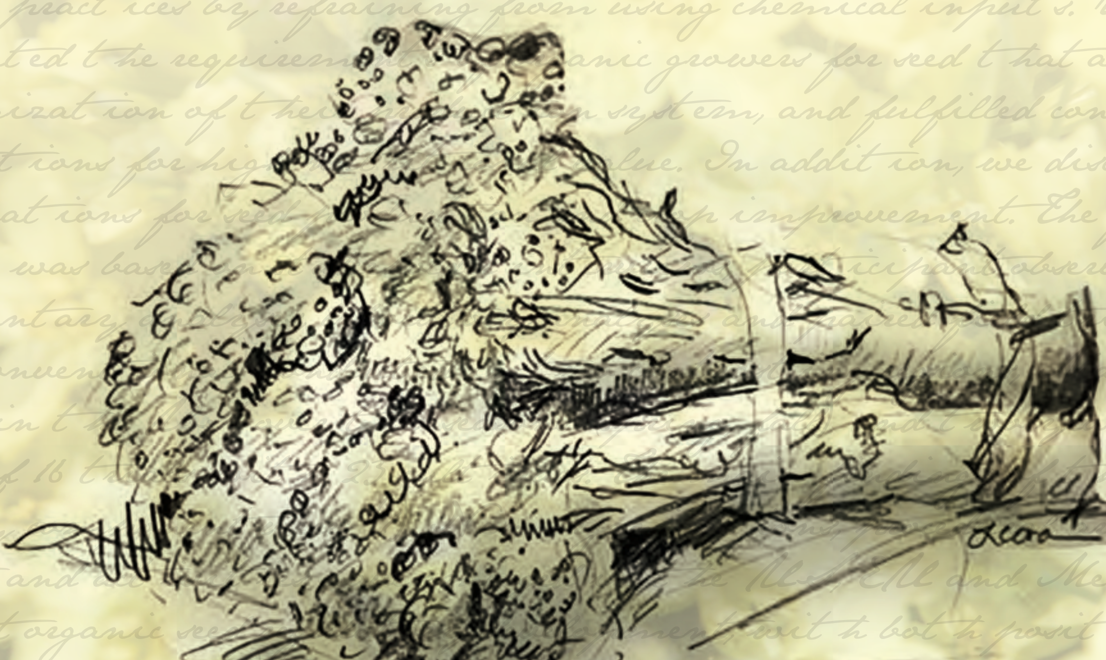
Breeding and Regulatory Opportunities and Constraints for Developing Broccoli Cultivars Adapted to Organic Agriculture



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Breeding and regulatory opportunities and constraints for developing broccoli cultivars adapted to organic agriculture

Erica N.C. Renaud

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Preface

After years of dedication to deeper knowledge of organic plant breeding and regulatory policy for the purpose of understanding and advancing the organic seed movement, the completion of this thesis is a momentous event. Many individuals and organizations have contributed to the success of the research, and to all I am truly grateful.

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Abstract

This thesis is about the regulatory and technical challenges to the organic seed and breeding sector. This study specifically explored the mutual influence of the regulatory environment for organic seed sector development in the United States (US), Europe Union (EU) and Mexico, and the extent to which broccoli (*Brassica oleracea* var. *italica*) cultivars performed differently under organic conditions compared to conventional conditions, measured by selected horticultural and phytochemical traits. Currently, organic farmers depend largely on cultivars bred for conventional farming systems. However, organic farming practices often differ substantially from conventional practices by refraining from using chemical inputs. We investigated the requirements of organic growers for seed that allowed optimization of their production system, and fulfilled consumer expectations for high nutritional value. In addition, we discuss the implications for seed production and crop improvement. The field research was based on stakeholder interviews, participant observation, documentary analyses, laboratory analyses and paired field trials (organic/ conventional) conducted in two contrasting regions, Maine and Oregon in the US, over two seasons (spring, fall) and two years for a total of 16 trials with 23 cultivars. The main findings of the regulatory component were: (1) New organizations, procedural arrangements and activities have emerged in the US, EU and Mexico to support organic seed regulatory development, with both positive and negative results; (2) Official guidance on the interpretation of the regulation in the US has not been sufficiently decisive to prevent divergent interpretation and practice, and in consequence the needs of a rapidly growing economic sector are not being met; and (3) Growth of the organic seed sector is hindered by regulatory imbalances and trade incompatibilities within and between global markets. For the field studies the main findings were: (1) In the partitioning of variance, location and season had the largest effect on broccoli head weight. For glucoraphanin and lutein, genotype was the major source of total variation; for glucobrassicin, region and the interaction of location and season; and for neoglucobrassicin, both genotype and its interactions with season were important. For δ- and γ- tocopherols, season played the largest role in the total variation followed by location and genotype; for total carotenoids, genotype (G) was the largest source of variation and its interactions with location and season. For both horticultural and phytochemical concentrations, Management (M) main effect and G × M interactions were often small but G × M × E (location and season) were large; (2) Cultivars with both greater head weight and stability under conventional conditions generally had high head weight and stability under organic growing conditions, although there were exceptions in cultivar rank between management systems. Cultivars highest in tocopherols and carotenoids were open pollinated or early maturing F_1 hybrids. Distinct locations and seasons were identified where phytochemical performance was higher for each compound; (3) Larger genotypic variances and increased error variances were observed in organic compared to conventional management systems led to repeatabilities for several horticultural and phytochemical traits that were similar or even higher in organic compared to conventional conditions; (4) The ratio of correlated response (predicting performance under organic conditions when evaluated in conventional conditions) to direct response (predicted performance in organic when evaluated under organic conditions) for all traits was close to but less than 1.0 with the exception of bead uniformity. This would imply that in most cases, direct selection in an organic environment could result in a more rapid genetic gain than indirect selection in a conventional environment; (5) Correlations among phytochemical traits demonstrated that glucoraphanin was negatively correlated with the carotenoids and the carotenoids were highly correlated with one another; and (6) There was little or no association between phytochemical concentration and date of cultivar release, suggesting that modern breeding has not negatively influenced the level of tested compounds and there were no significant differences among cultivars from different seed companies. Based on the findings strategies for seed system models are discussed.

Keywords

Organic seed regulation, stakeholder analysis, crop improvement, *Brassica oleracea*, horticulture traits, phytochemical concentrations, selection environment, seed system models

Abbreviations

ACA	Accredited Certifier Association
AMS	Agricultural Marketing Service
AMSAC	Mexican Seed Trade Association
AOSCA	Association of Official Seed Certifying Agencies
APHIS	Animal and Plant Health Inspection Service
ASTA	American Seed Trade Association
ATTRA	Appropriate Technology Transfer for Rural Areas
COFEMER	Mexican Federal Commission of Regulatory Improvement
COFEPRIS	Mexican Federal Commission for the Protection Against Phytosanitary Risk
ECO-PB	European Consortium for Organic Plant Breeders
ESA	European Seed Association
FAO	Food and Agriculture Organization
FAS	Foreign Agriculture Service of the United Nations
FFSC	Family Farmers Seed Cooperative
IFOAM	International Federation of Organic Agriculture Movements
IPPC	International Plant Protection Convention
JC & CAC	Joint Crops and Compliance, Accreditation and Certification Committee
NAPPO	North American Plant Protection Organization
NOP	National Organic Program
NOSB	National Organic Standards Board
NOVIC	Northern Organic Vegetable Improvement Collaborative
OFPA	Organic Foods Production Act
OFRF	Organic Farming Research Foundation
OMRI	Organic Materials Review Institute
OREI	Organic Research and Education Initiative
OSA	Organic Seed Alliance
OSP	Organic Seed Partnership
OTA	Organic Trade Association
PSI	Public Seed Initiative
SAGARPA	Mexico Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food
SARE	Sustainable Agriculture Research and Education
SCOF	Standing Committee Organic Farming
SENASICA	Mexican Sanitary, Food Safety and Food Quality National Service
SOS	State of Organic Seed
USDA	United Stated Department of Agriculture

Chapter 1

General Introduction

1.1 Introduction

This thesis is about the regulatory and technical challenges in the organic seed and breeding sector, taking broccoli (*Brassica oleracea* var. *italica*) in the USA as the model case. In this chapter the theme is introduced and background information is provided. The problem addressed by this thesis is introduced, and the research objectives, hypotheses and main research questions are presented, followed by the research design and methodology, and the outline of this thesis.

