliable market standard. Researchers disseminated trial results through an online organic vegetable variety trial database (https://varietytrials.eorganic.info) and at farmer meetings, public workshops, and at agricultural conferences.

The researchers initially developed the collaborative based on the fact the research locations all had a similar latitude, which was hypothesized to minimize “noise” in the data. While climates held similar seasonal patterns and organic farmers held similar models of diversified vegetable production for regional markets with similar range of crop species produced there were also differences between environments and farm scale. New York has a highly variable climate due to elevation differences and proximity to bodies of water with moderating influence. Wisconsin has a similar climate, but is a continental state, with hot humid summers and harsh winters. In the Pacific Northwest, Oregon and Washington have much milder winters and more rain as compared to WI and NY.

The researchers initially aimed to apply statistical analysis to the mother and daughter sites separately, utilizing the three on-farm locations as blocks with the intent to gain greater understanding of regional adaptation versus broad adaptation. To this end researchers tested a core set (8 out of 12 varieties) across all regions for two years. Each four-year cycle of funding provided an opportunity for the researchers to reflect on the collective experience, assess outcomes, update the crop-breeding focus, and adjust methods and approaches to managing the trial network. Sixty-eight farms participated in the on-farm trials over the course of the project by providing input on selection of crops and varieties for trials and conducting trials on their farms.

The farmer trial-network grew into a national network with regional hubs of activities. The network expanded by soliciting participation through the unique communication channels of each organization and by hosting informational meetings at agricultural conferences, promoting the project through regional and national media, and often directly inviting farmers with previous experience in collaborative on-farm research with the organizing institutions. Farmer participation in the trials expanded over time through ongoing outreach and by hosting public field days at the research station where the farmers, seed companies and other stakeholders would explore the trials together and discuss the following year’s trial plans. These events along with ongoing outreach allowed farmers to dynamically enter or exit the network throughout the course of the project (Table 1).

Researchers within each institution led the regional network facilitation in coordination with the national network. Research staff included plant breeders and trial network coordinators. Coordinators included graduate students and research staff with several individuals shifting roles over the course of the project. Starting in 2019, the NOVIC network in WI operated under the Seed to Kitchen Collaborative which managed data collection solely through the newly released online trial management tool, SeedLinked (www.seedlinked.com). In all states research staff and graduates students facilitated the on-farm trial network. Several MSc and PhD graduate students integrated the trial network and related participatory plant breeding projects into thesis chapters and peer review publications (McKenzie, 2013; Shelton and Tracy, 2016; Hultengren, 2017; Lyon, 2017; Loria, 2021).

Materials and methods

Eight of the authors were part of the research staff of the project. They complemented their experiences with study of the NOVIC project documents and reports over 2010-2022 and collected feedback from farmers. The authors developed and sent a survey in December 2021 to all farmers who had participated across the 12 years utilizing the online survey tool Survey Monkey (www.surveymonkey.com). Trial coordinators solicited farmer's participation in the survey through repeated emails, texts, phone calls and direct communication until May 2022, using a contact list of all 68 farmers who had participated in NOVIC over the 12-year period. In some cases, the farms no longer existed. Survey questions covered farm demographics (size, certification status, markets), queried various aspects of farmers' experience in the trials, explored impacts of the trials in their seed sourcing and other impacts related to the farming operation, and solicited input on challenges in participation in the trials (see Appendix A). Open-ended questions related to outcomes, impacts, challenges and advice for future trials allowed participants to elaborate on their experience through comments in addition to the ranked questions. Thirty-three farmers responded to the survey representing a 49% response rate. Respondents included 13 out of 19 farmer contacts in WA, three out of 11 in WI, eight out of 21 in OR, and 11 out of 17 in NY. The report of results in the following section indicates the number of respondents that answered each question out of the total survey participants. Survey participants were provided the option of skipping questions as "prefer not to respond" to capture as high of a response rate as possible while respecting survey respondents' will to participate. For example n=31 indicates that 31 out of 33 answered a given question.

Select farmers and plant breeders were invited for additional online interviews to deepen insights into their project experiences. The selected farmers participated at least three years in the trials, and they balanced representation across the trial regions and a diversity of scales of farms. Altogether, three plant breeders (from WI, OR, and WA) and nine farmers (three each from Oregon, Washington, and New York) participated in interviews. None of the WI farmers responded to invitations for interviews. Farmer and plant breeder interviews lasted one hour, were conducted through Zoom, and captured audio and transcription recordings. The first author conducted all interviews for consistency in process, took notes during the interviews and then reviewed the audio and transcribed recordings, tracking salient themes and responses that were either surprising or provided deeper insight into key research questions. The first author completed human subject ethics approval through Wageningen University and all participants provided consent through the survey form and verbal agreement in interviews. Table 1 provides an overview of the crops and project participants in each of three project phases, NOVIC 1, 2 and 3.

Table 1. Northern Organic Vegetable Improvement Collaborative (NOVIC) crops and number of participants during three project periods in all regions (New York, Wisconsin, Washington and Oregon).

	NOVIC 1 (2009-2013)	NOVIC 2 (2014-2018)	NOVIC 3 (2019-2022)
Crops of plant breeding projects - Included in trials in all locations during NOVIC 1 and 2 and select regions in NOVIC 3.	Pea, broccoli, carrot, sweet corn, winter squash (*Cucurbita moshata*)	Tomato, cabbage, sweet corn, sweet peppers, winter squash (*Cucurbita pepo*)	Cabbage, tomato, winter squash (var. species), sweet peppers, sweet corn, savory corn, cucumber
Additional crops selected by farmers for inclusion in trials conducted only in select regions.	Beets, cabbage, chicory/radicchio, kale, lettuce, peppers, spinach, tomatoes	Beans, beets, broccoli, carrots, endive fennel, kale, leeks	Beans, broccoli, Brussels sprouts, carrots, cauliflower, chicory/radicchio, kale, lettuce, spinach
Number of farmer-respondents in survey*	11	18	19

*The total number of participants in each project phase is not equal to the cumulative number of farmers across the 12-year project period due to the fact some farmers participated in more than one phase of the project.

Results

Adaptation of practices and roles over time

Each project period was used by the researchers to evaluate the collective experience and outcome of the trials based on feedback from the plant breeders, trial coordinators, and participating farmers. As a result, the researcher team (plant breeders and trial coordinators) adjusted the approach, practices and roles of the researchers and farmers in the subsequent phase based on lessons (Table 2, 3). In the early phase of the project, researchers and trial coordinators held a greater role in design and execution of the trials with farmers' input solicited for prioritization of crops and varieties in trials. At that time the researchers aimed to collect robust data across environments to inform the genotype by environment interaction of variety performance in organic systems. While they accomplished this to some degree, the researchers encountered capacity limitations in managing on-farm trials, and many gaps in data. Also, feedback that farmers' input was more essential than initially considered in optimizing usefulness of the trial results in the farmers' decision making. For example, it was important to farmers that planting dates and evaluation priorities reflected their own production practices. Phase two of the project shifted toward greater knowledge transfer between researchers and farmers, including training farmers in on-farm experimental practices and a greater emphasis on farmers' input on variety evaluation traits and selection of entries (crops and varieties) with less emphasis on quantitative data collection. Farmers provided, among others, qualitative descriptions of what they liked or did not like about varieties.

Over the course of the project the role of chefs, seed companies, and other market stakeholders grew in participation and researchers frequently hosted farmer-chef participatory culinary evaluations and events. National and regional seed companies increasingly participated in the project planning, workshops, and field days, providing recommendations for inclusion of commercially available varieties and in some cases unreleased breeding lines for testing. In interviews, farmers mentioned these events helped to expand their market relationships with chefs and seed companies and strongly influenced their variety adoption and use decisions. Plant breeders reported learning new culinary applications and desired traits from the chefs. For example, a habanero pepper lacking heat that was bred through NOVIC was favored by chefs for sweet dishes and flavored drinks and inspired chefs to help develop culinary evaluation methodologies for several other NOVIC crops including sweet pepper and winter squash. The Culinary Breeding Network (www.culinarybreedingnetwork.com) was launched as a new initiative during the second project period, directly due to the trial network and chef engagement related to NOVIC.

During the third four-year period the farmers' roles in directing the trials further expanded to include selection of crops, traits and entries (varieties) coordinated with regional autonomy rather than as a national network. This phase was also marked by shifts in leadership of trial coordination in Wisconsin, increased coordination of trials through the online application SeedLinked, and greater remote coordination as farmers and researchers alike struggled with the impacts of the COVID pandemic. Results of the current study present a deeper understanding of the motivations, lessons learned, and ramifications of these shifts in coordination of the trial network based on first-hand feedback from farmers, trial coordinators and plant breeders involved in the NOVIC network.

Table 2. The role of farmers and researchers in managing various aspects of on-farm trials conducted across three phases of participatory research in NOVIC.

Project	Trial design	Variety selection	Sourcing seed	Transplant production	Planting	Field management	Evaluation	Harvest	Presentation	Publication
NOVIC 1	R	F, R	R	R	F, R	F	R	R	F, R	R
NOVIC 2	F, R	F, R	R	F, R	F, R	F	F, R	F, R	F, R	R
NOVIC 3	F, R	F, R	R	F	F	F	F, R	F, R	F, R	R

F = farmer; R = researcher

Breeders' motivations for project structure and adaptations

The plant breeders reported in the interviews that they initially held ambitions for the qualitative and quantitative data from the multi-environment testing network to inform plant breeders, farmers, and seed companies of broad versus narrow adaptation of varieties, with the vision that the farms would represent broader range of microenvironments within a region. In the first two project phases the network conducted trials of all breeding crops in all locations with a core set of entries consistent across regions, repeated at least two years for statistical analysis, but in the final period the trial management this had shifted and exclusively included regionally prioritized crops and variety entries. After the first project period the research team realized that not all crops were appropriate for each region, for example overwintering carrots were suitable for OR and WA, but not WI or NY, and butternut squash did not mature in time for harvest in the mild maritime climate of western WA but was a crop breeding focus in NY.

Researchers experienced challenges in on-farm data collection during the first phase of NOVIC with resulting gaps in data and inconsistent quality of the data. The research team decided to adjust their approach in subsequent phases based on an apparent gaps and analysis of variance indicating that variability in farm environments and evaluator methods resulted in low statistical power in the on-farm trial data compared with the research station trials (Lyon et al., 2019). Plant breeders and trial coordinators reflected that evaluating crops with variable maturity timing and narrow harvest windows, such as sweet corn or snap peas, was challenging and resulted in poor evaluations when some crops were over or under mature at timing of evaluation. Additionally, farmers did not desire to repeat trials of less suitable varieties across years and were not interested in all the traits the breeders routinely collected, for example number of kernel rows in corn or length of flag leaf and they expressed frustration when the traits evaluated did not reflect their own priorities. One farmer in the interview expressed additional frustration with the researchers' efforts for consistent planting dates across locations when the ideal conditions for planting may vary by farm site within and across regions. While the project team acknowledged the limitations in relevancy and statistical power of the data from on-farm sites it hypothesized that farmers' experience in conducting on-farm trials still provided some agronomic value for the farmers and feedback to researchers, as well as social benefits including knowledge exchange and expanded access and use of varieties of organic seed. These considerations informed adjustments in the project management over the course of three project periods (Table 3). In subsequent project phases evaluations in addition to shifts toward visually scoring rather than measurements in evaluations, they limited on-farm evaluations to traits prioritized by farmers and solicited greater farmer feedback in *why* they liked or did not like a trial variety. This adaptation in trial management proved to be key in farmers' continued participation and improved satisfaction with trial results.

In the second and third phases of NOVIC the "mother" sites continued serving as the center for quantitative data collection, including yield data, for trial reports. In interviews with the plant breeders, they did not report using the on-farm data to direct their breeding decisions due to the variability and thus tended to base their breeding decisions on their own first-hand experience at the research stations. They did however report that they valued the farmers' scoring of traits as it was useful to validate or highlight inconsistencies in results compared with the research station results. The researchers released trial reports presenting results from the research station trials combined with farmers' ranking of variety performance and feedback on what they liked or did not like about varieties as well as their insights into novel uses or markets for varieties. Researchers also appreciated expanding their own exposure to new crops as trials included 27 different vegetable crops over the course of the project. The additionally valued informal feedback and information exchange from farmers through events and found the trial network to be very valuable in facilitating the release and market development of new varieties. At least 18 new varieties, representing 10 crops have been released to date because of the NOVIC project.

Table 3. Approaches, experiences, and adjustments to the Northern Organic Vegetable Improvement Collaborative (NOVIC) variety trial approach across three funding periods (2010-2012). (Source: farmer surveys and interviews, plant breeder interviews, and participant observations of network trial coordinators).

	Approach and adjustments	Researchers' experience with on-farm trials	Farmers' experience (feedback)	Lessons learned
NOVIC 1 (2010-2014)	Breeder identified trial protocols followed by all regions, evaluations include quantitative yield data, 5 of 6 crops and 8 of 12 entries in each crop consistent across	Data collection required extensive time of coordinators visiting farms, gaps in data and high errors limited statistical analysis and low usefulness for breeders, working with farmers provided	Farmers liked option of farmer-choice crops, some breeder identified evaluation traits were not relevant to farmers, data collection too time intensive, valued researcher support in evaluation and interactions with other farmers, some crops not	Farmer input on crop traits is important for their engagement, not all crop breeding is suitable to all regions, social engagement and knowledge exchange valued

	regions and replicated at least 2 years.	crop insights and collaboration more than data.	relevant for all region (example overwintering carrots in NY).	by farmers and breeders.
NOVIC 2 (2015-2018	Breeder and farmer collaborate on prioritizing evaluation traits, evaluation protocols shifted toward ratings rather than quantitative data, breeding crops continued across all regions unless not suitable to the region, core set of 6 out of 12 entries consistent across regions.	Data collection easier with less quantitative data, high engagement of farmers, seed companies and chefs in field days facilitating adoption of newly released varieties, trial reports easier to manage regionally rather than one national report, reports integrate research station data with farmer ratings and feedback.	Data collection easier to manage, still appreciated researcher assistance in evaluations, appreciated more flexibility in regional trial entries, but did not want to repeat testing entries that previously did not perform well, some appreciated seeing breeder entries, others frustrated if the breeding line was not available for sale.	High participation in regional events and interest in regional trial reports indicated that less quantitative yield data did not reduce interest in trial results, farmers' losing interest in re-evaluating the breeding crops and most enthusiastic to prioritize crops of regional interest.
NOVIC 3 (2019-2022)	Crops for trials selected by farmers on regional basis, researchers collaborated across regions only when crops overlapped, SeedLinked app introduced as online option for farmers submitting evaluation of trait ratings, on-farm data protocols directed by region and varied including +/- scores, comments, and qualitative ratings.	Sourcing seed and developing protocols by region for different crops each year increased time demand for trial coordination, trial reports emphasized research station data with less effort to visit all farms routinely to seek farmer evaluations, WI trials all coordinated through SeedLinked app, NY implemented +/- and comments as farmer feedback, seed companies and independent breeders value trials to test and release new varieties.	Appreciation for ability to regionally prioritize multiple crops for trials, mixed experience with SeedLinked app (easy and useful for some, technology barrier for others), desire for more on-farm visits from researchers, appreciated field days and tasting events, many increased on-farm seed saving to secure less available varieties or diversify farm income with relationships with seed companies established through project.	National network lost cohesion as the Covid-19 pandemic impacted the ability for face-to -face interactions. Researchers operated more regionally predominantly with remote coordination through SeedLinked and virtual meetings. Farmer-driven crop choices attracted new farmers to network. SeedLinked facilitated increased number of farmers, particularly in WI trials, but not fully adopted in all regions.

Farmers' motivations and benefits

When asked in interviews what motivated them to join and continue participating in the trials, farmers emphasized the exposure to greater diversity of varieties, exposure to new seed sources, and challenging their own assumptions about standard varieties as key reasons. Several farmers mentioned joining the project because they already had a trusted relationship with researchers and past positive experiences participating in on-farm research. In the Pacific Northwest regions farmers placed more emphasis, though not exclusively, on motivations of sourcing open pollinated varieties for on-farm seed production or to support regional and organic seed companies that rely on access to open pollinated varieties without intellectual property protections. The climate of the Pacific Northwest region of the US is optimal for producing seed of a wide range of dry- and wet-seeded vegetable crops and thus the region holds a greater number of small, regionally focused seed companies and a greater percentage of farmers engaged in on-farm seed production compared with the other regions (Organic Seed Alliance, 2013). While several farmers mentioned dedication to organic principles and sourcing organic seed when available, several also reported that identifying organic seed sources was not the primary motivation, but rather finding optimum varieties for their environment and markets regardless of organic certification or open-pollinated versus hybrid status. While trial coordinators strived to emphasize organically available hybrid and open-pollinated varieties in the trials, they also acknowledged that in some cases non-organic hybrids, often included as market standards (control or check crops), out-performed organic options posing a barrier to expanding organic seed usage. In these cases, coordinators hoped that while the NOVIC trials may have at times reinforced choice of non-organic hybrids perhaps the results may stimulate future organic breeding efforts to develop a competitive organic alternative. In some cases, farmers discovered new organic hybrids and in one case a farmer reported more than quadrupling their sales of Jalapeño pepper by adopting an organically available hybrid variety that vastly outyielded any other variety in the trials.

The value of community engagement, being part of a network, engaging in knowledge exchange, and building relationships with other farmers, breeders, seed companies and chefs were resounding themes of both motivation and benefits that reiterated in interviews with farmers and reflected in survey responses. In the survey, farmers were asked to value the different information sources in the project (Figure 1). Farmers placed a higher value on direct experience viewing the crop and discussions with other farmers and researchers over written reports and statistics. Respondents to the survey (n=31) ranked the following as very useful to extremely useful; first-hand experience (87%), walking the field with other farmers and researchers (84%), discussions with other farmers (72%) and conversations with researchers (71%) whereas multipage trial reports and statistical analysis was ranked as very useful to extremely useful by only 20% and 32% respectively. Single page reports and visual figures of the data were preferred over multi-page reports and statistics and ranked as very to extremely important by 71% and 68% respectively.