Organic farm practices often differ substantially from conventional practices in refraining from chemical-synthetic inputs such as fungicides, pesticides and mineral fertilisers) but also in the diversity of their crop rotations, number of crops, production area, and market outlets (Kristiansen et al., 2006). Organic farming systems are based on organically-derived inputs such as compost and animal manure and focus their management on stimulating long-term biological self-regulatory processes to achieve resilience for stable productivity. However, organic farmers have fewer options to intervene in the short-term when weather or soil conditions are not favourable for optimal crop growth (Mäder et al., 2002; Messmer et al., 2012). Therefore organic growers require cultivars with stable performance across variable growing conditions over years. Currently, organic farmers depend largely on cultivars bred for high external input conventional farming systems (Lammerts van Bueren et al., 2002). One of the challenges for the organic agricultural sector is to comply with the principles of organic agriculture concerning health, ecology, fairness and care, see Table 1.1, as formulated by the world umbrella organization for the organic sector the International Federation of Organic Agriculture Movements (IFOAM, 2012; Luttikholt, 2007). It includes that all farm inputs should be produced organically. Use of organic seed as a required farm input is a component in the overall organic certification process. Recent developments in the interpretation of organic seed regulation have created tensions between farmers and seed companies as to how to provide a sufficiently diverse assortment of cultivars suited for organic agriculture and meet the requirements (USDA AMS, 2002; Dillon and Hubbard, 2011).

Table 1.1 Four principles of organic agriculture as described by IFOAM (2012).

Principle	Description
Health	Organic Agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible
Ecology	Organic Agriculture should be based on living ecological systems based on living ecological systems and cycles, work with them, emulate them and help sustain them
Fairness	Organic Agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities
Care	Organic Agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment

The research program under consideration here was designed to investigate efforts to translate the requirements of organic growers for seed that will allow them to optimise their production system, and fulfil consumer expectation for the integrity of organic products, into a strategy for seed production and crop improvement. Broccoli was used as a model crop because it is one of the most important horticultural crops in the world's fastest growing organic product market, the United States (US). This study specifically explored the mutual influence of the regulatory environment and technical opportunities for organic seed sector development in the US, Europe Union (EU) and Mexico, and the extent to which cultivars performed differently under organic conditions compared to conventional conditions, measured by selected horticultural traits and phytochemical compound concentrations. The research was based principally on a range of stakeholder interviews, participant observation, documentary analyses, laboratory analyses, and paired field trials (organic/ conventional) conducted in two contrasting regions in the US, Northeast US (Maine) and Pacific Northwest (Oregon), over two seasons (spring, fall) and two years for a total of 16 trials with 23 cultivars (Figure 1.1).

Figure 1.1 Map of the US, showing the two broccoli field trial site locations in Maine and Oregon.

1.2 Background

1.2.1 Organic Agriculture in USA

The US organic market, with consumer sales of $US 31.5 billion (€23 billion) and 5.4 million production acres (2.2 million ha), is the fastest growing global market, with 9.5% market growth in 2012 (compared to 4.7% conventional) (Willer and Lernoud, 2014, OTA, 2013). Organic food sales value now represent 4.2% of all US food sales (OTA, 2013). Since the implementation of the United States Department of Agriculture (USDA) National Organic Program (NOP) in 2002, certified organic farmland in the US has nearly tripled (USDA AMS, 2002; USDA NASS, 2012). Organic production in the US is comprised of both large-scale growers concentrated in specific regions and numerous small scattered acreages across the country that produce in a broad range of environments to service local and diverse food markets (USDA ERS, 2011). Consumer preference for more sustainably produced foods, combined with the perception that organically produced food is more nutritious, are the primary drivers behind the growth in this demand (Stolz et al., 2011). While the organic market has been developing, so too have the organic agriculture production systems that support sector growth.

1.2.2 Broccoli in USA

Consumption of organic foods is partially driven by the perception that organically grown foods are more nutritious (Saba and Messina, 2003). Several studies have indicated that organic vegetables and fruits contain higher concentrations of certain secondary plant metabolites than those produced conventionally (Asami et al., 2003; Chassy et al., 2004; Brandt et al., 2011), although there are also studies that show no differences (Smith-Sprangler et al, 2012). Broccoli is a relatively abundant source of vitamins, including provitamin A (primarily beta-carotene, a carotenoid), vitamin C (ascorbate), and vitamin E (tocopherol) (USDA Nutrient Database, 2011). It is also a source of phytochemicals that have been associated with health promotion. Phytochemical groups with reported health activity found in broccoli include glucosinolates, tocopherols, carotenoids, and flavonoids (Brown et al., 2002; Kushad et al., 1999; Farnham et al., 2009). Several authors, e.g. Verhoeven et al. (1996), Keck and Finley (2004) and Here and Büchler (2010), reported that diets rich in broccoli reduce cancer incidence in humans. A strong case for a cause-effect association between consumption (dose) and reduction in disease risk exists for the glucosinolates (anti-cancer), tocopherols (cardiovascular) and carotenoids (particularly related to eye-health) (Higdon et al., 2007).

Broccoli has developed into a significant Brassica crop in organic agriculture due to market demand and its role in crop rotation. It was grown in the US on 743,088 organic production acres (300,717 ha) and generated $US 47,629,515 (€34,514,185 in sales in 2011 (USDA NASS, 2012). The main organic and conventional broccoli production areas in the US are California and Arizona comprising over 90% of the production acreage (USDA ERS, 2011; USDA NASS, 2012). While organic broccoli is in part grown in these primary production regions, there is also a range of growers distributed throughout the US, located primarily in northern latitudes, whose farms are subjected to more extreme hot and cold climatic conditions than are farms in the primary production areas (Heather et al., 1992; Farnham and Björkman, 2011a, 2011b; Lammerts van Bueren et al., 2011; Myers et al., 2012).

1.2.3 Organic seed regulation

During this period of market and production growth, the USDA developed the NOP standard, with which organic growers and processors must comply to receive their organic certification. The NOP standard, Section 205.204(a)(5) prescribes the use of organic seed in an organic production system whenever such seed is commercially available, and details how to apply for derogation if the organic seed is not available (USDA AMS, 2002). According to the standards of the IFOAM, 'certified organic seed' is defined as seed from varieties that may be derived from conventional breeding programs (excluding genetic engineering) that are produced under organic farming conditions for one growing season for annual crop species, and two growing seasons for perennial and biannual crop species (IFOAM, 2012). At the start of my study in 2007, the US organic seed regulation was (and still is) very much in development. Nevertheless, the evolving interpretation of the seed clause stimulated some seed companies to enter the organic market by investing in organic seed production, and has also raised the awareness of farmers about their cultivar requirements and their current and potential role in the organic seed chain (Dillon and Hubbard, 2011; Podoll, 2011). Other conventional seed companies are struggling with the implications of the organic seed regulation enforcement upon their seed business model. Currently, these seed companies supply organic farmers with post-harvest untreated seed of the conventional varieties that they have available. In addition to the involvement of the formal seed sector and farmer groups in the organic seed regulation, several new organizational structures have developed in response to the evolving regulatory environment. Various organizations have been formed with the overarching objective of guiding the enforcement process and supporting farmers in identifying varieties that best suit their production systems and markets.

1.3 Problem description

The challenge of designing a seed development and breeding strategy for robust cultivars adapted to organic agriculture raises both regulatory and technical issues that at the beginning of the study, and in fact since, had not been empirically researched or discussed fully in the scientific literature.

1.3.1 Challenges in developing an organic seed sector

While at the inception of the study the EU organic seed regulation was more developed, with clear guidelines and timelines for enforcement, the US organic seed regulation was not as well described (EU, 2007). There was tension among the multiple stakeholders concerned, including the formal seed sector and organic producers, as to how and when the NOP organic seed regulation should be enforced (NOSB, 2005, 2007, 2008a, 2008b, 2008c). Contention around enforcement stemmed from the fact that there was only a limited number of suitable and diverse cultivars available with sufficient quantities of seed for organic production. Organic farmers were concerned that 100% enforcement of the organic seed regulation would limit their choice of cultivars and force them into using cultivars not appropriate for its farming system or markets, and potentially of lower quality or of higher price. The introduction of the organic seed regulation in the US spurred a reaction from the global organic sector. At the start of the study, the US and the EU had established domestic organic standards and the seed clause sections of their respective regulations were in process of interpretation and implementation. Mexico was just beginning the process of developing its own federal organic standard (inclusive of a seed clause) (SAGARPA, 2013; USDA FAS, 2013). By 2014 all jurisdictions were challenged to determine how to implement organic seed policy, how they chose to do so has implications that affect global trade (Sonnabend, 2010; Dunkle, 2011). At present (March 2014), there were still no other studies that have evaluated the various stakeholders' interests and roles in the evolving organic seed regulations, or assessed how the US process differs from the EU process, or the implications for Mexico's evolving organic sector. At the start of the study, there also were no studies of the potential implications of the various outcomes of an enforced, or unenforced, organic seed regulation in the US, and the further scenarios that any outcome might entail.

1.3.2 Organic cultivar requirements for agronomic performance

The seed industry still finds it economically challenging to satisfy the needs of organic agriculture, and often does not understand the special requirements of organic agricultural systems with which they are unfamiliar. Organic farmers in general want varieties that are adapted to their location and are reliable under adverse conditions, rather than varieties that promise higher yields but may lose that yield advantage in production because of disease susceptibility or an inability to perform in an organic farming system. Lammerts van Bueren et al. (2002) have indicated such desired traits as a general organic 'crop ideotype', which needs to be specified for different crops. More specifically, organic farmers refrain from use of chemical inputs for weed management and pest and disease control, thus varieties must perform under different management conditions compared to conventional farms. Since the organic farming sector is comprised of diverse types of organic growers (ranging from small-scale direct market producers, through wholesale to large-scale operations producing for industrial processing enterprises), and since organic farmers have fewer tools at their disposal to influence their production environment to fit their crops, their variety needs differ significantly from those of their conventional counterparts (Drinkwater et al., 1995; Wolfe et al., 2008).

In the case of broccoli, at the start of the study it was known that some organic farmers' desired traits were the same as those of conventional producers, such as drought tolerance, insect and disease resistance or high yield. Other characteristics were thought to be more important to organic producers than to conventional growers: for instance, vigorous growth and ability to perform in soils with potentially low or fluctuating mineralization rates of nutrients, or the ability to cover the soil and withstand weed competition by having less erect architecture than displayed by modern broccoli hybrids. The few studies to articulate the required cultivar traits for organic farming systems had focussed mainly on arable crops, especially cereals (Wolfe et al., 2008); only a few had dealt with desired vegetable crop traits (e.g. Osman et al., 2008, for onions). No studies had been published on the desired traits for organic broccoli or other Brassica crops.

Some studies comparing performance of genotypes in organic and conventional management systems had shown that for certain traits, cultivar rank varies between the two management systems (e.g. for winter wheat: Murphy et al., 2007; Baresel et al., 2008; Kirk et al., 2012; for lentils: Vlachostergios and Roupakias, 2008; for maize: Goldstein et al., 2012), others had shown no differences in ranking of performance (for maize: Lorenzana and Bernardo, 2008; for cereals: Przystalski, 2008; for onions: Lammerts van Bueren et al., 2012). The inconclusive results of these studies raise questions as to the need for cultivars to be bred with broad adaptability or specific adaptation in order to meet the requirements of regional organic management and end uses.

1.3.3 Organic cultivar requirements for improved nutritional value

The genetic potential of organically-grown cultivars for high nutrient quality had been a concern for many years of the organic industry. Organic growers shared a general concern that modern elite cultivars (mostly F_1 hybrids) might lack the nutritional quality of older open pollinated cultivars (Murphy et al., 2008). Indirect evidence supporting this argument had been published by Davis et al. (2004), who compared USDA nutrient content data for 43 garden crops, from their statistical records from 1950 to 1999. Statistically significant declines were noted for 6 nutrients (protein, calcium, potassium, iron, riboflavin, and ascorbic acid), with declines ranging from 6% for protein to 38% for riboflavin. Davis et al. (2004) attributed the decreases in nutrient content in part to changes in the cultivars used. Cultivars in 1950 had been bred to be adapted to specific regions and a relatively low input agriculture system, while the more modern varieties had been selected for yield, disease resistance, broad adaptation in high input agriculture systems, and for increased 'shipability' and shelf life. It was hypothesised that selection of cultivars for traits such as growth rate, yield, pest resistance, or other non-nutrient characteristics, might be subject to metabolic trade-offs that result in limitations in the cultivars' abilities to incorporate soil minerals, transport them within the plant, or synthesize nutrients such as proteins, vitamins, and other phytochemicals (Morris and Sands, 2006).

The literature showed that concentrations of health-promoting nutrients in Brassicas depend on the cultivar, season and management system in which they were grown, including organic versus conventional conditions (Farnham et al., 2004; Charron et al., 2005a, 2005b; Meyer and Adams, 2008). It was widely accepted that genotype played an important role in determining the level of nutrients in a crop cultivar (Munger, 1979; Welch and Graham, 2004). What was unclear, however, was to what extent there is a genotypic effect and trade-offs between different nutritional compounds and whether the nutritional content of a cultivar was associated with certain genotypic classes, e.g. open pollinated versus F_1 hybrid. There was also no clear differentiation as to whether nutritional content in a crop was driven by genotypic class or whether it varies due to genotype by environment interaction. It was hypothesized that identification of growing conditions and genotypes that can provide products with various phytochemical content and putative disease-prevention activity could offer value-added commercial opportunities to commercial seed producers, the food industry, and an added value for the organic seed market.

Some studies published before the start of the work presented in this thesis had compared organically versus conventionally grown broccoli, in 'market basket' investigations, i.e. these studies were intended to reflect the nutritional quality of the crop as received in the consumers' 'basket' of produce (Wunderlich et al., 2008; Koh et al., 2009). The studies did not consider cultivar, soil quality, irrigation, climate, harvest stage, or post-harvest practices. No field studies comparing organically grown versus conventionally grown broccoli for the form and concentration of various phytochemicals have been performed. A further limitation of many of the studies available at the start of our own work was that the number of cultivars studied was too small to generalize the results (Harker, 2004). While a few research studies had compared cultivars based on their release date, data on the cultivar and production system (soil quality, temperature, rainfall) was not available (Davis et al., 2004). No research had investigated how open pollinated and hybrid cultivars of broccoli grown in different regions, under organic and conventional production systems, may vary in performance for horticultural traits and phytochemical concentrations at the onset of this study.

1.3.4 Breeding for organic systems

In addition to the fact that the organic sector remains of limited size, breeding for reliable varieties adapted to low-input, organic agriculture raises regulatory, technical and institutional issues that hitherto have not been discussed fully in the scientific literature. For instance, breeders interested in the organic market question whether direct selection under organic, low-input conditions is necessary to arrive at suitable cultivars. This would increase the breeding costs for conventional breeders because it would require maintaining two types of selection fields. Breeders alternatively could consider which traits to select in the specific target environment and which of the required traits are heritable independent of the environment, and therefore could select indirectly under conventional conditions. Could a breeding strategy for broccoli be developed in such a way that it combined selection under conventional systems in the earlier phases, with evaluation in organic systems of advanced breeding lines at a later stage of the breeding cycle? These models have been elaborated for cereals (Murphy et al., 2007; Löschenberger et al., 2008; Wolfe et al., 2008) and for onion (Osman et al., 2008) but not for the *Brassica* vegetables.

Another issue of concern to breeders who aim to service the organic market is whether breeding under low-input and variable growing conditions might be less efficient, because of the expected lower heritability of quantitative traits. Similar discussions had been going on for selecting in and for low-inputs conditions in Southern countries (e.g. Ceccarelli, 1996). Heterogeneous environments make it difficult to apply consistent selection pressure because it is often difficult to identify a single or a few superior genotypes across all sets of conditions. However, when the target system is characterized by heterogeneity of environmental conditions, varieties selected under high-yielding conditions may fail to satisfy farmers' needs under low-input conditions (e.g. Murphy et al., 2007). Because heterogeneous environmental conditions are a feature of organic systems, some researchers have emphasized the value of alternative breeding models such as decentralized or participatory selection (e.g. Myers and Kean, 2007; Chable et al., 2008; Desclaux et al., 2008). The formal breeding industry has become more interested in breeding for the organic market over the course of the study presented in this thesis, providing opportunities to contribute evidence to inform these discussions.

1.3.5 Breeding techniques

Breeding methods have evolved rapidly in recent years to service an expanding seed market. The organic sector has argued that several techniques used in conventional breeding programmes would not comply with the principles of organic agriculture (Lammerts van Bueren et al., 2007). Organic agriculture has philosophically and legally rejected the technology of genetic modification (GM), where GM organisms are defined as 'organisms in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination' (IFOAM, 2012). Under this definition of genetic modification protoplast fusion is also included, and is therefore not compatible with organic principles (Haring et al., 2009; Chable et al., 2012; Myers et al., 2012). Protoplast fusion was used to introduce cytoplasmic male sterility (CMS) for use in Brassica hybrid breeding programs. CMS has not been found to naturally occur in Brassica species such as broccoli. In some cases, CMS replaced the older technique based on self-incompatibility for hybrid seed production (Myers, 2014). Some breeding companies depend on the CMS technique in producing hybrid varieties and this influences their commitment to the organic sector. In the first decade of this century, organic grower groups in the US began developing their own regionally adapted open pollinated varieties in order to avoid purchasing varieties bred with techniques not in alignment with organic principles, and perhaps that were not appropriately adapted to their agro-ecosystems. Over the lifetime of our study discussion of the appropriate breeding techniques to use in organic breeding programs has featured predominantly in the European discourse (Rey, 2009). The issue in the future could have consequences for other parts of the world, including the US, especially in light of discussions at the IFOAM General Assembly in 2008 and in the National Organic Standards Board (NOSB), (the advisory board of the NOP) in 2013 where the role of CMS derived cultivars in organics was challenged (Rey, 2009; USDA NOP, 2013). A ban on certain breeding techniques in organic agriculture would have far reaching consequences for Brassicas, and would need to be considered in the analysis of an organic broccoli breeding strategy that is explored in this thesis.