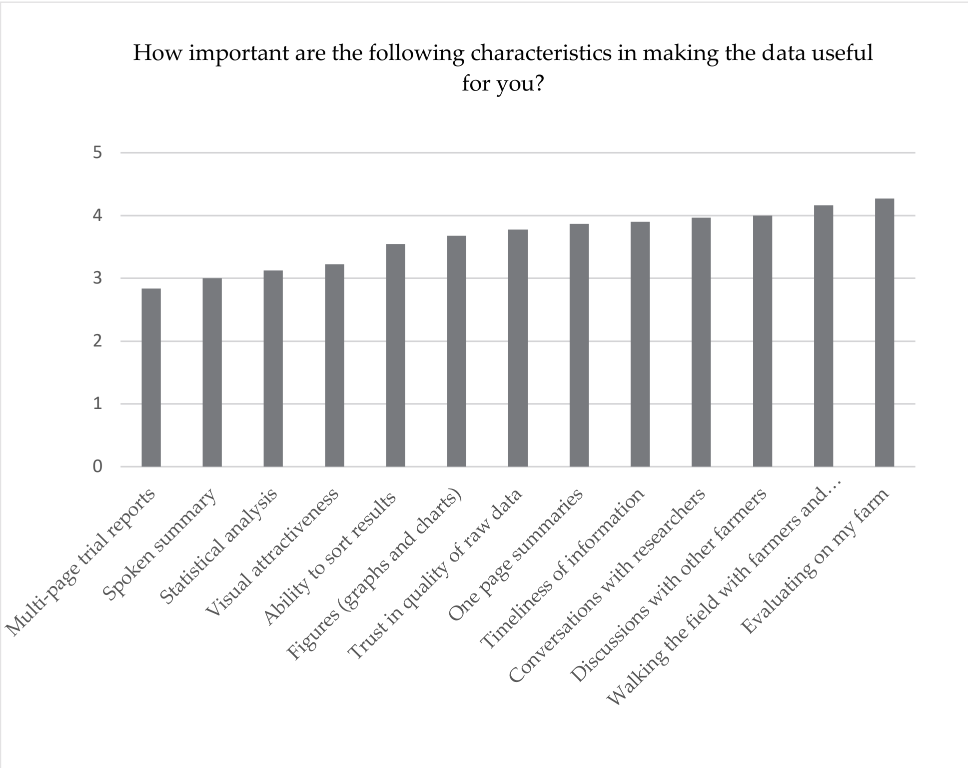


Figure 1. Average level of importance that farmers rated the various information sources in the Northern Organic Vegetable Improvement Collaborative (NOVIC) project from 2010 – 2022. Average value of importance was calculated as the average rating with 1=not at all useful, 2=slightly useful, 3=moderately useful, 4=very useful, 5=extremely useful. (Source: farmer survey responses, n=31).

Eighty-six percent of farmers responding to the survey (n=31), and all nine farmers interviewed, reported that they purchased and planted seed of new varieties as a direct result of participation in the trials; 90% indicated that at least some of the new varieties were of certified organic seed (Figure 2a and 2b). While this response indicates an outcome of increased organic seed adoption, several farmers commented during interviews that while organic seed is important to them, sourcing organic seed was not the primary motivation for involvement in the trial. During interviews farmers frequently reported crop diversification and development of new markets as positive outcomes and motivations for their continued involvement in the project. One participant noted that one seed company expanded sales of a new variety four-fold based on the demand built through engagement of chefs and farmers in the trials in Oregon.

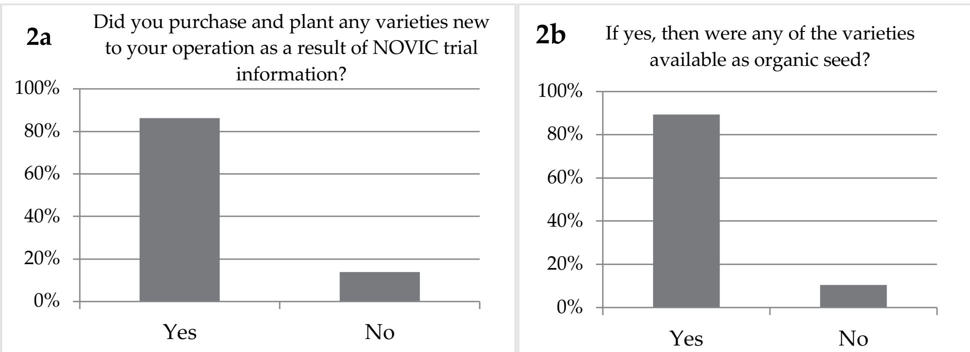


Figure 2. Percent of farmer survey respondents that indicated yes or no when questioned **a)** if they purchased and planted new varieties because of the NOVIC trial information (n=31) and **b)** if any new varieties they planted were available as organic seed (n=30). (Source: farmer survey responses).

Farmers varied in preferred methods for reporting on trial results. Internet access and familiarity with computer programs was a barrier to some growers who preferred handwritten evaluations, while others appreciated the online option and phone app utilizing the trial management tool SeedLinked (www.seedlinked.com) for submitting trial evaluations. When asked about unexpected outcomes in interviews several farmers mentioned that they gained scientific skills and appreciation for the importance of trial methods. Eighty four percent of survey respondents somewhat to strongly agreed that they had improved their skills in evaluating varieties (n=31). Thirty-eight percent of farmers surveyed reported starting new seed saving activities on their farms because of involvement in the trials and 13% started on-farm plant breeding because of involvement in the project (n=32). At least one farmer started a new seed company and noted that involvement in NOVIC trials was of critical influence in their business decisions due to the impact of gaining awareness that variety choice is crucial to farmers' success and learning about open-pollinated varieties and seed saving. Several interviewed farmers went on to produce seed for seed companies or collaborate with seed companies in on-farm trials under paid contracts, with two farmers changing their primary farm production toward seed rather than vegetable crops and a third increasing their seed production scale five times over the course of the project.

Overall farmers felt the compensation for the trials was fair with 86% indicating it as adequate in surveys (n=29). Farmers frequently commented in interviews that the greatest challenge was affording the time to layout the trial, often planting by hand, and conducting evaluations as well as following through with returning evaluation results. Most farmers (59%) reported in the survey that they completed the trial evaluation, but of those that did not "time constraints" and "data collection too much work" were ranked as the top reasons why. Keeping track of trials in a functional farm field resulted in lost data in some cases. Farmers appreciated when clear instructions and trial stakes were provided and at times expressed a desire for more field visits from the researchers as well as collaboration in the trial evaluation.

Regardless of challenges expressed, farmers overall appreciated the value of the trials with the second phase of NOVIC rating the highest value of their experience in the project and easiest evaluation process (Figure 3a and 3b). This sentiment was reflected in one farmer's comment, "the second phase was kind of the glory days of NOVIC when there was a lot of excitement in the field days and chef tasting events". The trial coordinators recognized that Covid-19 restrictions negatively impacted the ability to coordinate as many farm visits and field days as previous years during the third phase of NOVIC.

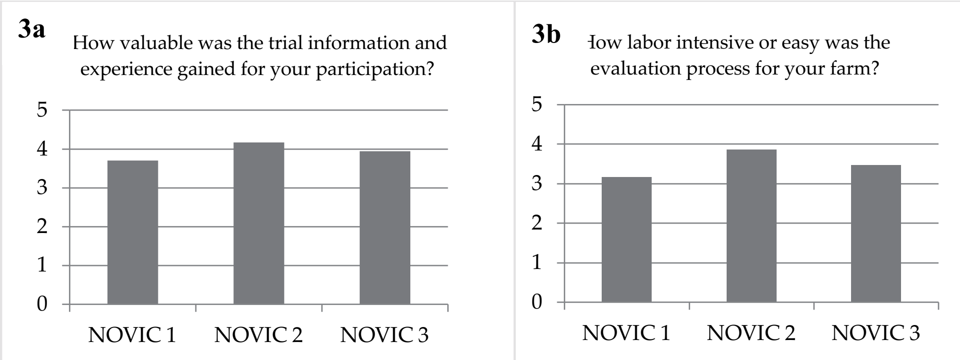


Figure 3. Relative weighted ratings by farmers of **a**) the value of information and experience gained, rated as 1=not valuable, 2=somewhat valuable, 3=valuable 4=very valuable and 5=extremely valuable; and **b**) The intensity/ease of the evaluation process rated as 1=extremely intensive, 2=somewhat intensive, 3=neither intensive nor easy, 4=somewhat easy, 5=very easy. (Source: farmer survey responses, n=30)

Project impacts extended beyond the initial goals of facilitating farmer adoption of new varieties, expanding organic seed usage, and building new markets and market-based relationships with added impacts of expanding farmers awareness of and direct engagement in the seed system based on survey results and interviews. Farmers themselves valued the skills they gained in critically evaluating a trial with awareness of scientific field techniques as reflected in survey responses (Figure 4) and reflected in interviews with specific comments on increased awareness of the value of accounting for edge effects, replicating when possible, including routine check varieties and evaluating the trial “blind”.

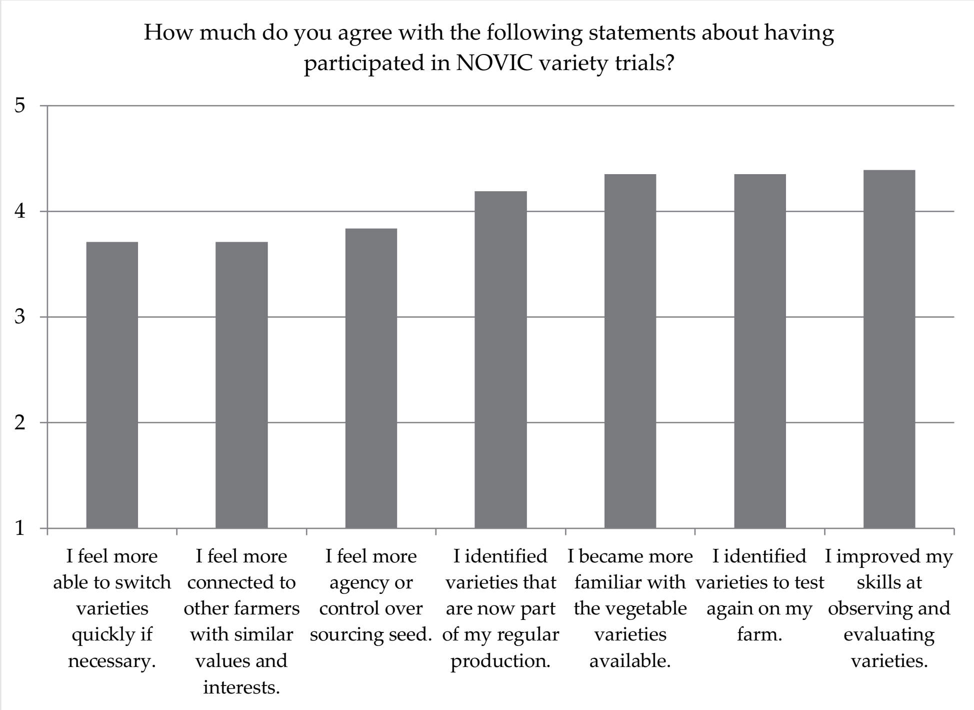


Figure 4. Farmers' ratings of agreement with statements related to their participation in the National Organic Vegetable Improvement Collaborative (NOVIC) trial network from 2010 - 2022. Indicates relative weighted value rated as 1=strongly disagree, 2=somewhat disagree, 3=neither agree or disagree, 4=somewhat agree, 5=strongly agree. (Source: farmer survey responses, n=31).

4

Discussion

The 12 years of experiences in NOVIC confirms the value of the network model in facilitating organic seed uptake and expansion of on-farm genetic diversity. Our findings reflect positive impacts reported by other researchers of participatory on-farm trial networks with similar aims of exposing farmers to greater seed choices, leveraging farmers' input in variety evaluations, and building network relationships to refine organic breeding priorities and bolster organic seed systems (Chable et al., 2008; Singh et al., 2014; Entz et al., 2015). The trial experience also reflected common challenges in collecting and analysing data from organic on-farm trials characterized by highly variable environments between farms, inconsistent evaluations, and in the case of many vegetable crops, gaps in data due to challenges in evaluating crops with a narrow window of maturity during a busy farming season (Lyon et al., 2019). The network initiated with broad and ambitious goals of integrating rigorous agronomic research in multi-environment trials to test for adaptation to organic environments nationally as well as regionally while also building a social network for knowledge exchange. Throughout the project the network had to reconcile trade-offs in allocation of finite capacities and create realistic expectations for the feasibility of on-farm trials to refine program goals and achieve impacts. This required flexibility of the researchers, responsiveness to network participants' feedback, and iterative adaptations in project management.

Design and evaluation of on-farm trials:
The network model proved effective in achieving critical program goals of facilitating adoption of suitable varieties of organic seed as evidenced by the high responses of farmers reporting integration of new crops and varieties in their production as well as diversification of sourcing and uptake of organic seeds. Despite challenges in quality of on-farm data, in the end the limitations did not negate the high value of farmers involvement from the perspective of the researchers as it added value to analysis of research station trials. Farmers' themselves weighted the value of their own first-hand experience in conducting trials as well as interactions with other network participants as the greatest sources of information influencing their variety selection.

Since the inception of the NOVIC network parallel efforts with similar experiences and goals have emerged as well as recommendations for alternative research designs for on-farm variety selection and testing in organic systems including for example Bayesian models, triatic design, lattice models (ie. Rivière et al., 2015; Zystro et al., 2018; Rivière et al., 2021). A common thread between these initiatives, similar to NOVIC, is recognizing the value of farmers' involvement beyond providing environmental testing locations. When asked to reflect on the fit of the mother-daughter trial design researchers felt the balance of three farms per crop made facilitation feasible while providing enough collective farmer feedback per crop to generate meaningful input in interpretation of trial results. One of the project breeders pointed out that the original application of the mother-daughter trial design included far more farm sites spread across villages in Malawi all focused on one single crop, corn, as a staple crop, not a horticultural, fresh eating crop as in the case of vegetables in NOVIC (Snapp, 1999). When asked about satisfaction with the research results one of the researchers reflected that the enormous diversity of crops and varieties impacted the ability to evaluate the same varieties across as many years and locations as would be possible with a more limited scope. At the same time the researcher noted that the diversity of crops and varieties kept farmers engaged and ultimately influenced the scope of their own breeding program as they learned of new crop types and qualities desired by farmers and thus initiated new breeding projects. The importance of regionality of interests in crops and variety needs also emerged as a theme throughout the project, an aspect that reflected the diverse and local market channels of participants with emphasis on direct market supply chains.

With 27 crop types evaluated over the 12 years and approximately a dozen variety entries per trial it is estimated that the NOVIC project evaluated at least 3,000 varieties over the project period. An even greater number is likely as some crops repeated over years with entries changing and in some cases researchers and farmers included a larger assortment of varieties to explore less-familiar crops, for example approximately 35 entries in chicory trials.

If the primary goal of a trial network is to inform breeders and seed companies of the genotype by environment interaction and broad or narrow environmental adaptation to organic environments as NOVIC initially set out to do, then trialing in more sites, or with greater replications, or streamlined trial management tools may be a more effective approach than the mother-daughter design. This would however require either fewer crops or streamlined facilitation. For example, the case of the US organic field corn testing network led by the Practical Farmers of Iowa which is focused on a single crop and extensive testing sites, or through crowdsourcing tools such as ClimMob or SeedLinked which enables remote coordination of a broad diversity of crops with less direct social engagement (Practical Farmers of Iowa, 2022; ClimMob, 2022; SeedLinked, 2022). Tradeoffs of scale of trials and capacity for network facilitation and social engagement are something all trial managers must contend with. Recent guides to organic on-farm trials from the LiveSeed project (de Buck et al., 2021; Rivière et al., 2021) presents a valuable decision-making matrix for trial managers balancing network facilitation, economic sustainability, experimental design and data quality management and presenting a range of network options.

Social knowledge exchange and on-farm trials:

Limitations in the NOVIC on-farm data did not overshadow the positive impacts achieved from significant social engagement through farm visits and convening farmers at field days, planning meetings and participatory tasting events. The NOVIC experience reflected in farmer surveys and interviews reinforces that farmers value knowledge exchange with breeders, other farmers and seed companies, chefs and other stakeholders, an element that can get lost in a larger geographically diffused network where frequent in-person social engagement is prohibitive. Likewise, breeders expressed the value of knowledge exchange with farmers as the greatest outcome and recognized the network stimulated multi-stakeholder engagement in development of organic seed systems by engaging not only farmers and breeders, but seed companies, culinarians, and other supply chain actors.

The important role of the trial facilitator cannot be over emphasized in decentralized participatory trial networks such as NOVIC. As researchers in the LiveSeed project stated, "thriving trial networks require skilled facilitators, capable of motivating and engaging network members and drawing from participatory techniques to make the most of farmers' and stakeholders' knowledge of their environment and specific value-chain needs" (Rivière et al., 2021). This was reinforced in the current study as NOVIC farmers repeatedly mentioned relationships and experience with the researchers as reasons for joining the network and being part of a community network to facilitate knowledge exchange keeping them involved over time. While graduate student involvement provided a valuable educational opportunity and source for committed coordinators it also resulted in turnover in the trial coordinator position. Awareness of impacts of turnover is critical to ensure the continuity in network facilitation and maintenance of farmer-researcher relationships in the transitioning of facilitation roles. However, institutionalizing such a role also implies a cost and the question emerges how permanent network costs could be covered.

While NOVIC achieved many positive outcomes, at times the trial coordinators and farmers alike experienced limitations in capacity, leaving gaps in communication and farmers wishing for greater engagement of researchers on their farm and at times resulting in turnover in participating farmers. A limitation of the current study was an inability to capture input from all farmers that participated in the NOVIC project as the researchers acknowledge it is likely that the farmers who did respond to surveys and interview requests represented those with the most positive experiences.

Conclusions

The 12 years of NOVIC offered valuable lessons of the challenges and opportunities in the network model to facilitate diversification of seeds options for organic farmers. The experience of NOVIC underscores the importance of recognizing the cost, time, and skills necessary to maintain and foster relationships in a participatory network and the potential return on investment in project impacts. The study shows how the initial objectives of breeders for the network to offer efficiently and effectively testing opportunities across farm environments remained challenging for quantitative data collection: both researchers and farmers struggled with capacity limitations, narrow evaluation windows of vegetable crop and evaluator consistency impacting quality of on-farm data. One of the greatest values of participatory on-farm research was deepening both farmer and researchers' knowledge of a crop, its seed and how it fits in the broader food and farming system. The results of this study provide evidence that NOVIC did achieve the projects' initial goals of expanding organic farmer's awareness and access to varieties that address their needs, facilitating adoption of organic seed sources, and developing and releasing improved varieties. In the case of NOVIC, however, evaluating outcomes only through the lens of variety adoption or breeders decision-making overlooks one of the greatest project impacts not initially articulated - deepening farmers engagement in the seed system. Plant breeding and seed system change is long-term work. Perhaps one of the greatest lessons learned was the importance of participatory decision making, flexibility and responsiveness necessary to engage the network over more than a decade resulting in expanded access to genetic diversity and the changes in awareness necessary to embed that diversity on farm.

References

Bonti-Ankomah S and Yiridoe EK (2006) *Organic and conventional food: A literature review of the economics of consumer perceptions and preferences*. Final report submitted to the Organic Agriculture Center of Canada. Available at:: www.organicagcentre.ca.

Brouwer B, & Colley M (2016). *Pacific Northwest organic plant breeding assessment of needs, 2016.* Port Townsend, WA: Organic Seed Alliance. Available at: www.seedalliance.org/publications.