1.4 Research objectives, hypotheses and main research questions

The overall objective of the research reported in this thesis was to analyze regulatory and technical challenges in the organic seed and breeding sector, using broccoli as a model crop and the US as the main location. The research aimed to analyze the tension between farmers' and seed companies' interests that has been created by the evolving organic seed regulation, and provide ways forward to develop the organic seed regulation to support the principles of organic agriculture and future crop improvement. In order to translate the diverse constraints and needs of organic farmers and other stakeholders involved in the broccoli seed chain into a strategy for plant breeders, the horticultural and phytochemical performance of commercially available broccoli cultivars grown under organic and conventional farming conditions in different broccoli producing areas (Maine and Oregon, US) were analyzed.

1.4.1 Research hypotheses

Hypothesis 1. An organic seed regulation is a necessary step toward an optimized organic seed sector.

Hypothesis 2. Cultivars bred for high input conventional growing conditions may not be optimal for organic farming systems.

Hypothesis 3. Organic production systems produce crops of higher nutritional value.

1.4.2 Research questions (RQs)

Research Question 1. *How do current and evolving organic seed regulations affect the organic seed and crop improvement system?*

This study traces how the evolution of organic seed regulation in the US, and in the EU and Mexico compared, has been guided by both formal policy development and by the informal interpretations, behaviours, actions and choices of the various stakeholders. Specifically, the main issues addressed are: (1) How do proposals for the wording and implementation of the US regulation constrain seed choices and give rise to unintended consequences?, (2) How have emergent organizations and procedures in the US responded to the tension between, on the one hand, sustaining seed differentiation to match the characteristics of local markets, organic production and agro-ecologies, and on the other, the narrowing of varietal choice in catalogued seed so as to expand commercial organic seed markets and encourage organic seed breeding?, (3) Why consensus on the content of formal organic seed policy has failed to develop in the US despite a high level of stakeholder engagement? How and why have the varying capacities of an increasing number of private and public stakeholders in the organic seed sector, each with specialized tasks and competencies, led to fragmentation rather than convergence of effort in the US?, (4) What are the implications of a lack of international organic seed regulatory harmonization for trade relations?, (5) What can different jurisdictions (US, EU and Mexico) learn from one another about each other's normalization experience in developing domestic organic seed regulatory processes?, and (6)

How can the lessons learned be applied to support further global development of organic seed sector governance?

Research Question 2. *Do currently available broccoli cultivars perform differently in organic compared to conventional production systems for horticulture traits?*

In order to analyse to what extent present commercial broccoli cultivars sufficiently meet the diverse needs of organic management systems such as adaptation to low nitrogen input, mechanical weed management and no chemical pesticide use, and to propose the best selection environments for crop improvement for organic production we conducted field trials to address the following questions: (1) Do currently available broccoli cultivars perform differently for head weight and other horticulture traits in organic compared to conventional management systems in different regions and different seasons?, (2) Is the relative ranking of cultivars the same under organic and conventional conditions?, (3) Does heritability differ for certain traits under organic conditions compared to conventional conditions?, and (4) Under which growing conditions and in what locations would selection for broccoli cultivars for organic agriculture be most effective?

Research Question 3. *Do currently available broccoli cultivars perform differently in organic compared to conventional production systems for phytochemical traits?*

In order to analyse to what extent present commercial broccoli cultivars differ in phytochemical concentrations when grown under organic and conventional conditions in different seasons and locations, and to identify differences in genotypic class performance for the concentration of phytochemicals associated with health promotion, the trials established to evaluate horticultural traits as described under research question 2 were harvested and analyzed for glucosinolates, tocopherols, and carotenoids by cultivar and by genotypic group. Specifically, we sought to address the following questions: (1) What is the impact on phytochemical variation of organic management system compared to other environmental factors including climatic region, season and their interactions [Genotype (G) x Environment (E) x Management System (M)]?, (2) Is there a significant difference in phytochemical content between different genotypes and genotypic classes (old and modern cultivars; open pollinated and F_1 hybrid cultivars; early and late maturing cultivars; and between different commercial seed sources)?, and (3) What is the best selection environment for a broccoli breeding program for enhanced phytochemical content?

1.5 Research design and methodology

The study design (Figure 1.2) sought to integrate regulatory analysis and technical studies. The methodology for the study of organic seed regulation is presented first, followed by the methodology for the technical parts of the research.

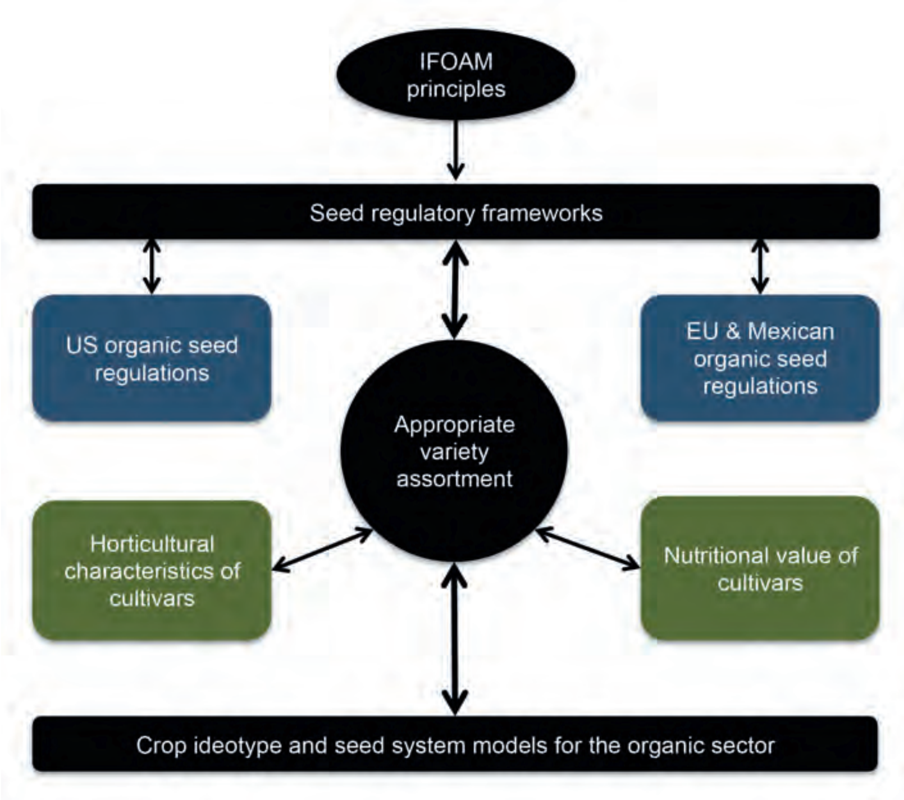

Figure 1.2 Schematic overview of the research design

1.5.1 Defining the current and evolving effects of organic seed regulation

The methodology to address RQ1 was based on an in-depth case study of governance processes and normalization of the organic seed regulation in the US, using four principal methods: (1) preliminary analysis of stakeholder categories in the organic seed value chain in the US, (2) interviews with selected individuals and organizations in each of the identified stakeholder categories, (3) review of successive regulatory and policy documents and stakeholders' written responses to these, and (4) participant observation at key policy meetings related to the organic seed regulation over the study period from mid-2007 to 2013. The case material was initiated by identification, analysis and categorisation of the stakeholders (i.e. the main public and private actors in the sector in 2007) in terms of their stakes, and their levels of interest in and influence directly and indirectly on the evolving organic seed regulation. Subsequently, semi-structured and structured interviews were conducted with selected individuals/organizations in each stakeholder category, in order to explore stakeholders' perceptions of organic seed regulation in light of their respective roles in the process and of the opportunities or barriers to regulatory development, as well as to identify the actions they were taking to guide the course of regulatory development and enforcement. Narrative analysis of the unfolding perceptions and organizational developments was carried out by: (1) mapping participants' changing concerns, concepts and contexts, (2) identifying key decision points in rule-setting and implementation processes from the stakeholders' perspectives, (3) mapping emergent networks and coalitions of interest, and (4) by documenting how resources of various kinds were mobilized by the stakeholders in response to the changing understanding of the regulation.

To further address RQ1, the research built on the interviews, observations and analyses performed for the US organic seed sector to include the governance of the EU and Mexican organic seed regulatory systems. The EU was selected due to the depth of its organic seed regulatory evolution, and because it is also a primary organic market that is comparable to the US (the two regions combined comprise 97% of global organic revenue). Mexico was selected because its commercial agriculture system depends to a large extent on seed imported from the US and EU; because over 80% of its certified organic exports are destined for the US, and because Mexico, while in the process of defining its own domestic organic legislation and regulation practices may benefit from the experiences of its trading partners. The approach to this part of the study was designed to allow detailed process tracking and within-case analysis. The case material was collected from mid-2007 through 2013. In each case, interviews were conducted with individuals to explore stakeholders' perceptions of the draft organic seed regulation, their respective role in the process, and their perceptions of opportunities for or constraints to regulatory development. The respondents who were identified through similar procedures as those outlined above for the US study. In all three jurisdictions, the respondents were asked to provide their perspectives on their respective organic seed regulations and, in the case of Mexico, also on the organic seed regulations in the countries to which they export organic product. The purpose was to reveal and compare the unfolding processes and interests that are shaping the emergent regulatory outcomes in each case throughout the study period. Relevant (grey) literature, expert reports and policy documents were reviewed for all three jurisdictions. Participant observation was carried out, in varying roles as researcher and stakeholder, at key organic seed meetings held in the US, the EU and Mexico throughout the study period.

1.5.2 Determining how currently available broccoli cultivars perform in organic production systems compared to conventional growing conditions with respect to horticultural and phytochemical traits

To answer RQ2, 23 broccoli cultivars including open pollinated (OP) cultivars, inbred lines, and F_1 hybrids were included in the field trials. These cultivars were selected to encompass the varietal diversity used by organic and conventional growers in the targeted trial regions as well as to represent diverse genotypes and phenotypes that differed in their year of commercial introduction and the commercial seed company of origin. The cultivars were grown in paired organic and conventional fields at two US locations (Maine and Oregon) in fall and spring of the 2006-07 and 2007-08 growing seasons. Field quality traits were evaluated including head shape, head surface, head colour, bead size, bead uniformity, plant height and an overall plot quality rating based on overall appearance, head quality and uniformity of the entire plot. After harvest, five broccoli heads were evaluated for head weight and head diameter. Hollow stem and days to maturity were also evaluated. The genotype by environment by management system trial analysis included a total of 16 trials.

In order to answer RQ3, the broccoli heads derived from the field trials described for RQ2 were analysed for phytochemical compound concentrations. As plots approached maturity, five broccoli head tissue samples were harvested fresh from each subplot at each trial location and were composited into a single sample per replication. Each sample was analyzed for the glucosinolates (glucoraphanin, glucobrassicin, neoglucobrassicin), tocopherols (δ-, γ-, α- tocopherol), and carotenoids (lutein, zeaxanthin, β-carotene) by high-performance liquid chromatography (HPLC). For the genotype by environment by management system analysis, data analysis included analysis of the partitioning of variance, trait means, genotypic correlations, ratio of correlated response to direct response, stability analysis, GGE biplots and phenotypic correlations. For the phytochemical trait analysis, phytochemicals were analyzed per cultivar and per genotypic group.

1.6 Outline of the thesis

The empirical core of the thesis is presented as four articles that report and analyse the findings of the studies outlined above. Figure 1.3 visualises the organisation of the thesis.

The thesis is structured as follows:

Chapter 1 introduces this thesis. It provides the context and justification for the research, background information on the importance, tensions and challenges of evolving an appropriate seed regulatory framework, and the implications for seed development and seed breeding in the organic sector. The problem addressed, research objectives, hypotheses and main research questions are stated. The research design and research methodology are presented for each part of the research.

Chapter 2 reviews and analyses the evolution of organic seed regulation in the US, as a model case of how challenges in a new regulatory area are being addressed. The study draws on formal interviews of key stakeholders, participant observation, and documents generated in the six-year period between mid-2007 and 2013. Analysis of the evolving interpretation of organic

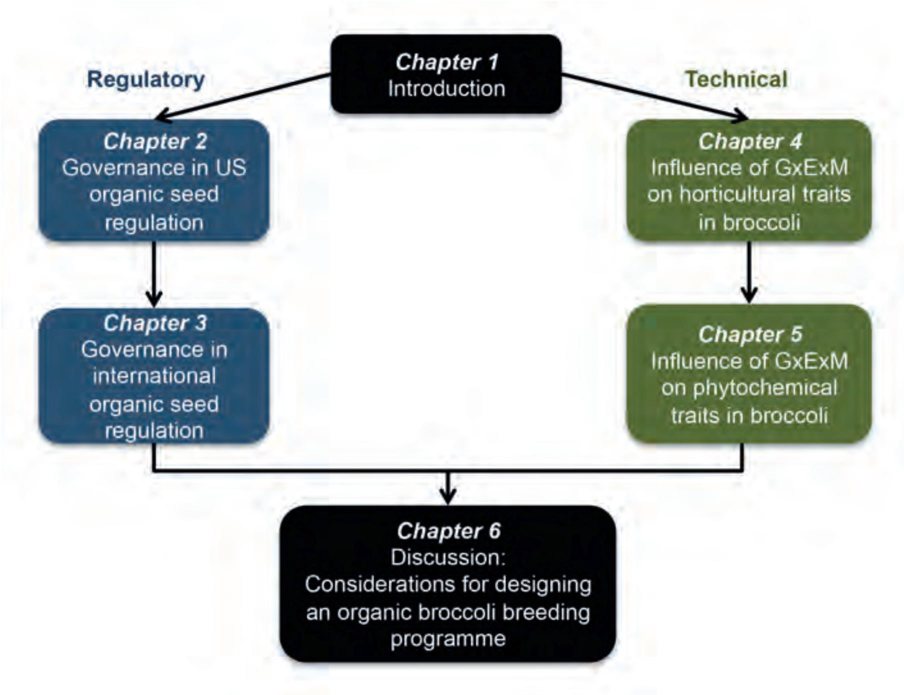

Figure 1.3 Schematic overview of the research design

seed regulation indicates that stakeholders in the seed sector have diverse interests; how they manifest their interests or direct their influence are shown to affect the evolution of the sector. New organizations, procedural arrangements and activities have emerged to support regulatory development, with both positive and negative results. Major findings are that the official guidance on the interpretation of the regulation has not been sufficiently decisive to prevent the spread of divergent interpretation and practices and that, as a consequence, the needs of a rapidly growing economic sector are not being met. The chapter concludes with lessons for key areas of regulatory interpretation and practice; and possible ways to make the governance of organic seed more effective are identified.

Chapter 3 analyses the evolution of organic seed regulation in the US, the EU and Mexico as model cases of how regulatory challenges in international organic agricultural policy-making are being addressed, based on a study conducted between mid-2007 and 2013. It reveals how growth of the organic sector is hindered by regulatory imbalances and trade incompatibilities among these three countries, arising from divergent stakeholder interests along the organic seed value chain, and the varying capacity for self-organising governance of the seed sector in relation to each state's regulatory role. Progress toward regulatory harmonisation in the organic seed sector among the three cases is compared. The chapter concludes with an assessment of the regulatory processes described and concludes with a synthesis of what the regions may learn from each other in the key areas of regulatory policy and practice.

Chapter 4 analyses whether the commercial broccoli cultivars available at the inception of the study adequately met the needs of organic management systems. This was studied by comparing horticultural trait performance of a set of 23 broccoli cultivars under two management systems (organic and conventional) in two regions of the US (Maine and Oregon), including Spring and Fall trials. On the basis of the genotype by environment by management system (GxExM) interaction analysis on the performance of the broccoli horticulture traits (eleven evaluated), recommendations for the best selection environments are made.

Chapter 5 presents the results of analysis of phytochemical content of the broccoli cultivars grown in the organic and conventional field trials described in Chapter 4, to determine the genotype by environment by management system (GxExM) interaction effect on their content. The phytochemicals quantified included: glucosinolates (glucoraphanin, glucobrassicin, neoglucobrassin), tocopherols (δ-, γ-, α-tocopherol) and carotenoids (lutein, zeaxanthin, β-carotene). On the basis of the results, recommendations for selection environments are made. Results of the comparative performance of cultivars from different genotypic classes (open pollinated vs. F_1 hybrids, old versus new and commercial seed sources, difference commercial seed sources) also are presented. In addition, genetic correlation between horticulture and phytochemical traits and the potential trade-offs between traits and the implications for breeding are discussed.

Chapter 6 assesses the main findings of Chapters 1-5 in the light of the objectives, hypotheses and research questions of this study. Through the combined analyses of the organic seed regulatory studies and the field trials that determined the horticultural and phytochemical trait performance of broccoli cultivars grown under organic and conventional management systems, we synthesise and discuss our results in terms of the following five propositions: (1) Regulatory clarity is the foundation for organic seed sector development, (2) Organic management systems influence horticultural and phytochemical trait performance, (3) A crop ideotype can serve as a communication tool to arrive at an appropriate variety assortment, (4) Genetic variation is a requirement to develop optimized cultivars, and (5) Multiple seed system models contribute to organic sector growth.