Chable V, Dawson J, Bocci R and Goldringer I (2014) Seeds for Organic Agriculture: Development of Farmer Participatory Plant Breeding and Farmers' Networks in France. In. *Organic Farming, Prototype for Organic Agriculture*; Bellon S and Penvern S (eds.). Springer: Dordrecht, UK, pp. 382–400. https://doi.org/10.1007/978-94-007-7927-3_21

Chable V, Conseil M, Serpolay E and Le Lagadec F (2008) Organic Varieties for Cauliflowers and Cabbages in Brittany: From Genetic Resources to Participatory Plant Breeding. *Euphytica* **164** (2), 521–529. https://doi.org/10.1007/s10681-008-9749-7

Chiffoleau Y and Desclaux D (2006) Participatory plant breeding: The best way to breed for sustainable agriculture? *International Journal of Agricultural Sustainability* **4**, 119–130. https://doi.org/10.1080/14735903.2006.9684795.

Colley MR, Dawson JC, McCluskey C, Myers JR, Tracy WF and Lammerts van Bueren ET (2021) Exploring the emergence of participatory plant breeding in countries of the Global North—A review. *Journal of Agricultural Science* **159**, 320–338. https://doi.org/10.1017/S0021859621000782.

ClimMob (2022) Online software for agricultural citizen science. Available at: https://climmob.net/blog/

Costanzo A (2021) Farm-based organic variety trials: a collective experiment with an organic farmers' network. Organic Research Center, United Kingdom. Factsheet no. 2.

Darby H, Monahan S, Cummings E, Harwood H and Madden R (2013) 2012 Vermont On-Farm Spring Wheat Breeding Trials, Northwest Crops & Soils Program.

University of Vermont. Available at: https://scholarworks.uvm.edu/cgi/viewcontent.cgi?article=1225&context=nwcsp

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

Dawson JC, Rivière P, Berthellot J-F, Mercier F, Kochko P, Galic N, Pin S, Serpolay E, Thomas M, Giuliano S and Goldringer I (2011) Collaborative plant breeding for organic agricultural systems in developed countries. *Sustainability* **3**, 1206–1223.

de Buck A, Rey F, Rivière P and Petitti M (2021) *Guidelines for organic on-farm variety trials*. Andreoni MP, Petitti M, Bruszik A, and Rey F (eds). LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/06/LIVESEED-BOOKLET-5_FNL_web.pdf

EU (2022) Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007 (OJ L 150, 14.6.2018, pp. 1-92). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02018R0848-20220101

Entz MH, Kirk AP, Vaisman I, Fox SL, Fetch JM, Hobson D, Jensen HR and Rabinowicz J (2015) Farmer participation in plant breeding for Canadian organic crop production: implications for adaptation to climate uncertainty. *Procedia Environmental Sciences* **29**, 238–239.

Entz MH, Kirk AP, Carkner M, Vaisman I and Fox SL (2018) Evaluation of lines from a farmer participatory organic wheat breeding program. *Crop Science* **58,** 2433–2443.

Goldringer I, van Frank G, Bouvier d'Yvoire C, Forst E, Galic N, Garnault M, Locqueville J, Pin S, Bailly J, Baltassat R, Berthellot J-F, Caizergues F, Dalmasso C, de Kochko P, Gascuel J-S, Hyacinthe A, Lacanette J, Mercier F, Montaz H, Ronot B and Rivière P (2019) Agronomic Evaluation of Bread Wheat Varieties from

Participatory Breeding: A Combination of Performance and Robustness. *Sustainability* **12**, 128. https://doi.org/10.3390/su12010128

Healy GK, Emerson BJ and Dawson JC (2017) Comparing tomato varieties for productivity and quality under organic hoop-house and open-field management. *Renewable Agriculture and Food Systems* **32**, 562-572. https://doi.org/10.1017/S174217051600048X

Healy GK and Dawson JC (2019) Participatory plant breeding and social change in the Midwestern United States: perspectives form the seed to kitchen collaborative**.** *Agriculture and Human Values* **36**, 879-889.

Hubbard K, Wood L, and Zystro J (2021) *State of Organic Seed*. Organic Seed Alliance. Port Townsend, WA, USA. Available online: www.stateoforganicseed.org.

Hultengren RL, Glos M and Mazourek M (2016) *Breeding, Research, and Education Needs Assessment for Organic Vegetable Growers in the Northeast*. Cornell University, Ithaca, NY, USA. Available at: https://ecommons.cornell.edu/handle/1813/44636

Hultengren R (2017). *Establishing breeding priorities and developing varieties for organic vegetable growers in the Northeast*. MS thesis, Cornell University, NY USA.

Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert CC and Messmer MM (2011a) The need to breed crop varieties suitable for organic farming using wheat, tomato and broccoli as examples. *NJAS Wageningen Journal of Life Sciences* **58**, 193-205.

Lammerts van Bueren ET, Osman AM, Tiemens-Hulscher M, Struik, PC, Burgers SLGE and van den Broek RCFM (2011b) Are specific testing protocols required for organic onion varieties? Analysis of onion variety testing under conventional and organic growing conditions. *Euphytica* **184** (2), 181-193.

Lammerts van Bueren ET and Myers JR (eds) (2012) *Organic Crop Breeding*. Wiley-Blackwell, Hoboken, NJ, USA, 312pp. ISBN: 978-0-470-95858-2

Loria K (2021) *Improvement of Common Bean (Phaseolus vulgaris L.) for regional food systems in the Northeast US*. A PhD, Cornell University, Ithaca, New York. Available at: https://ecommons.cornell.edu/handle/1813/109670

Lyon A, Silva E, Zystro J and Bell M (2015) Seed and Plant Breeding for Wisconsin's Organic Vegetable Sector: Understanding Farmers' Needs. *Agroecology and Sustainable Food Systems* **39**, 601-624. https://doi.org/10.1080/21683565.2015.1017786

Lyon A, Tracy WF, Colley M, Culbert P, Mazourek, M, Myers, J, Zystro J and Silva EM (2019) Adaptability analysis in a participatory variety trial of organic vegetable crops. *Renewable Agriculture and Food Systems* **35**, 296-312. https://doi.org/10.1017/S1742170518000583

McKenzie LR (2013) *Breeding an open pollinated broccoli for organic production systems using participatory methods*. A MS thesis, Oregon State University, Oregon USA.

Murphy KM, Campbell KG, Lyon, SR and Jones SS (2007). Evidence of varietal adaptation to organic farming systems. *Field Crops Res*earch **102**, 172—177.

NOP (2002) National Organic Program, 7 CFR § 205.204. Available at: https://www.govinfo.gov/app/details/CFR-2002-title7-vol3/CFR-2002-title7-vol3-sec205-2 04

Ortolani L, Bocci R, Barberi P, Howlett S and Chable V (2017) Changes in Knowledge Management Strategies Can Support Emerging Innovative Actors in Organic Agriculture: The Case Study of Participatory Plant Breeding in Europe. *Organic Farming* **3**, 20–33. https://doi.org/10.12924/of2017.03010020.

Practical Farmers of Iowa (2022) US Testing Network (USTN). Available at: https://practicalfarmers.org/programs/field-crops/u-s-testing-network/

Rahman SME, Mahmuda AM, Young-Tack L and Mohammad ZI (2021) Consumer Preference, Quality, and Safety of Organic and Conventional Fresh Fruits, Vegetables, and Cereals. *Foods* **10** (105) https://doi.org/10.3390/foods10010105

Renaud ENC, Lammerts van Bueren ET, Paulo MJ, van Eeuwijk FA, Juvik JA. Hutton MG and Myers JR (2014) Broccoli variety performance under organic and conventional management systems and implications for crop improvement. *Crop Science* **54**(4), 1539-1554.

Rivière P, Dawson JC, Goldringer I and David O (2015) Hierarchical Bayesian Modeling for Flexible Experiments in Decentralized Participatory Plant Breeding. *Crop Science* **55**, 1053-1067. https://doi.org/10.2135/cropsci2014.07.0497.

Rivière P, Goldringer I and Rey F (2021) *Selecting the appropriate methodology for organic on-farm variety trials*. Rey F and Flipon E (eds.) LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/07/PUBLICATIONITAB_LIVESEED.final_.pdf

SeedLinked (2022) Collaborative trials on SeedLinked. Available at: https://seedlinked.com/sign-up-for-2022-collaborative-trials-on-seedlinked/

Shelton AC and Tracy WF (2016) Participatory Plant Breeding and Organic Agriculture: A Synergistic Model for Organic Variety Development in the United States. *Elementa Science of the Anthropocene* **4**, 1–12. https://doi.org/10.12952/journal.elementa.000143.

Singh SP, Teran H, Lema M and Hayes R (2011) Selection for dry bean yield on-station versus on-farm conventional and organic production systems. *Crop Science* **51**, 621-630.

Snapp S (1999) Mother and baby trials: a novel trial design being tried out in Malawi. *Target – Newsletter of the Soil Fertility Research Network for Maize-based Cropping Systems in Malawi and Zimbabwe*. **17** (8).

Snapp S (2002) Quantifying farmer evaluation of technologies: the mother-baby trial. In: Bellon MR and Reves J (eds.) *Quantifying analysis of data from participatory methods in plant breeding*. Mexico, DF: CIMMYT.

Sperling L, Ashby JA, Smith ME, Weltzien E, and McGuire, S (2001) A framework for analysing participatory plant breeding approaches and results. *Euphytica* **122**, 439-450.

USDA/NASS (2019) National Agricultural Statistics Service, 2019 Organic Survey. Available at: https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Organic_Production/index.php

van Bruggen, AHC, Gamliel A and Finckh MR (2016) Plant disease management in organic farming systems. *Pest Management Science* **72**, 30–44. https://doi.org/10.1002/ps.4145

Vincourt P and Carolo P (2018) Alternative breeding process: at which extent Participatory Breeding should modify the concept of ideotypes in plant breeding? *OCL Journal. EDP Sciences*. https://doi.org/10.1051/ocl/2018061

Zystro J, Colley M, and Dawson J (2018) Alternative Experimental Designs for Plant Breeding. *Plant Breeding Reviews* **42**, 87-117.

Chapter 5

How the seed of participatory plant breeding found its way in the world through adaptive management

Published as:
Colley MR, Tracy WF, Lammerts van Bueren, ET, Diffley M and Almekinders CJ (2022) How the Seed of Participatory Plant Breeding Found Its Way in the World through Adaptive Management. Sustainability **14**(4), 2132.

Abstract

Participatory plant breeding (PPB), where farmers and formal breeders collaborate in the breeding process, can be a form of agricultural niche innovation. In PPB, new varieties are commonly adopted by the farmers involved and shared through seed networks, but few are released and commercialized; thus, the variety remains a niche innovation, used within a limited network of beneficiaries. PPB is increasingly emerging to address the needs of organic farmers in the Global North, yet barriers to implementation and institutionalization limit the ability to embed PPB into commercial channels of seed distribution. This case study of a PPB project in the US explores, through the lens of adaptive management, critical points in the commercial release of an organic sweet corn variety, which expanded the innovation beyond the niche environment. The authors show how evolving the actors' roles, expanding the network of participants, and leveraging opportunities that emerged during the process aided in shifting institutional and market norms that commonly restrict the ability to embed PPB varieties in the formal seed system. They further demonstrate that distribution through the formal seed system did not limit access through informal networks; instead, it created a ripple effect of stimulating additional, decentralized breeding, and distribution efforts.

Keywords: participatory plant breeding; adaptive management; seed systems; seed networks; niche innovation; organic seed systems; ripple effect

Introduction

Scope and relevance of the study

Participatory plant breeding (PPB) is a type of agricultural innovation, implemented internationally, wherein farmers, professional breeders, and other actors collaborate in variety development, commonly to address the needs of farmers underserved by the dominant seed regime (Witcome et al., 1996; Welzien et al., 2003; Morris and Bellon, 2004; Ceccarelli and Grando, 2019). PPB is a promising method to breed for organic systems and address shortages in diversity and quantity of organic seed available (Chiffoleau and Desclaux, 2006; Dawson et al., 2008; Shelton and Tracy, 2016; Colley et al., 2021). Arguments for the methodology include improving heritability by selecting under the environment of intended use, high rates of adoption at lower costs, and developing varieties that can be continually selected to improve adaptation over time (Chiffoleau and Descalux, 2006; Dawson et al., 2008; Shelton and Tracy, 2016).

One of the reasons why PPB is a good fit for organic systems is that organic farms are characterized by higher within and between farm agroecological and market variability than conventional farms (Chiffoleau and Desclaux, 2006; Dawson et al., 2008; Shelton and Tracy, 2016). This presents challenges for privately financed breeding programs to recoup expenses in plant breeding and fully serve the scale of the market, as well as the diversity of needs for organically produced seed of suitable varieties (Borgen, 2009; Mendum and Glenna, 2010; Hubbard and Zystro, 2016). While public funding for organic plant breeding increased over the last decade, the short-term nature of public grants often restricts the capacity to deliver finished cultivars to market (Borgen, 2009, Mendum and Glenna, 2010; Hubbard and Zystro, 2016; Colley et al., 2021).

PPB is proposed as a cost-effective model for addressing decentralized organic farmers needs for adaptation to specific agroecological conditions (Ceccarelli and Grando, 2006; Dawson et al., 2008), yet the barriers to implementation restrict institutionalization, including regulatory constraints, institutional norms, and limitations in financing (Mendum and Glenna, 2010; Hubbard and Zystro, 2016; Colley et al., 2021). Organic farmers are legally obligated to use organically produced seed, when available in appropriate form, quality, and quantity, as part of their certification requirements in Europe (EC 2018/848) and the US (CFR § 205.204) (EC, 2020; USDA 2002). As such, organic regulations are, in part, stimulating organic breeding activities, including PPB approaches (Hubbard and Zystro, 2016; Shelton and Tracy, 2016; Colley et al., 2021). The Organic Seed Alliance (OSA) conducts a national survey of organic producers every five years, as part of its State of Organic Seed (SOS) project to track progress, challenges, and opportunities in expanding organic seed use in the United States (US) (Dillon and Hubbard, 2011; Hubbard and Zystro, 2016; Hubbard et al., 2021). Surveys (conducted in 2010, 2015, and 2020) demonstrated that most organic producers in the US still rely on conventionally bred and produced seed for at least a portion of their crop production. Addressing barriers to PPB presents an opportunity to fill some of these gaps in the organic seed supply.

In most PPB projects, new varieties are commonly adopted by the farmers involved and shared through seed networks or collectives, but often are not formally released and commercialized (Chable et al., 2014; Colley et al., 2021). Projects generally start with agreements on the targeted traits and a breeding strategy but lack a clear strategy for the eventual dispersal and long-term stewardship of the variety, beyond the actors involved; thus, the new variety remains a niche innovation within a limited network of beneficiaries. Commercial seed systems commonly operate within the dominant agricultural innovation paradigm of centralized research and dissemination of innovation, as highly uniform varieties, suited to broad geographical distribution with markets and secured through restrictive intellectual property rights (IPR) (Ortolani et al., 2017). These IPR systems, supported by institutions and laws, implicitly create barriers to development of alternative seed economies. An example is the formal International Union for the Protection of New Varieties of Plants (UPOV) variety registration system, which is enforced in many countries (International Treat for Protection of New Varieties (UPOV); Grain, 2015). A variety released under UPOV must be highly distinct, uniform, and stable (DUS), traits that are not always valued in organic systems that prize on-farm biodiversity (Chable et al., 2014; Ortolani et al., 2017). These IPR systems are restrictive for fostering genetic diversity in agroecosystems and often reinforced in the institutional norms of academia, which regulate the IPR of public plant breeders in the US (Mendum and Glenna, 2010; Tracy et al., 2016). Overcoming these barriers often necessitates a paradigm, where formal release and commercialization are replaced with informal innovation networks, seed is exchanged (rather than sold), and conservation and maintenance are done by farmer innovators.

While innovation networks, based on the exchange of knowledge among diverse actors, is clearly a valuable model for fostering PPB and expanding on-farm biodiversity (Ortolani et al., 2017), there is also a need to leverage agroecology and PPB to expand beyond the niche innovation, in order to transform the dominant agro-food regime and expand the diversity of economic models for fostering PPB (Levidow et al., 2014). Barriers to commercialization by the formal seed registry system in Europe has perhaps incentivized the development of networks of on-farm innovation and exchange of bio-diverse seed (Bocci et al., 2012; Chable et al., 2014; Maze et al., 2020). Yet, the recent allowance in the European Union (EU) regulations for organic agriculture to apply for registry of heterogenous varieties may influence the potential for alternative seed economies (EC, 2020). Plant breeders in the US are not required to register new varieties in a variety registration system, as the US has not signed the UPOV'91 agreement. This has allowed the emergence of independent farmer plant breeders, commonly releasing open-pollinated varieties through small, regionally-based organic seed companies (Deppe, 2020).

Background of the current study

In the current study, we explore the experience of an ongoing participatory plant breeding (PPB) project on sweet corn in the US, initiated in 2008 (Shelton and Tracy, 2015; Colley et al., 2021b). The project provides the opportunity to analyze the challenges and opportunities encountered in the development, release, and seed distribution of the variety. In particular, the authors identified the critical points in the process of navigating issues of ownership, IPR, financial returns, and variety maintenance, related to the decision to release and commercialize the variety with a seed company, rather than through informal networks. The project members had no pre-determined plan to do so and, in retrospect, were not fully aware of the challenges they would encounter to address institutional barriers and navigate the terms of release to achieve the economy of scale for broad commercial access, while simultaneously fostering access and benefit sharing for smaller regional companies and independent farmer-breeders.

This PPB project was initiated to address organic farmers need for suitable varieties of organic sweet corn seed. Organic acreage of sweet corn in the US is less than 5% of the total seed market, so none of the large vegetable breeding companies are breeding sweet corn nor producing sweet corn seed under certified organic conditions. Typically, in conventional breeding programs, crop nutrition is supplied by synthetic fertilizers; weeds and other pests are controlled with synthetic pesticides, and seeds are treated with synthetic fungicides and insecticides. These options are not allowed under certified organic crop production. This creates two hardships for organic sweet corn farmers: one, they have extremely limited access to varieties that were developed for the very different environmental conditions and management challenges on organic farms; and, two, the inbred parent lines used to produce F1 hybrid varieties often do particularly poorly under organic conditions and, in many cases, are unable to establish a canopy large enough to compete with weeds and produce robust yields. Thus, it is difficult and costly, if not impossible, to produce seed of such varieties under certified organic conditions. When seed can be produced under certified organic conditions, it is often of lower quality and costly, due to the production challenges. The lack of availability of organically produced seed forces organic sweet corn growers to purchase conventionally produced seed that is not treated with seed treatments after harvest.

Organic sweet corn producers are challenged by the lack of access to organically produced seed of appropriate varieties, according to the last three State of Organic Seed Reports. In these national surveys, in the US, organic producers were asked to rank the most important crops and traits to breed for in organic systems. In each year, corn (Zea mays) (maize) ranked in the top four priority crops for breeding with yield, flavor, good germination, and disease resistance as top priorities. This is understandable, as well over 95% of sweet corn acreage in the US is devoted to the production of F1 hybrid varieties, and most farmers, shippers, and processors prefer the uniformity offered by these hybrids. Since most of the commercial production of sweet corn uses the F1 hybrid varieties, there is little incentive for seed companies to invest in the development of open-pollinated (OP) varieties. So, except for the small organic breeding community, there is essentially no breeding done for open-pollinated varieties of sweet corn. Many organic farmers are interested in open-pollinated varieties, because they can produce and save their own seed and adapt the variety to their unique conditions. Another advantage of open-pollinated cultivars is that it is often easier to produce seed of OPs than of conventional F1 hybrids under organic conditions. The OP varieties are also more vigorous and compete well with weeds. All of these characteristics are needed for robust seed production under organic conditions. There are a few independent breeders in the US developing open-pollinated sweet corn varieties; however, most of these are in the Pacific Northwest, and the varieties developed (at the time of the current study) were not broadly adapted and well-suited to production in other regions of the country.

The current study is based on a PPB project that was initiated to fill a gap in access to an organically adapted variety of sweet corn, with clear motivations and roles among actors involved in the breeding process (Shelton and Tracy, 2015; Colley et al., 2021b). Achieving their long-term objectives required strategic decisions to embed the innovation in the broader operating environment, i.e., the seed system. Herein, we identify the critical points in the process of moving from niche work to a broader operating environment, to amplify the scale of impacts, support access to organic seed, and stimulate ongoing breeding efforts. The initial project team, including a formal breeder and associated graduate students, certified organic produce grower, and non-profit project facilitator, evolved over the span of the project, and a broader network of participants developed. The actors developed pathways for the transfer of innovation by applying the concept of adaptive management. Adaptive management refers to the process of creating strategic innovation pathways, based on key decisions at critical points, emerging in the process that encompass social, economic, marketing, psychological, and legal considerations (Klerkx et al., 2010; Camancho-Villa et al., 2016; Ocvirk et al., 2018). In this case, the effort to release and commercialize the variety raised several issues that the group had not previously considered. Forging a pathway forward required clarifying ownership and IPR, variety commercial release mechanisms, stock seed production, and defining roles after release. The authors elaborate and clarify what these issues entailed and how the group opted for pathways that went in directions different from the current industrial paradigm. In addition, the authors demonstrate how these pathways supported the impact of the project.

Materials and methods

In the current study, the authors analyzed the process of the multiplication and diffusion of varieties developed in the ppb project and, thus, covers a time-trajectory after the ppb project itself. The breeding process and methodology of the PPB project is detailed in a prior study by Shelton and Tracy (2015). The current study is recounted based on the experiences of the project facilitator and the breeder (first and second author). The project facilitator, breeder, and associated graduate students kept field notes from meetings and visits conducted during the project. The authors also collaborated with other project members in recounting project details for accuracy and completeness. Project outcomes were further documented by consulting additional actors who entered later in the process of seed production and distribution of the sweet corn variety, including an Australian seed company, an independent farmer breeder, representatives from first company to commercialize the variety (High Mowing Organic Seeds), and the stock seed producer. The seed companies provided sales data to document seed distribution. Media promotion of the variety was assessed through the Meltwater tracking tool (www.Meltwater.com).

Results

The results are herein described as three project phases: Section 3.1, actors' motivations in the initiation of the breeding process; Section 3.2, from breeding to commercialization: the choices to be made; and Section 3.3, project outcomes, impacts, and on-going PPB roles. Four key issues requiring strategic decision-making (choices) are presented in Section 3.2, including: Section 3.2.1, clarifying ownership and IPR; Section 3.2.2, determining the variety release and terms of release; Section 3.2.3, establishing plans for stock seed production and maintenance; and Section 3.2.4, defining the roles of actors, following release.

Actors and motivations in the initiation of the breeding process

Farmers Martin and Atina Diffley of Organic Farming Works LLC are well-known for their consistent production of high quality organic sweet corn in the Minneapolis, Minnesota region of the US. In 2007, with more than 30 years of experience in growing organic sweet corn at his farm, Martin Diffley shared frustrations regarding sweet corn varieties with breeders Dr. John Navazio (OSA) and Dr. William Tracy, University of Wisconsin (UW)-Madison. Diffley depended on the F1 hybrid variety 'Temptation' for his early season sweet corn production, which was not available as organic seed. 'Temptation', owned by Monsanto (now Bayer), provided superior germination rates in cool spring soil conditions, compared to other varieties he had grown; however, Diffley desired a reliable, certified organic seed source for philosophical and regulatory reasons. Diffley was not alone, as OSA and Tracy heard similar needs expressed by other organic producers. The need was later reflected in the 2010 US State of Organic Seed producer survey, in which organic producers reported "yield, quality, and emergence" as top breeding priorities for organic corn (Dillon and Hubbard, 2011). There was also a desire to develop sweet corn varieties whose seed could be reliably and cost-effectively produced under organic conditions, in accordance with the United States Department of Agriculture (USDA) National Organic Program (NOP) regulations. OSA and Tracy's program shared the mission of serving the public good by breeding crops with qualities that optimize organic agriculture and expand access to organic seed sources. Thus, Navazio and Tracy proposed (to Diffley) to collaborate on a PPB project to develop an organically bred, on-farm, reproducible, open-pollinated, sugary enhanced (SE) variety with good eating quality, yield, and emergence that Diffley could produce. The actors agreed to collaborate in developing a new variety to suit Diffley's needs, with the shared acknowledgement of the broader goal of expanding access and benefit sharing to additional farmers, in order to maximize positive impacts on organic agriculture. The project launched with the clear goal of breeding a new variety to benefit organic farmers, but with no discussion as to the ownership, name, production, maintenance, or distribution of the new variety.

The partners from the three entities, farming couple from Organic Farming Works LLC, Farmington, MN, USA, and breeders of OSA, Port Townsend, WA, USA, and UW-Madison, Madison, WI, USA, devised a breeding scheme that leveraged their collective knowledge and resources. They collaborated in all phases of breeding and decision-making, i.e., prioritizing traits, making selections in the field, and negotiating the naming and final release of the new variety with shared investments in the breeding efforts. Tracy's program provided the initial germplasm, advised on breeding methods, including utilization of a winter nursery for generating new crosses, and graduate students (Jared Zystro and Adrienne Shelton) to support the breeding activities, including data collection and reporting. OSA's team of researchers facilitated the knowledge exchange and decision-making process and supported the breeding methods, evaluation, and reporting. Diffley led the identification of breeding goals, managed the breeding trials at his farm in Minneapolis, Minnesota, and collaborated in the evaluation of breeding plots. The group looked to Diffley to prioritize traits and assess quality, based on his knowledge of the market standards and agronomic challenges of the farm's environment. The three entities met annually to discuss breeding strategies, evaluate results of the prior year, and set field plans for the following year. The initial material consisted of two breeding populations, each based on intermating four commercial sugary enhancer sweet corn F1 hybrids. One population was roughly five days earlier in maturity and designated 'early', the other designated 'late'. The breeding process followed a recurrent full-sibling selection, with annual evaluation of replicated plots of breeding families on Diffley's farm and regeneration and crossing of remnant seed from selected families at a winter nursery in Chile, managed by Tracy's program. As previously mentioned, details on the breeding methodology and timeline of the first 4 years is described by Shelton and Tracy (Shelton and Tracy, 2015). The three entities convened each year at peak harvest to evaluate the entire trial, including bite-testing ears from each plot. Disease resistance and agronomic performance were also evaluated (Shelton and Tracy, 2015).

From breeding to commercialization: the choices to be made

The three initial entities agreed to share equal decision-making power throughout the release process, as they had from the start, and worked together to devise a strategy that met both the hurdles in releasing a new variety and their collective goals. Unlike many PPB projects, the primary beneficiary, Diffley, had no experience or interest in seed production. This required the actors to consider the impacts of their decisions and adopt new roles to determine the pathway and achieve their objective of broad access to organic seed. The university and non-profit actors needed to fulfill the intent of the funders, USDA Organic Research and Extension Initiative (OREI), and the Organic Farming Research Foundation (OFRF), Santa Cruz, CA, USA, to serve organic stakeholders through broad access and benefit sharing, though only one farmer participated in the initial breeding. The university was also constrained by federal and institutional rules and procedures, regarding the ownership of IP. Ultimately, the actors recognized the need to engage a broader network of participants to accomplish their goals and address the limits of their collective ability to produce, market, distribute, and maintain seed of the variety. They expanded project boundaries and engaged additional actors to embed the variety within the broader commercial operating environment. The roles of the various project participants, throughout project initiation to variety release, are summarized in Table 1.

Table 1. Roles of project participants throughout project initiation to variety release.

	Farmer (Martin Diffley, Organic Farming Works LLC (Farmington, MN, USA)	**NGO (Organic Seed Alliance) (OSA) (Port Townsend, WA, USA)**	**University (University of Wisconsin-Madison) (Madison, WI, USA)**	**Seed Company (High Mowing Organic Seed) (HMOS) (Wolcott, VT, USA)**
Initial project goals	Ensure seed security, crop productivity, and market acceptance.	Expand diversity, quality, and quantity of organic seed for farmers.	Breed for organic and regional needs of farmers.	Fulfill variety needs of organic farmers while supplying 100% certified organic seed.
Project roles in participation	Provide field space and farming knowledge. Lead prioritization of traits. Evaluation of breeding lines.	Facilitation of breeding project. Networking with stakeholders outside of project actors.	Provide breeding materials, technology, and infrastructure.	Testing late generation breeding populations with critical knowledge of market demands.
Project roles during and after release	Participate in evaluation and field seed selection with stock seed producer.	Negotiate and manage contract terms and financial transactions. Promotion and marketing of variety. Management of stock seed. Continue PPB in sweet corn	Advising on stock seed variety maintenance protocols. Continuing to select and breed divergent populations out of initial project breeding population	Finance seed production and royalties to support ongoing variety maintenance and future PPB projects. Manage variety marketing and distribution.

Clarifying Ownership and IP

Breeding activities were initiated in 2008, with partial funding from OFRF, and continued in 2009, with 4 years of funding from the OREI, as an activity embedded in the broader collaborative project, the Northern Organic Vegetable Improvement Collaborative (NOVIC). This project was subsequently renewed twice, providing 12 years of funding, which allowed the project team to continue breeding new varieties out of the original population for adaptation in diverse regions. The variety released and commercialized through this PPB project was ultimately named 'Who gets kissed?'. At the time of release, the actors did not yet have additional funding secured to support the breeding partners ongoing collaboration in stock seed management and additional participatory plant breeding activities.

All three parties were committed to the concept of open access, which would allow others to use the variety for any purpose they wished, especially adapting the variety to their region and farming system. However, as an employee of the University of Wisconsin, Tracy was constrained by federal, state, and university rules and regulations that made this challenging (Shelton and Tracy, 2016). It is common in the USA that a contract for a variety release and any royalties are managed not by the breeder but by the university technology transfer department. It is also common in the US university system for administrators to collect a significant portion of the royalties, rather than returning it all to the breeder to support their program. The Wisconsin Alumni Research Foundation (WARF) is the designated technology transfer organization for the University of Wisconsin-Madison, and all potential IP developed at UW-Madison must be disclosed to WARF. WARF has the right of first refusal on all disclosed IP. If WARF refused, then the USDA has the right to choose to claim ownership.

Applying restrictive IP, in the form of a utility patent, plant variety protection, or restrictive license, was not only financially impractical, given the project budget, but antithetical to the project's aim of broad access and benefit sharing and desire to stimulate ongoing breeding efforts, utilizing the heterogenous variety. Upon disclosure, Tracy and WARF officials discussed the unique partnership, variety, and philosophical issues of the organic community, regarding IP. WARF officials chose not to pursue IP on the variety, as did, in turn, the USDA; thus, the rights to release and commercialize the variety was provided to the project partners.

Variety Release and Terms of Release

The actors realized the challenges of stabilizing an open-pollinated population and recognized that achieving the uniformity level of an F1 hybrid was not possible. Thus, the team needed to determine when the population was uniform enough and of high enough quality to release as an open-pollinated variety. Release of a heterogenous variety does not present a regulatory problem in the US, as there is no formal registry system, as in Europe and elsewhere. The group, with Diffley's lead, decided that, when 75% of the ears were of exceptional size and eating quality to meet Diffley's premium market, then the population was ready for commercial production and release. In the 2013 evaluation of the breeding populations, the partners collectively determined that the late maturing breeding population had reached this point and it was, thus, ready for release (Shelton and Tracy, 2015).

The network of collaborators involved in the NOVIC project served as a testing network, with on-farm and on-station variety trials in four states across the Northern tier of the US (Oregon, Washington, Wisconsin, and New York). This provided the opportunity to assess performance across other Northern environments and raise awareness of the new variety. The NOVIC network exchanged varieties and shared trial results with organic seed companies, in addition to farmers. The breeders provided samples of the sweet corn to companies for trial, and one company, in particular, expressed interest in commercialization, High Mowing Organic Seeds (HMOS), located in Hardwick, VT, USA. This company only sells certified organic seed and distributes nationally. At that time, there was not organically bred F1 hybrid sweet corn varieties on the market, and the open-pollinated varieties were highly variable and lacked consistent yield and quality. Thus, a new open-pollinated variety, of commercial quality that they could produce and sell would fill a gap in their market. There were no regional seed companies or farmers who expressed interest in producing the seed at that time. The actors agreed to explore partnering with HMOS to commercialize the variety but needed to carefully consider the terms of a contract for commercialization, in order to ensure they could achieve the project goals of wide accessibility, as well as the breeders' ability to remain involved in variety maintenance through this pathway.

The actors had to consider that the public funding source supported the breeding costs, but it did not support the costs of commercialization or ongoing stock seed management. The actors also did not know if there would be another grant cycle to support ongoing breeding with the two populations. Recognizing their dependance on a single, unstable funding source motivated the actors to explore the potential to recoup a financial return on commercialization, in order to support their ongoing PPB efforts.

The three partners agreed to equally share in any revenues. The actors negotiated for royalties on commercial sales, without IPR to support their ongoing involvement. For the seed company to ensure enough sales to support their investments in marketing and production they requested exclusive access to the stock seed and asked that it not to be released to other companies, at least for the first three years. This agreement provided a sales advantage to the seed company and allowed the breeders to work directly with one company in the management of stock seed. The breeders were concerned that selling to only one company would too narrowly restrict access to the diversity of scales of organic seed companies emerging and serving regional markets. Thus, the company agreed to sell wholesale quantities of seed of the variety to smaller companies for repackaging to extend the channels of distribution. Without IP, the variety could also clearly be purchased for the purpose of regenerating for on farm use and/or for additional breeding efforts.

Seed stock production and maintenance

The quality and stability of varieties of many crop species may be managed with minimal selection toward the ideotype, commonly managed by the seed company. This is true of highly self-pollinated crops, such as common bean, tomato, and oats. Cross-pollinated crops, such as sweet corn, spinach, beets, and the cucurbits, are heterogenous and heterozygous and require considerable diligence to guard against outcrossing with foreign pollen, inbreeding, and natural selection away from quality traits. Given the demand in the organic community for non-GMO crops, as well as the free crossing nature between sweet corn and grain corn pollen, contamination is also of great concern. The group realized that increasing and maintaining the new variety would require continual monitoring and selection to ensure no genetic drift or contamination occurred. This factor weighed on the actors' negotiations of terms of release and commitments to continuing collaborating in the ongoing stock seed management. The actors desired to work directly with a stock seed producer, with secure isolation from GMO corn crops, who also held an interest in collaborating in the monitoring and selection of the variety. They identified an ideal sweet corn seed producer and negotiated with HMOS to contract for seed production with this farmer. The three actors committed to visiting the farmer during production and directing the seed selection process. They also committed to routinely screening and selecting the stock seed, in a high disease pressure environment (Madison, WI, USA), every few years, to ensure the seed was produced under low disease for quality purposes (Dixon, MT, USA) but resistance maintained by periodic selection under the high-pressure environment. Commitment to these activities contributed to the need for additional funding the support their costs of involvement.

Defining roles following release

The parties drafted a contract, stipulating the terms of release, that addressed exclusivity, royalties, wholesale, and retail sales. It also specified collaboration between the company and breeders in stock seed management, promotion, and marketing. The contract clarified that the co-breeders served as equal parties (OSA, UW-Madison, and Organic Farming Works LLC), and they agreed to equally share in the royalties to support their continued collaboration. The non-profit served as the fiscal entity, for the purpose handling the contract and associated costs of stock seed production and distribution of royalties. In this instance, the non-profit's freedom to operate facilitated the unconventional participatory process and shared benefits.

The breeders and seed company also shared concerns of market acceptance, as the ears were more variable than a F1 hybrid, with mainly white and yellow bicolor kernels and occasional light pink ones. Thus, they carefully considered the naming, storytelling, and promotion of the variety, to acknowledge that a variety could retain a level of diversity, while providing a quality product. The challenge of public acceptance of intravarietal diversity presented the opportunity to educate on the value of genetic diversity and long history of farmers' role in improving, adapting, and stewarding populations from land races to heirloom varieties. The non-profit, university breeder, and seed company worked together in their promotion of the project to recount the farmer-centric participatory process and value of diversity, adaptability, and farmer-stewardship in organic systems. They also chose the name, 'Who gets kissed?' to reflect the historical acceptance of diversity in a variety. Historically, many communities collaborated in annual seed harvests and sometimes played games to keep the work fun. One big community task was to remove the husks on the ears of corn after harvest, so they could be stored for winter. The story goes that one playful version of the husking circle was that whoever husked an ear that had a red kernel amidst the white and yellow rows got to pick who to kiss in the circle. This lighthearted game reflects the historical acceptance and even celebration in retaining genetic and phenotypic diversity within a variety. The actors collaborated in developing a press release, social media, and marketing materials that promoted the participatory breeding process in variety improvement and retention of biodiversity. The media picked up the story, resulting in more than 100 media articles reporting on the project's story across the USA (Ocvirk, 2018).

Project outcomes, impacts, and ongoing PPB roles

In the first year of sales, 'Who gets kissed?' brought in the highest recorded sales of a new release at High Mowing Organic Seeds within the first year than any previous new release from the company. Sales went to 49 US states and Canada, with more than 2500 kg sold by 2020. Wholesale distribution resulted in sales by at least 14 regional seed companies in the US. The breeding team continued to maintain the variety quality through trials and stock seed production, in partnership with an organic seed grower in Montana, USA. In 2018, an organic seed company, by the name of The Biodynamic Seed Company, in Australia, trialed 'Who gets kissed?', as they were seeking an open-pollinated sweet corn to produce for the Australian organic seed market. In Australia, all imported corn seed is required to be treated with chemical fungicides prior to import, and there are no domestic companies breeding or producing sweet corn seed for the organic market. Thus, an open-pollinated variety of high quality was desired for domestic production. 'Who gets kissed?' performed very well in their trials, and the company requested approval to produce and distribute the variety to wholesale and retail seed companies. The company willingly offered 10% royalties, recognizing the value of supporting the ongoing participatory breeding efforts. Production and commercial sales launched in Australia in 2021, with 21 kg sold in the first year.