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Chapter 2

The Development and Implementation of Organic Seed Regulation in the United States

The Development and Implementation of Organic Seed Regulation in the United States

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Abstract

This article reviews and analyses the evolution of organic seed regulation in the US, as a model case of how challenges in a new regulatory area are being addressed. The study draws on formal interviews of key stakeholders, participant observation, and documents generated in a six-year period between 2007 and 2013. The article addresses three main issues: (1) how proposals for the wording and implementation of the regulation constrain seed choices and give rise to unintended consequences, (2) how emergent organizations and procedures have responded to the tension between sustaining seed differentiation to match the characteristics of local markets, organic production and agro-ecologies, and the narrowing of varietal choice in catalogued seed so as to expand commercial organic seed markets and encourage organic seed breeding, (3) why consensus on the content of formal seed policy has failed to develop despite a high level of stake holder engagement. The study revealed that the official guidance on the interpretation of the regulation has not been sufficiently decisive to prevent divergent interpretation and practices, and therefore the needs of a rapidly growing economic sector are not being met. The article concludes by drawing lessons for key areas of regulatory interpretation and practice, and by identifying possible ways to make organic seed governance more effective.

Keywords
Organic seed regulation, organic agriculture, regulatory processes, stakeholder interests, United States (US)

2.1 Introduction

The increasingly global scale of agricultural trade poses special challenges to new entrants into the commercial seed sector, with the 10 largest seed suppliers controlling 65.4% of the global market (Howard, 2009). As a result, breeders are focusing efforts on fewer crops and varieties. Organic producers' seed needs are particularly poorly served by commercial breeders and seed markets (Lammerts van Bueren et al., 2002). Climate change and other threats to natural resources are bringing additional challenges to seed systems around the world. Agricultural policy makers and related stakeholders are seeking to create regulatory frameworks for seed which promote trade competitiveness and sustain or increase yield while increasing the options for agro-biodiversity and resilience in agricultural systems. The evolution of organic seed regulation in the United States (US), the world's largest organic market, may be taken as an example of such efforts and is analysed here as a model case of how stakeholders define and protect their interests in the interpretation and implementation of regulatory requirements.

In 2011, US organic sales reached $32 billion, growing at 8% over 2010 (OTA, 2012), while US organic production acreage reached 2 million hectares by the same year (Willer and Kilcher, 2012). Although the organic seed sector underlying this market growth is increasing, organic growers continue to largely depend on conventionally produced seed (Dillon and Hubbard, 2011). In 2002, the United States Department of Agriculture (USDA) developed a domestic organic regulatory standard - the National Organic Program (NOP) to govern the US organic sector. The regulation includes a clause governing organic seed usage in certified organic farming systems (Section 205.204(a)) which prescribes the use of organic seed in an organic production system whenever such seed is commercially available (USDA AMS, 2002). According to the standards of the International Federation for Organic Agriculture Movements (IFOAM), 'certified organic seed' is defined as seed from varieties that may be derived from conventional breeding programs (excluding genetic engineering) which are produced under organic farming conditions for one growing season for annual crop species, and two growing seasons for perennial and biannual crop species (IFOAM, 2012). This article traces how stakeholders in the US have responded to efforts to govern the organic seed sector. Official governmental guidelines as to how the regulatory clause should be interpreted and translated into practice have not been formally published. The steps for compliance have evolved in practice but harmonisation and transition toward 100% compliance has been hindered by divergent interpretations and interests. Although the results of the study reported here indicate that stakeholders agree that organic seed usage is necessary, the question remains as to how to achieve this goal without forsaking the integrity of the organic production system by use of organically produced seed, profitability, maintaining biodiversity in production systems, and access to an appropriate and sufficient diversity of seed varieties. At stake is the assurance of an appropriate assortment of organic varieties in sufficient volume and suited to various organic farming conditions, without use of chemical herbicides, pesticides and fertilisers. In this perspective, the development of the organic seed regulation can be considered a stepping stone towards a seed industry that breeds well-adapted varieties which support optimized organic production systems.

The central aim of this chapter is to analyse the development of organic seed regulation in the US over six years from 2007 through 2013 through the lens of historical institutionalism (Steimo, 2008; Hall and Taylor, 1996). This lens enables identification of patterns in social, political and economic behaviour over time. The study traces how the evolution of organic seed regulation in the US has been guided by both formal policy development and by the informal interpretations, behaviours, actions and choices of the various stakeholders. Specifically, three main issues are addressed: (1) how proposals for the wording and implementation of the regulation constrain seed choices and give rise to unintended consequences, (2) how emergent organizations and procedures have responded to the tension between sustaining seed differentiation to match the characteristics of local markets, organic production and agro-ecologies, and the narrowing of varietal choice in catalogued seed so as to expand commercial organic seed markets and encourage organic seed breeding, (3) why consensus on the content of formal seed policy has failed to develop despite a high level of stake holder engagement. The study also explores how the varying capacities of an increasing number of private and public stakeholders in the organic seed sector each with specialized tasks and competencies has led to fragmentation rather than convergence of effort. The dynamic relationships which have evolved between varying coalitions of interest and in the various networks that have emerged have both shaped regulatory governance as well as challenged the expectation that the seed sector would self-organize under regulatory pressure.

2.2 Materials and methods

The case study of organic seed regulation in the US is based on interviews with individuals and organizations defined as 'stakeholders,' the review of policy documentation, and on participant observation at key policy meetings related to the organic seed regulation over the study period.

2.2.1 Stakeholder identification

The case material was initiated by a typological analysis of stakeholders and categorisation by the principal researcher, following analytical procedures described in Reed et al. (2009) for the main public and private actors in the sector in 2007, in terms of their stakes, and their interests affected directly and indirectly by the evolving organic seed regulation. This procedure was informed by the principal researcher's long experience of working in the US organic seed sector and knowledge of the stakeholders. The stakeholder identification process used in our research yielded seven stakeholder categories: organic certifiers, small-scale organic growers, large-scale organic growers, organic food buyers, formal sector seed companies, non-profit organisations, and policy and legislative bodies. The preliminary analysis was further refined by sorting each stakeholder category by their influence on the organic seed sector (following Jiggins and Collins, 2003): (1) Primary: those who are directly affected, either positively or negatively, by organic seed regulations (2) Intermediate: the intermediaries in the delivery or execution of research, resource flows and activities, (3) Key: those with the power to influence or 'kill' activity, and their level of influence (low, intermediate, high) on the development of the US organic seed regulation.

2.2.2 Stakeholder analysis

Subsequently, semi-structured and structured interviews were conducted to explore stakeholders' perceptions of organic seed regulation in light of their respective roles in the process and of the opportunities or barriers to regulatory development, as well as to identify the actions they were taking to guide the course of regulatory development and enforcement. Twenty preliminary semi-structured interviews were held with individuals from each stakeholder category, using a checklist developed to ensure consistent coverage of the main themes discussed. The preliminary interviews were followed by 74 one-hour in-depth interviews (Kvale, 1996) with individuals or representatives of organizations, who were identified by the principal researcher and the respondents in the first round of interviews for their high level of influence within each stakeholder category. All stakeholders identified for interviews agreed to participate in the study. They included organic certifiers (n=8), small-scale organic growers (n=26), large scale growers (n=14), organic food buyers (n=5), representatives of formal seed companies who are involved in organic and/or conventional seed production (n=10), non-profit organization representatives (n=6), and policy and legislative body personnel (n=5) with regulatory influence. Each interview began by presenting to the respondent a written statement of the organic seed regulation, followed by exploration of a set of questions common to all respondents. These were complemented by questions appropriate to each stakeholder category's specific interests. Information from the preliminary and in-depth interviews was recorded as written notes taken during or immediately after each interview. Qualitative analysis (Denzin and Lincoln 1994) of the notes was carried out manually, using (1) the tools of content analysis to identify, group and analyse the key concerns expressed by the respondents (Krippendorff, 2004), and (2) the tools of discourse analysis (Patton, 1980), to identify key concepts and the interconnections between them, and the interconnections between the changing regulatory context and the discourse.

Tracking and analysis of organizational developments

Monitoring of the organic seed regulatory process continued through to 2013 and included the collection and analysis of grey literature such as successive policy documents that were created and circulated by the stakeholders, and participant observation by the principal researcher who attended key meetings throughout the study period. Narrative analysis of the history of organizational developments was carried out by (1) mapping participants' changing concerns, concepts and contexts, (2) identifying key decision points in rule-setting and implementation processes from the stakeholders' perspectives, (3) mapping emergent networks and coalitions of interest, and (4) by documenting how resources of various kinds were mobilized by the stakeholders in response to the changing understanding of the regulatory requirements.

2.3 Findings

The findings are presented as historical narratives related to the following main themes: (1) the organic regulatory process in the US (Table 2.1), (2) stakeholder interests and stakes 2007-2013 (outlined in Table 1.2ab), and (3) the associated organizations and related contextual developments (outlined in Table 1.3). They are organised under sub-headings derived from the concerns introduced in the introduction and in the design of the study: (1) Rule-setting and implementation processes, (2) Contexts, concerns and concepts, (3) Emergent organisations and networks, and (4) Resource mobilisation.