After the release of 'Who gets kissed?', the Organic Seed Alliance and UW Madison breeders continued to collaborate in farmer-participatory sweet corn breeding for organic production. The initial breeding process resulted in two distinct, but related, populations, differentiated by the timing of maturity (early versus late). As previously mentioned, 'Who gets kissed?' was derived from the later-maturing population, which suited the climate of the Upper Midwest region, where Diffley farmed, as well as many other regions of the US. However, it was too late maturing to suit producers in mild climates, such as the northern maritime Olympic Peninsula of WA (US), where the Organic Seed Alliance collaborated with farmers in on-farm breeding. Farmers in this region were similarly dependent on 'Temptation', which concerned the local organic foods cooperative that purchased produce from local growers. Thus, the Food Co-op of Port Townsend, WA, US, provided an initial year of funding for the team to launch a participatory breeding project, which they called "Olympic Sweet", utilizing the "early population", and later continued under the scope of the NOVIC project. Three local farms collaborated in the Olympic Sweet breeding project, including an educational farm that integrated the half-sibling selection methods into their applied farmer training program. In Wisconsin, Tracy continued selecting out of 'Who gets kissed?', in order to shift the population to achieve an earlier and more uniform timing of maturity. The variety is tentatively called 'Who gets kissed too?'.

Tracy has also developed a variety from the early population, called 'Quick Kiss'. Additionally, at least three farmer-breeder projects utilized 'Who gets kissed?' and the early population as a breeding parent, and one was released in 2020 as a new variety, 'Sweet kisses', pledged under the Open Source Seed Initiative (Open Source Seed Initiative, 2021). Actors' motivations, from a philosophical, economic, agronomic, and practical point of view, influencing their decisions for the variety release pathway, are summarized in Table 2.

Table 2. Actors' motivations, influencing decisions for variety release pathway.

	Philosophical	Economic	Agronomic	Practical
Farmer, Organic Farming Works LLC	Preference for organic seed and avoiding seed from companies that sell GMOs.	Compensation necessary to continue aiding in variety selection to maintain quality.	Seed available in adequate quantity, quality, and price to serve needs of commercial-scale organic producers.	Needs someone else to manage seed production and distribution, but willing to continue participating in stock seed selection.
Plant breeders of UW-Madison	Serve public good by making the variety accessible to farmers and breeders for ongoing variety improvement efforts.	Financial returns needed to support ongoing breeding and variety maintenance and improvement work.	Important to maintain qualities of good emergence and eating qualities.	Can provide field space for variety evaluation and continued breeding, but not for seed production.
NGO (OSA)	Avoid restrictive IP. Expand access to organic seed of the variety to maximize impacts.	Financial returns necessary to support NGO involvement in education on the variety and breeding process and support of stock seed maintenance.	An organically available sweet corn reduces farmers' dependance on non-organic seed sources.	Able to advise seed producer and seed company and support promotion of variety through press releases and other media.

Discussion

The current study demonstrates how the adaptive management a PPB product can develop from an agricultural niche novelty into an innovation that is embedded in the broader environment to achieve economies of scale and support the sustainability of a PPB program. The authors show that addressing the emerging obstacles, responding to opportunities, and expanding the roles of actors and the network of participants was necessary in shifting institutional and market norms that commonly restrict the ability to embed PPB varieties in the formal seed system. This required negotiating with external policy makers, such as university administrators, and creatively developing alternative pathways for seed production and distribution. The actors also had to consider their own roles, beyond the breeding process, and commitments to the project long term. The variety release pathway in the current study was forged in response to the unique context and circumstances the actors faced. While the experience was unique, the lessons learned reinforce that PPB is, by nature, a dynamic innovation process, based on knowledge exchange and activities, tailored to address the context specific needs and abilities of participants. For this reason, being responsive, creative, flexible, and willing to engage with unusual commercial partners, i.e., being adaptive in the management of the process, is critical in innovation systems, such as PPB, that do not follow a prescribed pathway for the transfer of innovations. 'Who gets kissed?' achieved commercial success and sustained sales over the past 8 years, but that is only one lens of success.

The non-restrictive release was critical to ensure that distribution through the formal seed system could be managed in a manner that did not limit access through informal networks, but instead created a ripple effect of stimulating additional, participatory, and independent breeding and distribution efforts. While the current PPB project served the participating farmer's needs and led to breeding additional varieties for diverse climates, the authors acknowledge that the agronomic value of the variety is limited in scope. There are more challenges to be faced when varieties spread to other parts of the world, where growing conditions, pests, diseases, and consumer preferences differ from those in the target region. The involvement of only one farmer in the initial breeding project presented a risk of limiting project beneficiaries and, as pointed out by Chiffoleau and Desclaux (2006) potentially strengthening the power of decision-making in select farmers of high socio-economic status, who are not representative of all stakeholders concerned. This consideration weighed upon the actors' motivations to ensure the variety was released in a manner that expanded access and stimulated additional farmer-participatory and independent breeding efforts.

The concept of ownership and IP, in this case, as with most PPB projects, is contrary to the intent of the PPB program serving the public good. As such, the project partners chose to develop a formula that combined broad access with benefit sharing. The reality is that many public breeding institutions are underfunded and encouraged by policy makers to pursue private investments and royalties on innovations to support not only their programs but institutional administration, as well. In this case, the formal breeder was able to convince the university officials that IP was not appropriate. The participatory nature, with multiple actors undertaking the breeding activities, and program goals of the government funding agency helped influence the university's decision not to pursue IP. In this case, the university breeder also held seniority in the department, and the authors acknowledge that the ability to negotiate is not always equitable in university systems. The authors have heard similar reports from other university breeders that if the farmer is a primary decision-maker in on-farm breeding, rather than the breeder, then determining ownership is much more ambiguous, resulting in university officials opting not to pursue IP. This underscores the need to address university policies, if we are to institutionalize PPB in public programs.

The opportunity and decision to collaborate with a willing commercial partner, who committed to marketing the seed and was willing to share benefits, was an important feature in the sustainability of this PPB initiative. Many PPB programs depend on grant funding, as in the current case, and limits in grant timelines often limits the ability to see projects to full fruition (Colley et al., 2021a; Hubbard and Zystro, 2016; Mendum and Glenna, 2010). Fortunately, in the case of NOVIC and the PPB sweet corn project, the funder (OREI) allows projects to apply for up to three renewals, recognizing the long-term nature of plant breeding. At the time of the release of 'Who gets kissed?', the actors did not know if renewed funding would be granted, influencing the desire to ensure some economic return to sustain their participation. Ultimately, the royalties alone would not have sustained the extent of the continued breeding work, but it did provide financial flexibility to support stock seed production and marketing efforts. Ironically, royalty funds also covered the costs of open access publishing of the current article. In the current study, the willingness of the seed company to provide royalties, without restrictive IP, is a promising precedent in supporting PPB. There is evidence that this arrangement is becoming more common in the US, with organic and regional seed companies supporting independent breeders through royalties, as well (Deppe, 2020).

Like many PPB programs, one of the primary goals of the initiative was the development of genetically diverse, open-pollinated populations that could be selected to evolve over time and adapted to new environments. The actors contended with the challenge, encountered by many other PPB practitioners, of defining the ideotype of a variety and assessing marketability, when the goal of uniformity is moderated by breeding objectives of adaptability, resilience, and retention of biodiversity (Chiffoleau and Desclaux, 2005; Vincourt and Carolo, 2018). In this case, the commitment of the seed company to promote the virtues of PPB and value of diversity in their marketing enabled the commercial success. This demonstrates how the engagement of diverse actors in a value chain can be instrumental to promote novel and heterogenous varieties and support the ability to embed PPB in the market economy. The importance of actors that can successfully access the market has also been crucial in other PPB cases, albeit in different forms. In the PPB case of the late blight-resistant potato in the Netherlands, the seed companies were already involved in the PPB program as actors; however, the missing actors to adopt the new PPB varieties were supermarkets. A separate action was needed by the Dutch umbrella organization for organic agriculture to convince retailers of the value of the new disease-resistant PPB varieties, which ultimately succeeded in creating a covenant among all Dutch supermarkets to replace the current late blight susceptible varieties with more robust PPB varieties over time (Keijzer et al., 2021). In other PPB projects, aiming at resistant varieties, such as scab-resistant apples and mildew-resistant grapes, benefitting farmers in the first place, demonstrated the need to find alternative ways to involve the market actors in accepting the new varieties and communicate the added value to consumers (Nuijten et al., 2018).

If the end goal of a PPB program is to expand farmers' access to improved varieties, then projects must be embedded within a seed system, whether formal or informal. In some cases, the seed system may be maintained through on-farm seed saving or managed through a seed network (Colley et al., 2021a; Bocci et al., 2012; Maze et al., 2020). This case, and others, show that commercialization may be accomplished by a variety of business models. In any case, if the distribution and/or commercialization pathway is not considered or developed over time, then the improved variety is at risk of limited adoption and eventual loss. PPB is a dynamic process that encompasses a diversity of models, operating within varied socioeconomic contexts (Chiffoleau and Desclaux, 2005; Colley et al., 2021a; Li et al., 2014). Thus, the pathway to embedding PPB innovations in the seed system must address the unique context and circumstances. As the current study demonstrates, reflexively adapting as the pathway unfolds and partners face the emerging challenges can be a successful way of addressing the contextual uniqueness (Klerkx et al., 2010; Camancho-Villa et al., 2016). In this case, the commercial pathways and informal networks were able to operate complimentarily, to benefit stakeholders of varied scales, simultaneously supporting production economies and expansion of agrobiodiversity. Similarly, Li et al., 2014 described how public and private interests may work together to simultaneously breed F1 hybrid varieties, as well as conserve and improve farmers' land race varieties through PPB. The current study reinforces prior experiences by contributing an additional example of how navigating the institutional and policy constraints can be overcome to integrate PPB varieties into commercial environments, without excluding the potential for supporting farmer-centric PPB and independent breeders in the process. The authors hope the experience and lessons learned inspire other PPB practitioners to apply adaptive management concepts, within their own contexts, to navigate obstacles and respond to opportunities necessary, in order to realize the potential of PPB as an innovation pathway for agroecological seed systems.

References

Borgen A (2009) Present and future system organization for organic plant breeding. In: Proceedings of the 1st International IFOAM Conference on Organic Animal and Plant Breeding—Breeding Diversity. Santa Fe, NM, US, 25–28 August 2009. Available at: https://orgprints.org/id/eprint/22156/

Bocci R, Chable V, Kastler G and Louwaars N (2012) Farm Seed Opportunities, Recommendations for On-farm Conservation in Europe. In *Agrobiodiversity Conservation: Securing the Diversity of Crop Wild Relatives and Landraces*; CAB International: Wallingford, OS, UK; pp. 137–141.

Camancho-Villa TC, Almekinders C, Hellin J, Martinez-Cruz TE, Rendon-Medel R, Guevara-Hernandez F, Beuchelt TD and Govaerts B (2016) The evolution of the MasAgro hubs: Responsiveness and serendipity as drivers of agricultural innovation in a dynamic and heterogenous context. *Journal Agricultural Education and Extension* **22**: 455–470. https://doi.org/10.1080/1389224X.2016.1227091.

Ceccarelli S and Grando S (2006) Decentralized-participatory plant breeding: An example of demand driven research. *Euphytica* **155**, 349–360. https://doi.org/10.1007/s10681-006-9336-8.

Ceccarelli S and Grando S (2019) Participatory Plant Breeding: Who Did It, Who Does It and Where? *Experimental Agriculture* **56**, 1–11. https://doi.org/10.1017/S0014479719000127.

Chable V, Dawson J, Bocci R and Goldringer I (2014) Seeds for Organic Agriculture: Development of Farmer Participatory Plant Breeding and Farmers' Networks in France. In. *Organic Farming, Prototype for Organic Agriculture*; Bellon, S., Penvern, S., Eds.; Springer: Dordrecht, UK; pp. 382–400. doi.org/10.1007/978-94-007-7927-3_21.

Chiffoleau Y and Desclaux D (2006) Participatory plant breeding: The best way to breed for sustainable agriculture? *International Journal of Agricultural Sustainability* **4**, 119–130. https://doi.org/10.1080/14735903.2006.9684795.

Colley M, McCluskey C, Lammerts van Bueren E and Tracy W (2020) The ripple effect of participatory plant breeding: A case study in use of organic sweet corn. In: *Proceedings of the International Conference on Breeding and Seed Sector Innovations for Organic Food Systems by EUCARPIA Section Organic and Low Input Agriculture jointly with LIVESEED, BRESOV, ECOBREED, FLPP projects and ECO-PB*, Riga, Latvia, 8–10 March 2021; Institute of Agricultural Resources and Economics: Riga, Latvia, 2021; pp. 119–120. Available at: https://www.eucarpia.eu/images/publications/2021_EUCARPIA_LIVESEED_Abstract_E-Book.pdf

Colley MR, Dawson JC, McCluskey C, Myers JR, Tracy WF and Lammerts van Bueren EL (2021) Exploring the emergence of participatory plant breeding in countries of the Global North—A review. *Journal of Agricultural Science* **159**: 320–338. https://doi.org/10.1017/S0021859621000782.

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

Deppe CS (2020) Freelance plant breeding. *Plant Breed. Rev.* **44**, 113–186.

Dillon M and Hubbard K (2011) *State of Organic Seed Report*; Organic Seed Alliance: Port Townsend, WA, USA, 2011. Available at: https://seedalliance.org/publications/state-of-organic-seed-report/

EC (2020) *New European Regulations for Organic Production and Marketing (EU 2020/460)*; European Commission, Brussels, Belgium. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32020R0464

GRAIN (2015) UPOV 91 and Other Seed Laws a Basic Primer on How Companies Intend to Control and Monopolise Seeds. Available at: https://grain.org/article/entries/5314-upov-91-and-other-seed-laws-a-basic-primer-on-how-companies-intend-to-control-and-monopolise-seeds

Hubbard K and Zystro J (2016) *State of Organic Seed, 2016*. Organic Seed Alliance, Port Townsend, WA, USA. Available at: www.stateofroganicseed.org

Hubbard K, Wood L and Zystro J (2022) *State of Organic Seed 2022*, Organic Seed Alliance: Port Townsend, WA, USA. Available at: www.stateoforganicseed.org

International Union for the Protection of New Varieties of Plants (UPOV) Available at: https://www.upov.int/portal/index.html.en

Keijzer P, van Bueren ETL, Engelen CJM and Hutten RC (2021) Breeding Late Blight Resistant Potatoes for Organic Farming—A Collaborative Model of Participatory Plant Breeding: The Bioimpuls Project. *Potato Research.* Available at: https://doi.org/10.1007/s11540-021-09519-8

Klerkx L, Aarts N and Leeuwis C (2010) Adaptive Management in Agricultural Innovation Systems: The Interactions Between Networks and Their Environment. *Agricultural Systems* **103**, 390–400. https://doi.org/10.1016/j.agsy.2010.03.012.

Levidow L, Pimbert M and Vanloqueren G (2014) Agroecological Research: Conforming or Transforming the Dominant Agro-Food Regime? *Agroecology and Sustainable Food Systems* **38**, 1127–1155. https://doi.org/10.1080/21683565.2014.951459.

Li J, Lammerts van Bueren ET, Leeuwis C and Jiggins J (2014) Expressing the public value of plant genetic resources by organising novel relationships: The contribution of selected participatory plant breeding and market-based arrangements. *Journal of Rural Studies* **32**: 182–196. https://doi.org/10.1016/j.jrurstud.2014.07.009.

Maze A, Calabuig A, and Goldringer I (2020) Commoning the seeds: Alternative models of collective action and open innovation within French peasant seed groups for recreating local knowledge commons. *Agriculture and Human Values*. Springer, Verlag **38**(2). Available at: https://hal.inrae.fr/hal-02979790/document

Meltwater (2022) Available at: https://Meltwater.com

Mendum R and Glenna LL (2010) Socioeconomic Obstacles to Establishing a Participatory Plant Breeding Program for Organic Growers in the United States. *Sustainability* **2**, 73–91.

Morris ML and Bellon M (2014) Participatory plant breeding research: Opportunities and challenges for international crop improvement system. *Euphytica* **136**, 21–35.

Nuijten E, de Wit J, Janmaat L, Schmitt A, Tamm L and Lammerts van Bueren ET (2018) Understanding obstacles and opportunities for successful market introduction of crop varieties with resistance against major diseases. *Organic Agriculture* **8**: 285–299. https://doi.org/10.1007/s13165-017-0192-8.

Open Source Seed Initiative (OSSI) (2022) "Freed" Seed: Sweet Kisses. Available at: https://osseeds.org/seeds/

Ocvirk G (2018) *Strategic Management of Market Niches: A Model Framework*; Springer Gabler: Weisbaden, Germany. pp. 1–230. https://doi.org/10.1007/978-3-658-20364-1.

Ortolani L, Bocci R, Barberi P, Howlett S and Chable V (2017) Changes in Knowledge Management Strategies Can Support Emerging Innovative Actors in Organic Agriculture: The Case Study of Participatory Plant Breeding in Europe. *Organic Farming* ***3*****,** 20–33. https://doi.org/10.12924/of2017.03010020.

Shelton AC and Tracy WF (2015) Recurrent selection and participatory plant breeding for improvement of two organic open-pollinated sweet maize (*Zea mays* L.) populations. *Sustainability* **7**, 5139–5152.

Shelton AC and Tracy WF (2016) Participatory Plant Breeding and Organic Agriculture: A Synergistic Model for Organic Variety Development in the United States. *Elementa Science of the Anthropocene* **4**, 1–12. https://doi.org/10.12952/journal.elementa.000143.

Tracy WF, Dawson JC, Moore VM and Fisch (eds) (2016) Intellectual Property Rights and Public Plant Breeding: Recommendations and proceeding for intellectual property protection of publicly developed plant germplasm. In Proceedings of the Seeds and Breeds for the 21st Century Conference. Raleigh, NC, USA, 12–13 August*, 2016.* University of Wisconsin-Madison: Madison, WI, USA. Available at: https://agronomy.webhosting.cals.wisc.edu/wp-content/uploads/sites/147/2018/05/Proceedings-IPR-Summary.pdf

USDA/NIFA: United States Department of Agriculture/ National Institute of Food and Agriculture. National Organic Program (2002) Available at: https://www.ams.usda.gov/about-ams/programs-offices/national-organic-program

Vincourt P and Carolo P (2018) Alternative breeding processes: At which extent Participatory Plant Breeding should modify the concept of ideotypes in plant breeding? *EDP Science* **25**, 1–6. https://doi.org/10.1051/ocl/2018061.

Witcombe, JR, Joshi A, Joshi KD and Sthapit BR *(* **1996)** Farmer participatory crop improvement. 1. Varietal selection and breeding methods and their impact on biodiversity. *Experimental Agriculture* **32**, 445–460. https://doi.org/10.1017/S0014479700001526.

Weltzien E, Smith ME, Meitzner LS and Sperling L (2003) *Technical and Institutional Issues in Participatory Plant Breeding-From the Perspective of Formal Plant Breeding: A Global Analysis of Issue, Results, and Current Experience*. Centro International de Agricultura Tropical (CIAT): Cali, DC, USA.

5

Chapter 6

General Discussion

Introduction to the general discussion

The overall objective this thesis was to improve our understanding of how participatory approaches can aid in developing and disseminating cultivars that address the agronomic, market, and social needs of organic farmers in the US (see Chapter 1). The four studies (Chapters 2-5) presented are grounded in recent experiences in organic plant breeding and seed systems work including applied projects in the US and an exploration of collective experiences across US, Canada and Europe. Research on seed systems development has by nature an interdisciplinary character as understanding dynamics of seed systems necessitates the knowledge of natural and social sciences. As such the four studies that form the empirical core of this thesis aimed to analyze components of the seed system including variety development, variety testing and adoption, and commercialization and dissemination of seed of improved varieties through the lens of agronomic and socio-economic research frameworks. The research analyzes the efficacy of participatory approaches to address each of these components and presents the opportunities, obstacles, and tensions encountered.

In the following section of this chapter, I present key findings from the analysis of each of the four research studies. Thereafter, I discuss these research findings and implications for the broader field of participatory research in plant breeding and organic seed systems. The chapter then concludes with an analysis of implications to society, research gaps, and potential pathways forward for future research to expand upon the scope of this thesis.

Main findings of the studies

Implementation of participatory plant breeding in the Global North

***Research question 1**: What are the outcomes and impacts of PPB implementation in the Global North to date and what can we learn from prior experiences?*

A state-of-the-art review of the literature identified clear synergies between participatory plant breeding (PPB) and organic seed systems as evidenced by the large number of projects in the Global North motivated to address organic farmers' agronomic, social and market needs (Chapter 2). A review of 47 projects across 22 crop species provided the material for evidence on outcomes, impacts and lessons on PPB in the Global North. The analysis also revealed clear parallels between motivations of PPB in the Global North and Global South, namely addressing gaps in seed needs of farmers underserved by the dominant conventional seed sector and bolstering seed security. Many projects in the Global North emphasize addressing agronomic needs for varieties with qualities to optimize organic farming which are not prioritized by the conventional seed industry such as weed competitiveness, and other adaptations to organic systems and regional agro-ecological environments. Reviewed projects also aimed to address regulatory constraints related to organic seed system development, such as avoidance of prohibited breeding techniques (i.e. cell-mediated cytoplasmic male sterility in Brassica crops) and breeding suitable open-pollinated varieties that can be produced organically as alternatives to F1 hybrid varieties that are only available in conventional form.

The literature study showed that an understanding of the drivers of PPB cannot be explained only through the lens of organic seed production systems. There is a clear philosophical and socio-political movement underpinning the emergence of PPB that is developing an alternative paradigm for our relationship with food and agriculture despite institutional barriers. Control of seed by the dominant seed industry, resulting in loss of farmers' seed sovereignty, is a core issue motivating PPB as society grapples with impacts of extreme intellectual property restrictions and consolidation in the seed industry. Restoring agrobiodiversity and mitigating climate change emerged as recurring themes underscoring the sense of urgency for not only farmers, but for society as well to reframe the role of seed in alternative agricultural systems. A consistent theme emerging from the breadth of experience in PPB appeared to be the diversity and complexity of not only the agroecosystems, but also social systems that participatory approach aim to address. Participatory approaches are thus necessitated to address and leverage the biological and social diversity to realize the potential for agroecological seed systems to address societal needs. Yet the complexity of the system is both a strength, building social and agricultural resilience, and an enormous challenge to organize, implement and institutionalize. The scope of projects demonstrates limited institutionalization of PPB with barriers including inconsistent funding, regulatory barriers to commercialization, and lack of institutional support for PPB are apparent.

Agronomic improvement for organic systems

Research Question 2: *Do carrot cultivars perform agronomically different under organic and conventional management practices across different locations and years?*

In Chapter 3, I present an analysis of multi-environment trials of carrot to evaluate if carrot cultivars perform agronomically different under organic and conventional management practices across different locations and years. The study aimed to inform organic and participatory plant breeding strategies for improvement of carrot production and breeding in organic systems. The results indicate that selection under conventional growing conditions would likely correlate to improved performance in organic conditions. However, based on the correlated response calculations that were less than 1 in all cases, it is possible genetic gains could be realized more quickly by selecting directly under organic management. A comparison of the ranking of variety performance and stability across the range of growing environments also demonstrated that there are instances when varieties perform similarly across management systems while others exhibit a different response pattern in organic compared with conventional growing environments. In organic systems in Wisconsin carrot varieties responded with higher yields under organic management compared with conventional while in Indiana no differences in yield were identified. These results challenge assumptions that there is a yield gap between organic and conventional production systems: this may not hold true for carrots.

Results indicate that breeding for improved early season top growth, which is desirable for quick canopy establishment to suppress weed growth, is possible in carrot as genotypes presented variation for this response. It also demonstrated evidence of the potential to breed for specific adaptation in organic management as well as adaptation across organic and conventional systems. This conclusion is based on variation in the patterns of variety responses in high and low yielding environments. Response patterns are similar for some varieties across organic and conventional systems, while other varieties present different patterns of adaptation. For example, the hybrid variety Uppercut presented a slope of 1.28 in conventional and 1.27 in organic demonstrating similar patterns of performance across environments in the two systems. Red Core

Chantenay, however, presented a slope of 2.26 in conventional and 1.00 in organic demonstrating favorable response to environment in high yielding environments in conventional systems compared with organic. The slope of Red Core Chantenay in conventional also crosses the slope of the environmental mean, thus exhibiting a yield less than the environmental mean in low-yielding conditions. A key implication of the analysis in Chapter 3 is that differences in variety performance in organic versus conventional systems are highly contextual of the conditions of the research, including the location, year and genotype and genotypic class of carrots studied. For example, results in Chapter 3 varied between hybrid F1 varieties, open-pollinated populations (OP's) and breeding lines when comparing ranking of variety performance between organic and conventional systems.

Variety testing and adoption in organic seed systems

Research question 3: *Is a participatory farmer-research network an effective approach to expand organic farmers' access to organic seed of vegetable cultivars that support their production system and markets in the USA? And is the mother-daughter trial design a suitable model for achieving this objective?*

An analysis of participant experiences in the NOVIC (Northern Organic Vegetable Improvement Collaborative) project, presented in Chapter 4, validated the effectiveness of the participatory network approach in expanding organic farmers' access to organic seed of vegetable cultivars that support their production systems and markets. It is estimated that the NOVIC network collectively evaluated more than 3,000 varieties across 27 crop types and 86% of farmers who responded to surveys reported integrating new varieties into their operation because of their participation. The network approach enabled testing across diverse on-farm environments thus adding value of farmers' first-hand feedback on variety performance and a broader set of environments for evaluating regional suitability of varieties. While this information added value to reports of trial results, an analysis of farmers' experience in the network indicates that first-hand experience and social interaction with other network members had the greatest impact on the usefulness of information gained. This finding underscores the importance of the social aspects of network experience and the importance of diverse forms of knowledge, beyond the data generated from the cross site participatory variety trials.

The analysis also revealed tensions among researchers and farmers when striving for rigorous, quantitative data from on-farm trials and the limitations in capacity and timing necessary to capture evaluations of horticultural crops during a busy farming season. The mother-daughter trial design did not prove effective in generating consistent and robust enough data necessary to generate meaningful analysis of variance evaluations from the on-farm sites (daughter sites). However, the design was successful from capturing feedback and scoring variety performances from on-farm sites, information that added value to reports when combined with analysis of results from evaluations conducted at research station sites (mother sites). When queried on the fit of the mother-daughter model to achieve the network goals, network facilitators indicated that coordinating three farm sites per crop stuck an effective balance in enabling diverse participation in the network while constraining the number of on-farm sites to a scale that was manageable in terms of facilitating trial logistics (ie. set up of trial, distribution of seed, collection of evaluations, and scheduling on-farm visits). Network facilitators also reflected that shifting the protocols for on-farm trials from quantitative data collection (including yields) to an emphasis on scoring traits and soliciting farmers' qualitative? feedback proved essential for effectively coordinating the number of farmers actively participating in the network each year (approximately 12-20 farmers per region per year).

Analysis of the experience of researchers and farmers alike underscored the intrinsic value in the social engagement of the network including interactions with other supply chain actors such as chefs and seed companies. Analysis of network governance highlighted the critical importance of farmers' inclusion in decision making and the critical value of adaptive management and flexibility in network facilitation necessary to sustain participation and achieve shared goals.

Variety release and commercialization of PPB seed

Research question 4: *How can PPB varieties become embedded in the broader operating environment to broaden impacts and expand access to organic seed of new cultivars?*

Chapter 5 of this thesis analyzes the experience of releasing of a PPB sweet maize variety in the US. This study demonstrated that embedding the variety in the broader operating environment, in this case the commercial organic seed sector, required addressing emerging obstacles, responding to opportunities, and expanding the roles of actors and the network of participants involved. Strategic decisions at key points in the release process proved necessary to address institutional barriers, such as negotiating with university policy makers and developing new relationships and creative pathways to enable release and successful commercialization. Analysis of the case study demonstrates that PPB is a dynamic process and does not conform to norms of public plant breeding at institutions or fit the dominant paradigm of centralized, vertically integrated technology development and commercialization. In this case, like many PPB projects, the actors aimed to develop a genetically, and somewhat phenotypically, diverse open-pollinated variety and release the variety without intellectual property protection to expand access and benefit sharing of the PPB effort. These two aspects exemplify how a PPB variety may not fit into the commercial norms of product uniformity and exclusivity in rights to commercialization. The analysis reveals that adaptative management was critical in navigating a pathway for release that met the goals and capacities of the actors involved. In other words, willingness to explore opportunities, address obstacles as they emerged and remain flexible in decision making. The case studied revealed that collective ownership between actors aided in avoiding the innovation (PPB variety) from becoming restricted by institutional barriers, namely the application of restrictive intellectual property rights by the university technology transfer department. In this case shared ownership and memorandums of understanding between a non-profit, university plant breeder and farmer facilitated the freedom to operate necessary to release rights to commercialization without intellectual property.

The outcomes reveal that creative partnerships and alternative business models can aid in promotion of the value of a genetically heterogenous PPB variety to organic seed buyers and generate returns on investment necessary to continue the variety maintenance, seed production and distribution of the PPB variety. If there is not a clear pathway toward integration with the broader operating environment at the initiation of a PPB project, then adaptive management offers a strategic approach for stakeholders to confront barriers and devise a strategy that addresses common goals. Otherwise, the innovation is at risk of remaining a niche technology. More than a decade after release, the outcomes of the commercialization process demonstrate the ability to achieve national and even international commercial distribution of a PPB variety without application of restrictive intellectual property and how broadening access beyond the initial actors stimulated additional PPB efforts of other independent and participatory plant breeders.

Discussion of the research findings

Reflection on the body of research presented in this thesis reveals that at the foundation of organic plant breeding and seed systems lies the generation and management of biological and social diversity. In Chapter 2, the literature review, this diversity was apparent through the wide range of PPB methods used to address diverse agroecosystems and involve diverse actors. In organic seed systems diversity is means to managing the stability of agroecosystems and celebrated in the variety of our food crops (Chable, 2014; Ortolani, 2017). Market diverse markets is also critical to support economic resilience of organic food systems (Mendum and Glenna, 2010; Levidow, 2014). Commercial seed systems on the other hand commonly operate within the dominant agricultural innovation paradigm of centralized research and dissemination of innovation, as highly uniform varieties, suited to broad geographical distribution with markets and secured through restrictive intellectual property rights (IPR) (Ortolani et al., 2017). A challenge in organic plant breeding and seed systems is balancing the genetic diversity within and across varieties to achieve goals of resilience and at the same time addressing societal conditioning to expect uniformity and consistency in our food crops, even at times within the organic sector (Vincourt and Carolo, 2018). Chapter 3 highlighted the importance of genotypic diversity in agroecosystems, demonstrated by the varied response of carrot varieties and genotypes to conventional and organic system environments. In Chapters 4 and 5 social diversity came to the fore, emerging as a critical component of success in PPB projects. The NOVIC network brought to light the value of diverse actors in exploring crop genetic diversity and sharing research and trial results as well as the importance of reconciling diverse vantage points that balance farmers' and breeders' goals in participation. In the process of releasing a PPB sweet maize variety the navigation over time of the social context with a diverse set of actors proved essential to achieve shared goals and expand the access and benefit sharing of PPB seed.

Diversity is at the core of healthy agroecosystems and ecological and societal resilience (Kremen and Miles, 2012; Ceccarelli and Grando, 2022). Genetic diversity of seeds and varieties is necessary to foster the resilience of organic cropping systems given the decentralized nature of organic farms and varied scales of production. Organic agricultural systems are additionally characterized by high levels of social diversity within food systems at the local, regional, and national levels. Diverse networks and markets are continuously emerging and changing to enable the complexity of organic food systems to function. Coping with this diversity, in its various agro-ecological and socio-economic dimensions, is both a challenge and an opportunity for participatory organic plant breeding and seed systems.

Participatory approaches are thus pivotal in building up and organizing collective efforts to support the diversity of plant breeding and seed system models necessary to enable the functioning of organic, agroecological, and socio-economic systems (Ceccarelli and Grando, 2022). The participatory approach offers an alternative to the top-down paradigm of the centralized, industrial seed system model focused on narrow genetic uniformity and controlled markets (Desclaux et al., 2008; Bocci and Chable, 2009; Serpolay et al., 2011; Lammerts van Bueren et al., 2018; Chable et al., 2020). In contrast to the industrial seed system model PPB models aim to expand genetic diversity within and across crops and fields and provide diversified models for sharing and distributing seed. This contrast exposes how and why the conventional seed industry is not well suited to fulfil all the needs of diversified organic agroecological systems and why participatory models are well suited to address gaps and expand options for accessing suitably adapted varieties and seeds. Participatory approaches come in many different forms (Serpolay et al., 2011; Lammerts van Bueren et al., 2018; Chable et al., 2020; Colley et al., 2021). Their organization and management is more horizontal and decentralized as they must accommodate and at the same time rely on more diversity. Such models are needed to effectively manage diversity in biological and social conditions - which make the food systems resilient. The empirical core of this thesis explored critical experiences in participatory approaches and led to this conclusion.

Participatory plant breeding to address agronomic diversity of organic farms

A wide range of diversity of suitable varieties adapted to local and regional environments is necessary to optimize the agronomic functioning of organic farming systems. Organic environments are often characterized by greater variation within fields and across farms compared with conventional farms as farmers refrain from chemical inputs and rely on biological systems to mitigate crop stress and provide for crop nutritional needs. Since all crop variety improvement is based on selection for optimum genotype by environment (G × E) interactions, plant breeders must consider this environmental diversity in developing effective selection strategies for organic systems.

In conventional plant breeding the standard approach is to minimize environmental variation using chemical inputs to create uniform growing conditions to maximize the genotypic expression for selection of a given trait. Participatory plant breeding takes a different approach by leveraging environmental variation as an opportunity to select for specific adaptation to the target environment (Ceccarelli, 1994; Cecarelli and Grando, 2007). This is accomplished by generating breeding populations with wide genetic diversity or leveraging genetically diverse historical populations and then selecting under the environment of intended use through decentralized approaches to develop varieties with adaptation to the specific local or regional environment (Dawson et al., 2008; Ceccarelli and Grando, 2022). Several examples of participatory breeding strategies presented in the case studies in literature review in Chapter 2 employed this approach. In a PPB tomato breeding project in Italy researchers developed genetically diverse breeding populations which were selected for three generations at the research station and on four collaborating farms. Subsequent replicated trials comparing the resulting progeny revealed that the highest yielding farmer selected populations out yielded the commercial standards and demonstrated optimum performance when grown on the farm where they were selected, demonstrating specific adaption to the selection environment (Campanelli et al., 2015). Additional examples from the case studies in Chapter 2 demonstrating methods resulting in varieties with successful specific adaptation included a decentralized wheat breeding network in France with entirely on-farm selection (Dawson et al. 2011) and a participatory Broccoli breeding project in the US (McKenzie, 2013). Analysis of the breadth of PPB in Chapter 2 revealed that regional adaptation is a driving motivation of most PPB projects as 85% (40 out of 47) of the PPB projects across 27 crop types identified regional adaptation as a primary breeding goal. Similarly, in the NOVIC network, analyzed in Chapter 4, researchers tested the adaptability of varieties across the network of testing environments and found variation in patterns of adaptation in broccoli and squash varieties with some varieties adapted broadly while others were specifically adapted to high or low yielding environments, demonstrating the potential for successful selection for either pattern in organic systems.

In Chapter 3, the analysis of multi-environment trials in carrot revealed variation in patterns of variety adaptation to high and low yielding environments for all traits evaluated. In addition, the patterns of adaptation differed between organic and conventional management systems indicating the potential for varieties to exhibit specific adaptation to optimum or stressful environments may vary depending on the production system. These findings reinforce the emphasis in the literature that specific environmental adaptation of varieties is particularly important in organic systems where fewer options are available to alter the growing environment. Additionally, testing in organic conditions may be necessary to identify optimum adaptation for organic systems (Dawson et al., 2008, 2011; Chiffoleau and Desclaux, 2011; Goldringer et al., 2019). This thesis supports the premise that participatory selection methodologies as decentralized approaches are a crucial element in development of varieties for specific adaptation and can contribute to greater genetic diversity across the landscape of diversified organic farms.

Key findings in all four chapters of this research reflect other researchers' conclusions that organic farmers need varieties with a diversity of agronomic qualities and that the prioritization of traits in conventional breeding programs often overlooks critical qualities desired by organic farmers (Lammerts van Bueren et al., 2011; Lammerts van Bueren and Myers, 2012). The prioritization of early seedling vigour and weed competitiveness in organic carrot breeding is a prime example of this as early crop establishment is a critical time when organic farmers are at risk of significant crop loss due to competition with weeds for nutrients, water, and light (Colquhoun et al., 2017; Turner 2017; Colley, 2021). As conventional farmers commonly apply herbicides to control weeds during crop establishment early seedling vigor is not as high of a priority in conventional carrot breeding, as evidenced by the lack of literature assessing genetic variance for early season growth. The findings of Chapter 3 are a promising indicator of the potential to improve carrot varieties for early seedling vigour and crop establishment. Results also revealed variation in the stability of varieties for early season top height and width in organic and conventional management systems when evaluated over an index of low to high yielding environments. This indicates the potential to apply decentralized participatory selection strategies to develop specific genotypes for adaptation to organic environments thus expanding the future diversity of genetic options for organic farmers to address cropping system challenges.