2.3.1 Rule-setting and implementation processes

As early as the Organic Foods Production Act of 1990 (OFPA, 1990); clause 7 U.S.C. 6508 (a) of the OFPA recommended that US organic growers make responsible seed choices that complied to organic principles:

“*Seeds, Seedlings and Planting Practices* - For a farm to be certified under this chapter, producers on such farm shall not apply materials to, or engage in practices on, seeds or seedlings that are contrary to, or inconsistent with, the applicable organic certification program.”

In 2000, the first USDA National Organic Program (NOP) was published attempting to regulate the entire organic sector. It included a descriptive clause governing organic seed usage in a certified organic farming system, which subsequently was incorporated into the USDA NOP standard passed in 2002 (Code of Federal regulations (CFR) Section 205.204(a)). The Organic Seed Regulation reads as follows:

“205.204 Seeds and planting stock practice standard.
(a) The producer must use organically grown seeds, annual seedlings, and planting stock: Except, that, (1) Non-organically produced, untreated seeds and planting stock may be used to produce an organic crop when an equivalent organically produced variety is not commercially available: (2) Non-organically produced seeds and planting stock that have been treated with a substance included on the National List of synthetic substances allowed for use in organic crop production may be used to produce an organic crop when

an equivalent organically produced or untreated variety is not commercially available."

205.2 *Commercially available* – the ability to obtain a production input in an appropriate form, quality, or quantity to fulfil an essential function in a system of organic production or handling, as determined by the certifying agent in the course of reviewing the organic plan."

The regulation did not provide protocols or allocation of roles or responsibilities for the interpretation of *equivalent* and *commercially available* seed. The subsequent steps taken in the official process are inventoried in Table 2.1.

Table 2.1 Summary timeline of key events and decision points in the interpretation of the USDA NOP Organic Seed Regulation 1990-present

Timeline	Position Change	Intended Impact/Function
November 28, 1990	OFPA signed into law as Title 21 of the 1990 Farm Bill	US Organic Agriculture Law
December 22, 2000	USDA NOP published in the Federal Register	Proposed US Organic Agriculture Rule
March 7, 2001	Commercial Availability: Docket Number TMD-00-02-FR	Definition of Commercial Availability
October 22, 2002	USDA NOP Final Rule implemented	Approved US Organic Agriculture Standard
August 17, 2005	NOSB to NOP Recommendation: Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 1
November 30, 2007	NOSB to NOP Recommendation: Further Guidance on the Establishment of Commercial Availability Criteria	Organic Seed Guidance Document Version 2
April 3, 2008	NOSB JC & CAC Recommendation: Further Guidance on Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 3
September 22, 2008	NOSB JC & CAC Recommendation: Further Guidance on Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 4
November 19, 2008	Formal Recommendation by the NOSB to the NOP: Commercial Availability of Organic Seeds	Submitted Organic Seed Guidance Document to NOP
June 6, 2011	NOP Guidelines Released for Public Comment	NOP Organic Seed Guidance Released for Public Comment
March 4, 2013	NOP Guidance: Seeds, Annual Seedlings, and Planting Stock in Organic Crop Production	NOP Final Organic Seed Guidance

Sources: USDA AMS, 2002; USDA NOSB 2001, 2005, 2007, 2008a; b; c; USDA NOP 2011, 2013

The National Organic Standards Board (NOSB), a stakeholder board comprised of organic farmers, organic processors, environmentalists, consumers, an organic retailer, an organic certification agent, and a scientist with recognized expertise in organic agriculture, has statutory powers which provide formal procedures for public notice and comment. It was set up to offer recommendations to the NOP to consider regarding interpretation and implementation of the national standard, yet their recommendations are not binding. In 2001, the NOSB submitted recommendations (NOSB, 2001) for the criteria and procedures that might be used for assessing organic seeds and planting stock. It assigned responsibility for documentation of commercial availability to certifiers (recorded through organic farm plans, as set out in CFR Section 205.201(a)(2) and verified by routine inspection processes). The determination of commercial availability of organic seed was based on the appropriate form, quality, and quantity criteria. The NOSB requested that the Accredited Certifiers Association (ACA), the organization representing organic certifiers in the US, develop procedures and capacity for their inspection processes to verify the availability of organic seeds and planting stock. The recommendations further laid out guidelines for interpretation of the organic seed rule, of which the clear definition of equivalency and type was identified as important for interpretation of the organic seed regulation:

- *Equivalency* is defined as a variety exhibiting the same 'type' (such as the butterhead lettuce type) and similar agronomic characteristics such as insect and disease resistance when compared to the original varietal choice.

- *Type* is defined by the Federal Seed Act of 1939 (7 U.S.C. 1551.) as either (A) a group of varieties so nearly similar that the individual varieties cannot be clearly differentiated except under special conditions, or (B) when used with a variety name.

Subsequently, a subcommittee of the NOSB, the Joint Crops and Compliance, Accreditation, and Certification Committee (JC & CAC), was formed to further develop the recommendations. A revised version inclusive of public comment was submitted to the NOSB in 2005. The reissued recommendations stressed the need to ensure the consistent application of organic seed requirements (NOSB, 2005). A number of new requirements shifted more responsibility for compliance to growers by stating that growers should justify to certifiers their need to use non-organic seed through a description of their site-specific agronomic conditions and/or marketing considerations. Furthermore, growers were required to provide written evidence to certifiers that they had contacted at least three organic seed suppliers before requesting non-organic seed, and to provide written description to certifiers of variety trials that had compared organic with non-organic seed of the requested variety. For their part, certifiers were required to annually evaluate the documentation from growers, enforce the organic seed requirement on growers and on commercial operations that purchased organic produce from growers, and file a report listing the seed varieties for which they had granted exceptions.

In 2007 and 2008, the NOSB released additional draft revisions of the guidance document successively broadened the allocation of responsibilities among the NOP, growers and the certifiers (ACAs) for enforcing compliance (NOSB, 2007; 2008ab). The drafts proposed that the relevant information could be more effectively managed if certifiers were provided with a list of the non-organic seed the growers used, with details of any issues relating to the equivalency of organically grown and conventionally grown seed varieties, and information concerning the growers' need for specific agronomic or market traits. The NOSB proposed that the information be passed to an independent third party for publication in a national database, and that certifiers maintain and submit upon request to the NOP copies of growers' lists of seed varieties for the crop varieties permitted by each agency (NOSB, 2008ab). Failure to comply would place the certifiers in violation of their responsibility, rendering them liable to loss of their status as certifiers. In 2008, the NOSB approved the draft recommendations but requested that the committee further 'redistribute the burden' of data collection and reporting to a broader stakeholder group.

The final NOSB recommendations submitted to the NOP in 2008 included new language on the monitoring of an individual growers' percentage use of organic seed as a tool for assessing 'good faith effort'. Documentation of the levels of organic seed usage and evidence of improvement in the percentage versus total seed usage by the ACA's clientele should be audited as part of the NOP accreditation review (NOSB, 2008c). The recommendations strengthened NOP's role in training certifiers on the seed rule and on the recommendations.

However, in doing so, the recommendations indicated that certifiers might fail audits by not following the guidance or by not warning growers that two years' of non-compliance in using available organic seed could result in the revocation of organic certification. In addition, the concept of a 'two-way national database' maintained by an independent party was included, implying the need to establish a national database populated with organic seed availability, as well as organic growers' varietal needs and quantities.

In 2011, the NOP released its response to the 2008 NOSB final recommendations (NOP, 2011) supporting: (1) the role of certifiers in assessing the annual progress of growers in sourcing organic seed and in ensuring progress by comparing current source information to previous years, (2) the recommendation that certified operations must establish a documented procedure for sourcing organic seed which includes the identity of the seeds sought, the search methods used to source organic varieties, and that demonstrates the use of organic seed or the commercial unavailability of organic seeds, and (3) the recommendation that growers must demonstrate verification of sourcing seed from a minimum of three sources confirming that organic seed cannot be avoided because of the price of the seed.

The NOP's response added a section about the criteria and procedures for securing an exception to organic seed usage. The NOP's response omitted: (1) the recommendation that certifiers be required to quantify the percentage increase in organic seed usage per year and to record varieties for which exceptions were permitted, (2) the recommendation that commercial purchasers of organic food crops require that suppliers who were contractually required to grow selected varieties use organically produced seed to grow those varieties, (3) the recommendation that growers perform on-farm trials to support exemption requests, and (4) the requirement for a 'two-way' organic seed sourcing database. A two month public comment period generated requests from several stakeholders reiterating reincorporation of the omitted content outlined above (OTA, 2011). On March 4, 2013 the NOP presented its final guidance on 'Seeds Annual Seedlings, and Planting Stock in Organic Crop Production' (NOP 5029), and none of the originally omitted sections of the guidance were reinstated (NOP, 2013).