Participatory networks expand awareness of agrobiodiversity and seed security

The overwhelming response of farmers surveyed and interviewed in the NOVIC network (Chapter 4) indicated one of the greatest impacts of participation was expanding awareness of the seed system, including dynamics of control within the conventional seed system and implications for seed security. Farmers expressed a desire to engage more directly in crop diversity management either through their conscious choice of seeds to purchase and plant or by engaging more directly in on-farm conservation and generation of genetic diversity. The social network fostered knowledge exchange among farmers, plant breeders, and seed companies including regional seed companies and independent plant breeders. Discussions on variety assortment and access to organic seed opened the "black box" of seed as farmers asked questions about why a hybrid variety would never be available organically or why a variety suddenly dropped from the market. NOVIC network participants also reported expanding the diversity of seed companies they purchased from and gained familiarity and appreciation for their interdependence with regional seed companies. In at least one case, during the COVID pandemic, a farmer commented that their entire tomato production depended on purchasing from a regional seed company they learned about through the NOVIC network. When national companies placed seed orders on hold, they turned to the regional company for all the seed needed for their annual production. These examples demonstrate how participation in a network fosters not only expansion of adoption of seed diversity, but the awareness and appreciation of the value of diversity of seed stewards and the resilience of decentralized seed access.

Participatory models are also fostering multi-actor approaches to support market development of PPB bred varieties. Involvement of chefs, food cooperatives, and direct sales such as community supported agriculture and farmers markets are all contributing to diversification of markets and not only accepting diversity of farmers' crop varieties but also celebrating that diversity (Healy and Dawson, 2019). This is critical as PPB varieties often do not fit within the ideotype of the wholesale produce distribution model. Genetic diversity is at the heart of cultural food pathways and the culinary richness of humanity. Protecting and expanding our crop diversity is directly connected with honoring our human diversity. The NOVIC network developed methods for multi-actor participation in variety evaluations by engaging chefs through the Culinary Breeding Network and Seed to Kitchen Collaborative (Penuales, 2017; Healy and Dawson, 2019). These relationships were instrumental in developing value-added markets for new, diverse, and non-confirming varieties of PPB seed. Novel, multi-actor networks are also highly evident in PPB in Europe with examples highlighted in Chapter 2 including the PPB maize network, VASO, in Portugal that connects farmers, bakers and eaters to collaborate in development and marketing of traditional maize bread, Broa (Mendez-Moreira and Pêgo, 2012). In Europe, a "peasant seed" movement is emerging with networks such as the Réseau Semences Paysannes in France, the Red de Semillas in Spain and the Rete Semi Rurali in Italy. Bocci and Chable (2009) describe peasant varieties as "a concept that encompasses two main aspects: the seed, the reproductive part of the plant linked to its terroir, and the variety, shaped by history and coevolved with farmers". They go on to explain that scientists working with these networks are developing participatory plant breeding projects with the aim to broaden agrobiodiversity. The networks include "citizens, farmers, consumers, traders, researchers etc., combining their skills to endow themselves with the resources for working with seeds conceived for an agriculture that lends living beings, including plants, another dimension than that of material, commercial commodities".

The NOVIC plant breeders likewise reported in interviews that participatory evaluation of diverse crop types and knowledge exchange with farmers as well as regional seed companies and independent breeders, resulted in expanding their own awareness of the agrobiodiversity of crops. Feedback from the network farmers and other value chain actors directly resulted in more than one NOVIC plant breeder expanding the diversity of the crops and crop qualities included in the breeders' programs. This shows that networks do not only foster multi-actor collaboration and impact but are also a necessary ingredient to cope with the diversity that organic breeding and seed supply are targeting.

Participatory approaches to manage diversity and access to PPB seed

All seed systems must include a pathway for dissemination of seed to transfer from the plant breeding phase to access and adoption of new varieties. In organic seed systems the diverse and decentralized nature of organic farms and markets presents challenges in efficiently and effectively financing participatory plant breeding as well as the marketing and distribution of PPB seed. While there is evidence that PPB is expanding variety choice and seed diversity for farmers as presented in Chapters 2 and 4, the review of literature in Chapter 2 identified that PPB breeders often encounter obstacles to the commercialization of new PPB varieties, and it seems in some cases that devising a variety release plan is an afterthought of the breeding process. Projects reviewed in Chapter 2 tended toward a few divergent paths in the breadth of PPB programs, 1) on-farm management and regeneration of PPB seed (Lazor, 2008; Enjalbert et al., 2011; Westengen et al., 2018), 2) dissemination through farmer network models (Chable et al., 2009; da Via, 2015), or 3) commercialization in partnership with a seed company or farmer seed cooperative (Chable et al., 2014; Almekinders et al., 2014). Chapter 5 explored some of the barriers to commercialization and demonstrated how adaptive management aided in forging a pathway that resulted in commercial release and distribution of a PPB variety. Adaptive management, applied in this case describes an approach to the participatory processes that allows navigation of the operating environment. Over time, as the process and pathways unfold, the adaptive orientation of decision-making presents diversity in actors' views and conditions thus informing choices in management.

In the US seed may be sold without formal testing and registration and thus a proliferation of smaller regional seed companies and independent plant breeders is expanding (Deppe, 2020). A recent analysis of organic seed networks in the US identified indicators of resilience in relationships between actors in the organic seed systems with emphasis on the strength of regional resilience (Wood, 2022). This analysis also revealed supply chain gaps in seed particularly in regions where regional seed systems are less established. In the NOVIC project the national variation in environments and demographics of network participants revealed similar differences in regional seed system development. NOVIC participants in the Northwest region of the US are in an environment conducive to seed production and thus have access to more regionally based seed companies that produce and sell regionally adapted seed. The region held the highest concentration of NOVIC network participants reflecting the social willingness to explore regional and alternative seed sourcing options in this region. In other cases, encountered in Chapter 2, 4 and 5, PPB actors were not suited to save seed or do not want to save seed and thus depend on the maintenance and production of seed of PPB varieties from other entities, commercial or otherwise. Recounting the motivations of the PPB commercial release process presented in Chapter 5 demonstrates that commercial access of certified seed was a necessity for the farmer who participated the plant breeding process to adopt the variety into their own production as they held no interest or capacity in seed production.

Research gaps, needs, and future research pathways

Participatory approaches in plant breeding and seed systems are imperative to provide resilience to food systems. They mobilize the collective action necessary for society to begin to restore agrobiodiversity and address impacts of climate change and related lack of food security (Ceccarelli and Grando, 2022). Doing so, as demonstrated in this discussion, necessitates research and implementation of a diversity of breeding methods and models. Additional research is needed to test decentralized selection strategies across a wide diversity of crop types. The body of literature includes promising examples of applying "evolutionary" PPB in self-pollinating grains to develop specific adaptation by generating genetically diverse breeding pools and applying subsequent cycles of selection on-farms (Murphy et al., 2005; Döring et al., 2011; Enjalbert et al., 2011; Goldringer et al., 2019; Ceccarelli and Grando, 2022). While Chapter 3 identified examples of PPB across crop types (grains and horticultural crops) and diverse mating systems (self and cross pollinating) there are only a few examples of the "evolutionary" approach applied in horticultural crops (Petiti, 2020). Biennial root crops are also limited in experimental testing of selection strategies for decentralized PPB approaches. The lack of examples is likely related to the reproductive and environmental challenges of on-farm seed saving of many biennial crops. While the biennial cycle can present challenges in on-farm seed management, in root crops such as carrot it also offers an opportunity to apply participatory selection within a diverse cropping system as several varieties (or breeding populations) can be evaluated and selected in single year without risk of cross pollination. Research is needed to assess the potential to apply decentralized and evolutionary selection strategies in biennials to improved adaptation to agroecological systems. Perennials are also an important element of agrobiodiversity and environmental sustainability, particularly in mixed cropping systems. The review in Chapter 2 identified a single example of PPB in perennial crops. Research is needed to inform strategies for participatory perennial breeding, particularly ones that expand breeding population sizes by involving farmers in evaluation of seedlings rather than waiting until clonal cultivars are available. With PPB, applying selection across environments and testing for qualities attributed to improved adaptation may be more feasible than with centralized programs for long-lived crops, particularly addressing qualities related to tolerance to drought, flooding and extreme temperatures given impacts of climate change.

Variety trials are a key component of plant breeding from screening for suitable parents to evaluating market potential of resulting varieties. Along with efficiency in breeding there is a need to improve efficiency and effectiveness of multi-environment trials to leverage decentralized on-farm testing strategies. While Chapter 4 discussed the challenges in acquiring on-farm data of horticultural crops, recent publications on alternative field trial design and related statistical analysis is promising (Zystro et al., 2019; Rivière et al., 2021; de Buck et al., 2021). An evaluation of the outcome of such models across crops is needed to confirm the fit of the models and assess efficiency and effectiveness in achieving goals in participatory breeding and testing programs. Given the limited resources and extensive need for decentralized testing, development of models for capturing and sharing environmental data in trial networks may also facilitate in identifying patterns of adaptation across environments to inform ongoing breeding and variety selection strategies.

While there is a sense of urgency in developing and deploying effective participatory methods for agronomic and environmental adaptation there is also a need for adapting those methods to fit within social constructs of agricultural communities and society. PPB and PVS honor knowledge diversity, bringing diverse actors together to collaborate in research and leverage different ways of knowing. In PPB formal breeders often lend an analytical view to the plant breeding process while farmers are skilled observers that inherently recognize G x E in the field. Combining farmers and researchers' views lends insights into development of new hypothesis (Dawson et al., 2011). This was evident in knowledge exchange in the NOVIC network where farmers and researchers' perspectives added value to reports of trial results and prioritization of qualities included in evaluation methods. Beyond the field, the resilience of seed systems is strengthened by participation of diverse actors including chefs, eaters, and other citizens contributing not only feedback on varieties, but also informing pathways to markets and building community support for alternative food systems.

A pluralistic view is needed to fully enable participatory models to function. It is said that plant breeding is both an art and a science. This classic statement embodies the importance of the balance between order, structure and testing with observation, intuition, and creativity. PPB is a promising model for leveraging diverse forms of knowledge in the coevolution of humans and plants. While PPB is increasingly embraced within the framework of organic agriculture for reasons revealed in the research chapters of this thesis, there remains gaps in the cultural diversity of farming communities participating in PPB networks (Healy and Dawson, 2019). As was seen in the NOVIC project, cultural and regional differences in the importance of particular crops, traits and marketing strategies means that participatory plant breeding projects must embrace the diverse needs of farmers to be fully successful. Supporting PPB projects led by communities who have not historically been part of public sector research projects is a key strategy to increase the relevance and reach of plant breeding for organic systems. This is both a critical opportunity and a challenge for established research institutions, and a commitment to centring equity is needed for both funders and practitioners of participatory plant breeding. Evolution of our social constructs and research frameworks is necessary to achieve these goals and requires participatory approaches that cultivate in human relationships the same qualities we aim to nurture in our crops - adaptability, flexibility, and resilience.

Diversity is essential to the resilience of both natural and socio-ecological systems. Diversity is also complex and careful management of diversity is both a challenge and an opportunity. While a strength of participatory approaches in plant breeding is expanding agrobiodiversity participation is also essential in managing that diversity to ensure it is functional, cared for, and adapting to ever changing circumstances - in other words resilient. Participatory approaches are also essential to address challenges in organizing and managing social diversity necessary to build resilience in our interdependent relationships between humans and plants.

References

Almekinders CJM, Mertens L, van Loon JP and Lammerts van Bueren ET (2014) Potato Breeding in the Netherlands: A Successful Participatory Model with Collaboration between Farmers and Commercial Breeders. *Food Security* **6,** 515–524. https://doi.org/10.1007/s12571-014-0369-x.

Bocci R and Chable V (2009) Peasant Seeds in Europe: Stakes and Prospects. *Journal of Agriculture and the Environment* **103**, 81-93.

Campanelli G, Acciarri N, Campion B, Delvecchio S, Leteo F, Fusari F, Angelini P and Ceccarelli S (2015) Participatory Tomato Breeding for Organic Conditions in Italy. *Euphytica* **204**, 179-197.

Chable V, Goldringer I, Dawson J, Bocci R, Lammerts van Bueren ET, Serpolay E, Gonzalez JM, Valer T, Levillain T, Van er Burg JW, Pimber M, Pino S and Kik C (2009) European Landraces On-Farm Conservation, Management and Use." *Bioversity Technical Manual*. no. 15, 9. Available at: https://www.bioversityinternational.org/fileadmin/_migrated/uploads/tx_news/European_landraces__on-farm_conservation__management_and_use_1347.pdf

Chable V, Dawson J, Bocci R, and Goldringer I (2014) Seeds for Organic Agriculture: Development of Participatory Plant Breeding and Farmers' Networks in France. In Bellon S and Penvern S (eds). *Organic Farming Prototype for Sustainable Agriculture* pp. 384-400. Dordecht: Springer Science. https://doi.org/10.1007/978-94-007-7927-3_21

Chable V, Nuijten E, Costanzo A, Goldringer I, Bocci R, Oehen B, Rey F, Fasoula D, Feher J, Keskitalo M, Koller B, Omirou M, Mendes-Moreira P, van Frank G, Naino Jika AK, Thomas M and Rossi A (2020) Embedding Cultivated Diversity in Society for Agro-Ecological Transition. *Sustainability* **12**(784). https://doi.org/10.3390/su12030784

Chiffoleau Y and Desclaux D (2011) Participatory Plant Breeding: The Best Way to Breed for Sustainable Agriculture? *International Journal of Agricultural Sustainability* **4**, 119–130. https://doi.org/10.1080/14735903.2006.9684795

Colley MR, Dawson JC, McCluskey C, Myers JR, Tracy WF and Lammerts van Bueren ET (2021) Exploring the emergence of participatory plant breeding in countries of the Global North—A review. *Journal of Agricultural Science* **159**, 320–338. https://doi.org/10.1017/S0021859621000782.

Colquhoun J, Rittmeyer BA and Heider DJ (2017) Tolerance and Suppression of Weeds Varies among Carrot Varieties. *Weed Technology* **31**(06), 1-6.

Da Via E (2015) Food sovereignty in the fields: Seed exchange and participatory plant breeding of wheat landraces in Italy. In Trauger A (ed). *Food Sovereignty in International Context: Discourse, Politics and Practice of Place* pp. 198-211. Taylor & Francis.

Dawson JC, Murphy KM, and Jones SS (2008) Decentralized Selection and Participatory Approaches in Plant Breeding for Low-Input Systems *Euphytica* **160**(2), 143–54. https://doi.org/10.1007/s10681-007-9533-0

Dawson JC, Rivière P, Berthellot J-F, Mercier F, Kochko P, Galic N, Pin S, Serpolay E, Thomas M, Giuliano S and Goldringer I (2011) Collaborative plant breeding for organic agricultural systems in developed countries. *Sustainability* **3**, 1206–1223.

de Buck A, Rey F, Rivière P and Petitti M (2021) Guidelines for organic on-farm variety trials. Andreoni MP, Petitti M, Bruszik A, and Rey F (eds). LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/06/LIVESEED-BOOKLET-5_FNL_web.pdf

Deppe CS (2021) Freelance plant breeding. *Plant Breeding Reviews* **44**, 113-186.

Desclaux D, Nolot JM, Chiffoleau Y, Gozé E and Leclerc C (2008) Changes in the Concept of Genotype × Environment Interactions to Fit Agriculture Diversification and Decentralized Participatory Plant Breeding: Pluridisciplinary Point of View. *Euphytica* **16,** 533–46. Available at: https://doi.org/10.1007/s10681-008-9717-2

Döring, TF, Kovacs, G, Wolfe, MS and Murphy K (2011) Evolutionary plant breeding in cereals – into a new era. *Sustainability* **3**, 1944–1971.

Enjalbert J, Dawson JC, Paillard S, Rhoné B, Rousselle Y, Thomas M and Goldringer I (2011) Dynamic management of crop diversity: From an experimental approach to on-farm conservation. *Comptes Rendus Biologies* **334**, 458–468. Available at: https://doi.org/10.1016/j.crvi.2011.03.005

Goldringer I, van Frank G, Bouvier d'Yvoire C, Forst E, Galic N, Garnault M, Locqueville J, Pin S, Bailly J, Baltassat R, Berthellot J-F, Caizergues F, Dalmasso C, de Kochko P, Gascuel J-S, Hyacinthe A, Lacanette J, Mercier F, Montaz H, Ronot B and Rivière P (2019) Agronomic Evaluation of Bread Wheat Varieties from Participatory Breeding: A Combination of Performance and Robustness. *Sustainability* **12**, 128. Available at: https://doi.org/10.3390/su12010128

Healy GK and Dawson JC (2019) Participatory plant breeding and social change in the Midwestern United States: perspectives from the Seed to Kitchen Collaborative. *Agriculture and Human Values* **36**, 879-889.

Kremen C and Miles A (2012) Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecology and Society* **17**(40). https://www.ecologyandsociety.org/vol17/iss4/art40/

Lammerts van Bueren ET, Jones SS, Tamm L, Murphy KM, Myers JR, Leifert C and Messmer MM (2011) The Need to Breed Crop Varieties Suitable for Organic Farming, Using Wheat, Tomato and Broccoli as Examples: A Review. *NJAS - Wageningen Journal of Life Sciences* **58** (3–4), 193–205. https://doi.org/10.1016/j.njas.2010.04.001.

Lammerts van Bueren ET and Myers JR (2012) Organic Crop Breeding. Wiley-Blackwell. West Susex, UK. ISBN: 978-0-470-95858-2

Lammerts van Bueren ET, Struik PC, Eekeren N and Nuijten E (2018) Toward resilience through systems-based plant breeding. A review. *Journal of Agronomy for Sustainable Development* **38**(42). https://doi.org/10.1007/s13593-018-0522-6.

Lazor J (2008) A Vermont Farmers Breeding Club: Developing Varieties That Work For Us, Farmer Grant Report. Vermont, USA: Sustainable Agriculture Research and Education. Available online from: https://projects.sare.org/sare_project/fne07-613/

Levidow L, Pimbert M and Vanloqueren G (2014) Agroecological Research: Conforming-or Transforming the Dominant Agro-Food Regime? *Agroecology and*

6

Sustainable Food Systems **38**, 1127–1155. https://doi.org/10.1080/21683565.2014.951459.

Lyon A, Tracy WF, Colley M, Culbert P, Mazourek, M, Myers, J, Zystro J and Silva EM (2019) Adaptability analysis in a participatory variety trial of organic vegetable crops. *Renewable Agriculture and Food Systems* **35**, 296-312. Available at: https://doi.org/10.1017/S1742170518000583

McKenzie, L (2013) *Breeding an open-pollinated broccoli for organic production system using participatory methods*. A Ms thesis, Oregon State University, Corvallis, Oregon, USA. Available at: https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/v692t940f?locale=en

Mendes-Moreira P and Pêgo SE (2012) On-farm conservation and participatory maize breeding in Portugal: an overview. In Maxted N, Dulloo ME, Ford-Lloyd BV, Frese L, Iriondo JM and Pinheiro de Carvalho MAA (eds). *Agrobiodiversity conservation: securing the diversity of crop wild relatives and landraces*, pp. 131-136. Wallingford, England: CAB International.

Mendum R and Glenna L (2010) Socioeconomic Obstacles to Establishing a Participatory Plant Breeding Program for Organic Growers in the United States. *Sustainability* **2**, 73–91. Available at: https://doi.org/10.3390/su2010073

Murphy K & Lammer K & Lyon S & Carter B & Jones S (2005) Breeding for Organic and Low-input Farming Systems: An Evolutionary–participatory Breeding Method for Inbred Cereal Grains. *Renewable Agriculture and Food Systems* **20** 10.1079/RAF200486.

Ortolani L, Bocci R, Barberi P, Howlett S and Chable V (2017) Changes in Knowledge Management Strategies Can Support Emerging Innovative Actors in Organic Agriculture: The Case Study of Participatory Plant Breeding in Europe. *Organic Farming* **3**, 20–33. https://doi.org/10.12924/of2017.03010020.

Osman AM, Struik PC, Almekinders CJM and Lammerts van Bueren ET (2008) Can conventional breeding programmes provide onion varieties that are suitable for organic farming in the Netherlands? *Euphytica* **163**, 511-522.

Peñualas M (2017) Uniting Chefs, Eaters, and Plant Breeders: The 2017 Variety Showcase. *Food Tank*. Available at: https://foodtank.com/news/2017/09/culinary-breeding-network-eaters-breeders/

Renaud EC (2014) *Breeding and Regulatory Constraints and Opportunities for Developing Broccoli Cultivars Adapted to Organic Agriculture*. Wageningen University. ISBN 978-94-6257-030-6.

Rivière P, Goldringer I, Rey F (2021) *Selecting the appropriate methodology for organic on-farm variety trials*. Rey F and Flipon E (eds.) LiveSeed. Available at: https://www.liveseed.eu/wp-content/uploads/2021/07/PUBLICATIONITAB_LIVESEED.final_.pdf

Serpolay E, Dawson JC, Chable V, Lammerts van Bueren ET, Osman A, Pino S and Goldringer I (2011) Diversity of different farmer and modern wheat varieties cultivated in contrasting organic farming conditions in Western Europe and implications for European seed and variety legislation. *Organic Agriculture* **1**(3), 127-145

Turner S (2017) Genetic influences on shoot architecture in carrot (Daucus carota). A PhD Thesis, University of Wisconsin–Madison. Available at: https://search.library.wisc.edu/catalog/9912724632302121

Vincourt P, Carolo P (2018) Alternative breeding processes: At which extent Participatory Plant Breeding should modify the concept of ideotypes in plant breeding? *EDP Sci.* **25**, 1–6. https://doi.org/10.1051/ocl/2018061.

Westengen OT, Skarbø K, Mulesa TH, and Berg T (2018) Access to Genes: Linkages between Genebanks and Farmers' Seed Systems *Food Security* **10**(1), 9–25. https://doi.org/10.1007/s12571-017-0751-6.

Zystro J, Colley M, and Dawson J (2018) Alternative Experimental Designs for Plant Breeding. *Plant Breeding Reviews* **42**: 87-117.

Summary

The overall objective of the research of this thesis was to improve our understanding of how participatory approaches can aid in developing and disseminating cultivars that address the agronomic, market, and social needs of organic farmers in the USA. The four studies presented are grounded in recent critical experiences in organic seed systems research including applied projects in the US and an exploration of collective experiences across USA, Canada and Europe. Seed systems development is by nature an integrated science. As such the four studies that form the empirical core of this thesis aimed to analyze critical components of the seed system including cultivar development, cultivar testing and adoption, and commercialization and dissemination of improved cultivars. The research analyzes the efficacy of participatory approaches to address each of these components and analyzes the opportunities, obstacles, and tensions encountered. The following summary presents key findings from the research and discusses the relevance to the field of organic plant breeding and organic seed systems with emphasis on participatory approaches. I close with discussion of implications of the research to society and science, gaps in knowledge and suggestions for future research pathways.

Implementation of participatory plant breeding in the Global North

There are clear synergies between participatory plant breeding (PPB) and organic seed systems as evidenced by the large number of projects in the Global North motivated to address organic farmers agronomic, social and market needs (Chapter 2). A review of 47 projects across 22 crop species in the Global North provides evidence that PPB is expanding organic seed choices for farmers, thus addressing the primary objective of Chapter 2. The analysis also revealed clear parallels between motivations of PPB in the Global North and Global South namely addressing gaps in seed needs of farmers underserved by the dominant conventional seed sector and bolstering seed security. Many projects in the Global North emphasize addressing agronomic needs for varieties with qualities to optimize organic farming which are not prioritized by the conventional seed industry such as weed competitiveness, and adaptation to organic systems and regional environments. Projects also aim to address regulatory related constraints

related to organic seed such as avoidance of prohibited breeding techniques (ie. cell-mediated cytoplasmic male sterility in Brassica crops) and breeding suitable open-pollinated varieties that can be produced organically as alternatives to hybrid F1 varieties that are only available in conventional form.

The analysis reveals that understanding of the drivers of PPB cannot be explained only through the lens of organic seed systems. There is a clear philosophical and socio-political movement underpinning the emergence of PPB that is developing alternative paradigm for our relationship with food and agriculture despite institutional barriers. A core issue motivating PPB is grappling with impacts of extreme intellectual property restrictions and consolidation in the seed industry limiting farmers' and plant breeders' access to seed. Restoring agrobiodiversity and mitigating climate change also emerged as recurring themes that underscore the sense of urgency for not only farmers, but society to reframe and support alternative agricultural systems. The study concludes that a multi-disciplinary approach is essential to further research the complex intersection of agronomic, social, and political influences underlying PPB implementation and implications for future success.

Agronomic improvement for organic systems

Organic farmers need seed of varieties that are not only adapted to organic farming systems and local environments, but also hold qualities (traits) needed to address production challenges to optimize organic agriculture. In addition to the need for stable yields across years, weed management is a key production constraint in organic systems for carrot as germination is slow and erratic. No previous studies have assessed the potential to breed for early season top growth to improve varieties for their capacity to compete with weeds during the critical period of crop establishment. To this end, Chapter 3 aimed to assess the genetic variance and influence of growing environment on performance of diverse carrot varieties (genotypes) for early season top growth as well as root and top yields at harvest. Multi-environment trials located in Wisconsin (WI) and Indiana (IN), conducted across 4 years under organic and conventional management demonstrated that there is variation in genotypes for top height and width at 30 days after planting and 60 days after planting demonstrating the potential to breed for improved early crop establishment. The study also found evidence that selection under conventional growing conditions would likely correlate to improved performance in organic conditions, however when possible genetic gains could be realized more quickly by selecting directly under organic management. A comparison of the ranking of variety performance and stability of performance across the range of growing environments also demonstrated that there are instances when varieties perform similarly across management systems while other genotypes exhibit a different response pattern in organic compared with conventional growing environments. A key implication of the agronomic analysis in Chapter 3 is that differences in variety performance in organic versus conventional systems is highly contextual of the conditions of the research scope including the location, year and type of genotypic class studied. For example, results in Chapter 3 varied between hybrid F1 varieties, open-pollinated populations (OP's) and breeding lines when comparing ranking of variety performance between organic and conventional systems.

Variety testing and adoption in organic seed systems

All seed systems must include a pathway for testing and dissemination of seed to transfer from the plant breeding phase to adoption of new varieties. In organic seed systems the diverse and decentralized nature of organic farms and markets presents challenges in efficiently and effectively facilitating variety testing. The varied needs and environmental conditions can also be a challenge for organic plant breeders to ensure breeding goals are aligned with farmers' priorities for cultivar qualities and addressing unique environmental challenges. For these reasons a network approach to facilitate decentralized, on-farm testing of organic varieties to inform plant breeders and farmers of suitability is commonly employed in organic seed systems. In the USA, the Northern Organic Vegetable Improvement Collaborative (NOVIC) facilitated such a network over the course of 12 years. An analysis of participant experiences in NOVIC, presented in Chapter 4, revealed the tensions among researchers and farmers between striving for rigorous, quantitative data from on-farm trials and the limitations in capacity and timing necessary to capture evaluations of horticultural crops during a busy farming season. At the same time researchers and farmers alike experienced an intrinsic value in the social engagement of the network including interactions with other supply chain actors such as chefs and seed companies. In the end the network developed streamlined strategies to facilitate farmers' input on variety performance while ensuring the trials fit farmers' capacity and needs. An analysis of impacts identified uptake of new varieties and organic seed by farmers and highlighted the critical value of adaptive management and flexibility in network facilitation necessary to sustain network participation and achieve shared goals.

Variety release and commercialization of PPB seed

While there is evidence that PPB is expanding variety choice and seed diversity for farmers as presented in Chapters 2 and 4, the review of literature in Chapter 2 identified that PPB breeders often encounter obstacles to the commercialization of new PPB varieties, and it seems in some cases devising a variety release plan is an afterthought of the breeding process. Chapter 5 analyzes the key points in navigating a participatory decision-making process to enable release and commercialization pathway for a PPB variety of sweet maize. The actors had to address regulatory, institutional, and market barriers to embed the variety in the commercial seed sector. Doing so resulted in national and subsequently international distribution through partnership with an organic seed company. Analysis of the case demonstrates that not all farmers engaged in PPB want to save their own seed and in this instance the farmer desired commercial access to high quality, certified organic seed. Likewise, the formal breeders desired to benefit as many farmers as possible, not only the single farmer who engaged in the breeding process. A key outcome of the analysis highlights the importance of adaptive management in navigating the dynamics of variety release. Flexibility, collective ownership and creative partnerships were necessary to navigate pivotal decisions in the release process and overcome institutional and market barriers to embed a PPB variety in the commercial-organic seed sector. In retrospect, more than a decade after release, the authors reflect on long term implications for seed access and stimulation of ongoing PPB efforts.

Chapter 6 reviews the key outcomes of each research chapter, synthesizes and discusses the results reflecting on the common thread of the critical role of diversity in participatory plant breeding and seed systems. This theme emerged from outcomes of each of the research chapters revealing that the genetic diversity, agronomic and environmental diversity, and social diversity necessitates adaptive, participatory approaches in plant breeding and seed systems. The review of the literature in Chapter 2 revealed that PPB methods employ a diversity of approaches to address the unique social and environmental contexts of each PPB experience. Methods are commonly decentralized, with network models applied to a wide range of crops and actors. In Chapter 3 evaluation of diverse carrot genotypes in multi-environment trials revealed high genotypic variance for top growth demonstrating high potential to breed for carrots better able to cope with early season weed pressure, thus diversifying farmers crop management options. Finlay-Wilkinson adaptability analysis also revealed variation in patterns of adaptation between varieties grown under organic and conventional management with an overall conclusion that the genotype by environment interaction in carrot is highly complex and depends on the variety and environment and management system context. Chapter 4 explored how diverse participation in a network model can aid in evaluation of vegetable varieties while also facilitating knowledge exchange and relationship building in organic plant breeding and seed systems. It also revealed tensions between farmers' and breeders' capacity and goals in engaging in participatory trials. The experience underscored the need for adaptability in methodologies to address challenges including modifying evaluation procedures and reconciling limitations in the ability to capture data on horticultural crops in diversified farming operations with narrow harvest windows. Chapter 5 describes one pathway that resulted in wide distribution of a phenotypically diverse, yet organically suitable sweet maize variety. Navigating challenges and barriers to commercialization required flexibility and adaptive management to embed the variety the commercial seed sector resulting a ripple effect of expanded access and stimulating additional participatory plant breeding efforts.

Future research is needed to continue testing the efficacy of diverse participatory methods across crops, locations, and variability of years. Along with the need to expand genetic diversity and adaption of our crops to environmental diversity there is also a need for expanded diversity of participants. Research models and institutional frameworks must evolve and adapt to varied socio-economic contexts to enable diverse

participation in plant breeding and seed systems. To do so is imperative to the resilience of our ecosystems and the wellbeing of society.

Acknowledgements

It is clear to me now more than ever that the true value of my Phd experience laid in the journey as much as the destination. I embarked on this trajectory 6 years ago with the intent to hone my skills as a researcher, deepen my knowledge in participatory methods, and continue my professional development as a plant breeder. In the process I grew personally and professionally from the experience and built lasting relationships with my mentors and fellow researchers in ways I could not have imagined. I hope my experience as a mid-career student may inspire others to similarly continue to pursue academic pathways and scientific investigations with the eternal curiosity of a lifelong learner.

The work of this thesis represents the collective experiences of numerous individuals including the first-hand knowledge of the farmers' involved, the research insights of co-authors, and the hard work of many graduate students and field assistants. I'm grateful for the collaborative efforts and knowledge shared from of each of you. First and foremost, I'm honored by the mentorship and encouragement of my primary promoter Dr. Edith Lammerts van Bueren who generously provided the opportunity and commitment that made this experience possible. I'm thankful for the chance to follow her lead as an innovative female scientist. I extend my deepest gratitude to my co-promotors and advisors Dr. Conny Almekinders, who guided me through social realms of agricultural science; Dr. Julie Dawson, who provided a rich context of participatory methodologies and strengthened my statistical skills; and Dr. Jim Myers who patiently tutored me in plant breeding while always treating me with the respect of a colleague. In addition, I thank Dr. Phil Simon, for openly sharing his knowledge in carrot breeding and providing the opportunity to lead in publishing on our collaborative research. To Dr. Bill Tracy I'm grateful for your valuable feedback and honored to have co-conspired and collaborated in expanding the potential of participatory plant breeding. I'm eternally grateful to Jared Zystro and Michael Liou who kept me sane while patiently tutoring me through statistics and navigating the sometimes-maddening language of R. To my paranymphs, Cathleen McCluskey and Fleur Kilwinger, thank you for sharing in our collective pursuit of doctoral degrees, helping navigate publishing this thesis, gracefully looking out for me, and celebrating our accomplishments post-graduation. I thank Dr. Erica Renaud for introducing me to Edith and sharing her experience at Wageningen University. Leading up to my pursuit of a doctoral degree the work and words of several seeds people inspired me including Dr. John Navazio, Dr. Salvatore Ceccarelli, Dr. Cary Fowler, Dr. Kevin Murphy, and Dr. Lori Hoagland.

The vision and programs of Organic Seed Alliance provided not only the institutional framework, but the inspiration for the research questions and investigations presented. I thank Laurie McKenzie for critical edits and cheering me on, to Cara Loriz for leading an organizational space that enabled meaningful professional development, to Cathleen McCluskey for helping me navigate work-life-school balance, to Jennifer Turney for keeping the ship afloat and telling me I can do anything, and to all my co-workers for the constant encouragement and accommodations in workflow necessary to achieve my goals.

The intricate and dynamic web of my personal family and friendships provided the essential love, humor, and resilience necessary to achieve this accomplishment. I'm grateful to my husband, Arran Stark, who leaned in with unwavering love and support providing the family stability necessary for me to dive deeply into studies at critical times. He always believed in me, buffered my losses, and celebrated my successes. I will always remember my mother Carol Colley, with gratitude for embedding resilience in my character and believing I could achieve anything I put my mind to. I thank my father, Howard Colley, for the gift of a satirical sense of humor, necessary for maintaining sanity in difficult times, and a fascination with the wonders of evolution. To my brother, Kevin Colley, I thank for staying connected through our human experience. To my Aunt Helen Ryan for listening, laughing and having my back. To my sisterhood of friends thank you all for the constant flow of love, texting "you got this!" when my confidence lapsed, picking up kids whenever I needed, and celebrating small wins with a hug and a toast.

I dedicate this work to my children, Crenna Stark and Owyn Stark. I'm inspired by the unique, curious, and brilliant humans you are. I could not have become Dr. Colley without your love and support. I hope it encourages you to fulfill your own dreams. In the words of Mary Oliver,

Tell me, what will you do with this one wild and precious life?

Sincerely, Micaela Colley, October 10th, 2022

Education Statement

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Advancing organic agriculture utilizing participatory plant breeding, action learning and a systems approach

Post-graduate courses (5.1 ECTS)
- Root ecology; PE&RC (2016)
- Basic statistics; PE&RC (2017)
- Participatory plant breeding and resilient seed systems; PE&RC (2021)

Deficiency, refresh, brush-up courses (4 ECTS)
- Principles in plant breeding; WUR (2017)
- Advanced statistics; PE&RC (2017)

Laboratory training and working visits (1.8 ECTS)
- DNA extraction and PCR analysis of Brassica oleracea; Vegetable Breeding and Genetics, Oregon State University (2017)
- Evaluation and ranking of cavity spot incidence in replicated carrot trial; Vegetable Seed Pathology, Washington State University (2020, 2021)

Invited review of (unpublished) journal manuscript (1 ECTS)
- Experimental Agriculture: participatory plant breeding

Competence strengthening / skills courses (2 ECTS)
- Scientific publishing; WGS (2016)
- Data management; WGS (2016)

- Introduction to technology, science and society; WUR (2022)

Scientific integrity/ethics in science activities (0.3 ECTS)
- Uprooting racism in the food system; Soul Fire Farm (2021)

PE&RC Annual meetings, seminars and the PE&RC weekend (0.9 ECTS)
- PE&RC Weekend for first years (2016)

Discussion groups / local seminars or scientific meetings (4.7 ECTS)
- Organic plant breeding journal group; UW-Madison (2016)
- EU project LiveSeed engaged in knowledge exchange, and scientific meetings (2017-2021)

International symposia, workshops and conferences (11.2 ECTS)
- Symposium on Intellectual Property Rights and Public Plant Breeding; oral presentation; North Carolina, USA (2016)
- Organic Seed Growers Conference: Cultivating Resilience; oral presentation; Oregon, USA (2016)
- International Carrot Conference; oral presentation; Wisconsin, USA (2016)
- Organicology Conference; oral presentation; Oregan, USA (2016)
- Diversifood Final Congress; oral presentation; France (2018)
- Eucarpia International Conference on Breeding and Seed Sector Innovations in Organic Plant Breeding; oral presentation; online; Latvia (2021)
- IFOAM World Congress and pre-conference Seed Ambassadors; oral presentation; online; France (2021)

Societally relevant exposure (0.6 ECTS)
- Blog post: many hands breed better crops, Journal of Agricultural Science (2021)
- Pod cast: organic seed production for beginning farmers: featured project for beginning farmer rancher development program, USDA (2022)

Lecturing / supervision of practicals / tutorials (9 ECTS)
- Northern Organic Vegetable Improvement Collaborative (NOVIC), fundamentals of on-farm plant breeding (2018, 2019)
- Seed production for farmers (2020, 2021)

The research presented in this thesis was financially supported in part by the USDA National Institute of Food and Agriculture awards for the US projects Northern Variety Improvement Collaborative (NOVIC), awards number 2009-51300-05585, 2014-51300-22223 and 2018-51300-28430 and the Carrot Improvement for Organic Agriculture (CIOA) project award # 2011-51300-30903, 2016-51300-25721 and 2021-51300-34900. This research was additionally financially supported in part by the Jefferson County American Association of University Women and the research and education programs of Organic Seed Alliance. Financial support from Wageningen University for the printing of this thesis is gratefully acknowledged.

Cover design: Cathleen McCluskey, Organic Seed Alliance, Madison, Wisconsin, US

Photographs: Photos for chapter title pages of Chapter 3 and 5 are credited to Shawn Linehan Photography. All other photos are credit of Organic Seed Alliance.

Lay-out: Fleur Kilwinger, NL

Printing: Proefschriftmaken.nl


6001