2.3.2 Contexts, concerns, and concepts

This section outlines the range of stakeholders' concerns during the evolving US organic seed regulatory process, and their associated actions. Table 2.2a summarizes the various stakeholder categories, their level of influence and key concerns at the start of the official processes outlined above, while Table 2.2b indicates the subsequent shifts in stakeholders' concerns which had taken place by the end of the study in 2013.

What is at stake for organic certifiers?

The initial stakeholder analysis identified certifiers as the most influential in the interpretation of organic seed regulation because they were assigned the greatest responsibility for enforcement of the evolving regulatory process - a process that the NOSB emphasised should be uniformly rigorous and transparent. Their responsibilities included: compelling growers to use organic seed, verifying grower diligence in organic seed sourcing and on-farm trial verification and sanctioning growers who fail to comply. With 49 USDA certified organic certification agencies based in the US, and with each certifier allowed to define its own procedure for granting exceptions, inevitably there was from the start considerable variance in certifier practices, especially in regard to documentation of exceptions, for which there is inconsistency among certifiers' standards (Certifier interviews, 2007-2013).

The NOSB recommended that during the inspection process, certifiers request a list of non-available organic seed varieties from growers. The ACAs' publicly responded that certifiers do not have the capacity to document the varietal needs of growers or to record the gaps in organic seed supply (ACA, 2008). Interviews with certifiers further revealed that they do not necessarily trust their own ability to make exceptions because they do not have sufficient knowledge about organic seed availability and varietal performance (e.g. California Certified Organic Farmers (CCOF) interview, 2009). Other certification agencies, such as the Monterey County Certified Organics (MCCO), revealed that they certify organic seed companies and stay informed of their clients' commercial certified organic varietal assortment (2013). The ACAs' written response to the NOSB's recommendations indicated that certifiers in fact did not want to be responsible for developing a compliance infrastructure for the organic seed industry through their work, nor did they support a measured percentage

Table 2.2a Summary of organic seed system stakeholders' concerns, by category, based on a stakeholder typology, 2007-2009 (n=74)

Stakeholder Category	Stakeholder Type[1]	Level of Influence[1]	Key Concerns (2007-2009) (Citation rate: number of respondents)
Organic Certifiers (n=8)	Key	High	Lack of appropriate tools to regulate (n=8) Lack of knowledge on specific varieties (n=7) Reluctance to police the industry (n=5) Costly addition to certification process (n=4)
Small-Scale Organic Growers (n=26)	Primary	Low to High	Fear of loss of genetic diversity (n=25) Seed availability (n=21) Seed quality (n=13) Homogenization of the organic seed industry (n=11) GMO Contamination (n=7)
Large-Scale Organic Growers (n=14)	Primary	Low to High	Seed price (n=14) Seed availability (n=13) Seed quality (n=11) Seed product form availability (various organic seed treatments) (n=10)
Organic Food Buyers (n=5)	Intermediate	Low	Lack of knowledge on specific varieties (n=5) Reluctance to limit supply with narrowing varietal choices (n=4) More concerned with other farm inputs (fertilizers) and grower compliance (n=4)
Formal Seed Companies (n=10)	Primary	Low to High	Varietal assortment (n=10) Profitability (n=8) Loss of conventional seed sales (n=6) Organic seed production capacity (n=5) Organic seed quality (seed borne diseases) (n=5)
Non-Profit Organizations (n=6)	Intermediate	Low to High	Lack of organic seed sourcing tools (n=4) Diversity (n=4) Lack of organic breeding programs (n=4) Reluctance to corporate control of process (n=3) GMO contamination (n=2) Growers not included in process (n=2)
Policy & Legislative Bodies (n=5)	Key	High	Seed availability and quality (n=5) Appropriate allocation of roles and responsibilities for enforcement (n=4) Interpretive guidelines for enforcement (n=4) Grower alienation (n=3) Global organic seed and agriculture regulation (n=2)

Sources: Stakeholder Analysis (columns 1-3, 2007); content analysis of stakeholder interviews (column 4, 2007-2009).

[1]*Notes to Table 2.2a b:* Stakeholder categorization (Jiggins and Collins, 2003)

Stakeholder Type	Definition	Levels of Influence
Primary	Those who are directly affected, either positively or negatively	Low to High
Intermediate	The intermediaries in the delivery or execution of research, resource flows, and activities	Low to Intermediate
Key	Those with the power to influence or 'kill' activity	High

Table 2.2b Summary of organic seed system stakeholders' shift in concerns, by category, based on a stakeholder typology, 2013

Stakeholder Category	Shifts in Stakeholder Concerns by 2013
Organic Certifiers (n=8)	Lack of a timely evaluation and quantification process for organic seed usage Improvement in appropriate tools to interpret organic seed usage had been achieved Lack of varietal knowledge persisted Do not want to limit the variety assortment available to growers Costs have been incurred for the development of tools to determine an organic growers attempts at sourcing organic seed
Small-Scale Organic Growers (n=26)	Concern that enforced regulation will narrow genetic diversity persists Recognize that organic seed availability is increasing year over year Quality of organic seed available in the market has improved Do not want big companies to control the organic seed market Fear of GMO contamination persists
Large-Scale Organic Growers (n=14)	Concern about seed price persists Recognize that they must use some organic seed to reach minimum certification requirements Continued lack of interpretative regulatory guidelines perpetuates non-organic seed use Acknowledge that there is an increase in organic seed availability Acknowledge that the quality of organic seed has improved Acknowledge that there are now several organic seed treatment options on the market
Organic Food Buyers (n=5)	Desire to know more about organic seed varieties available Continued lack of knowledge concerning specific varieties Enforcing grower compliance with use of permitted non-seed farm inputs
Formal Seed Companies (n=10)	Interpretive organic seed regulatory guidelines for enforcement are required for investment Difficult to determine which varieties to produce organically Profitability Loss of conventional seed sales when varieties are produced organically as well Need for increased acres in organic seed production and develop capacity to be successful Organic seed quality (seed borne diseases) has improved, but still a risk
Non-Profit Organizations (n=6)	Lack of breeding programs for better adapted varieties Limits to on-farm genetic diversity if growers are required to use organic seed only Optimization of tools to identify organic seed availability such as the AOSCA database Reluctance to the corporate seed industry controlling organic seed sector development GMO contamination Desire to have growers involved in the seed production, varietal trialling and breeding processes, not just the seed industry controlling the development of the organic seed sector
Policy & Legislative Bodies (n=5)	Finalization of NOP interpretive guidelines for enforcement imminent and will guide process Seed availability and quality has improved Appropriate allocation of roles and responsibilities within the chain have evolved over time Grower alienation due to seed availability, price and limits to diversity persist Harmonization of organic standards with major trading partners is being achieved

*Sources***:** Stakeholder category (column 1, 2007); content analysis of documents reviewed and participant observation in key meetings informed the data in column 2, 2007-2013.

increase in organic seed usage per year as a method to drive organic seed usage. However, some certifiers, such as Maine Organic Farming and Gardening Association (MOFGA), acknowledged that in practice a measured increase in seed usage per year was a commonly used technique to monitor organic seed usage improvements, and to ensure that 'organic seed usage would come to fruition' (MOFGA interview, 2007).

The first formal quantification in US of organic seed usage by organic growers, reported in the State of Organic Seed (SOS) report published by the Organic Seed Alliance (Dillon and Hubbard, 2011) recorded that 60% of the growers surveyed had indicated that their organic certifier had requested that the grower make greater efforts to source organic seed. It further reported that certifiers were enforcing the use of the organic seed rule with increasing stringency and that sanctions had increased in the three years prior to the report's publication. Examples of this enforcement were noted in 2010 when the first certification suspensions were enforced on two growers for use of chemically treated seed and lack of demonstrated attempt to source organic seed (USDA NOP Adverse Action List, January 2011).

What is at stake for organic growers?

The interviews with organic growers (n=40) revealed that their main concern in relation to the organic seed rule was their perception that there was a limited quantity and diversity of quality organic seed varieties available in the marketplace. Production in the organic sector is spread across diverse agro-ecosystems, serving a diversity of markets and evolving enterprises. The range stretches from small-scale diversified growers who, according to the interview respondents, require a wide varietal assortment to satisfy customers in local and niche markets, to large scale commercial growers who require large quantities of a more narrow but modern seed assortment to meet the needs of highly competitive commercial retailers serving markets spread across a large geographic area. Growers at both ends of the spectrum expressed a concern that the enforcement of the organic seed regulation could limit their choice of varieties, thereby forcing them to use varieties not appropriate for their farming system or markets, or to use seed of potentially lower quality, at a higher price. The ACA (and individual certifiers) have reported that their clients (i.e. growers) have had poor experiences with organic seed due to seed quality issues of low or poor germination or low yield (ACA, 2008).

The SOS report (Dillon and Hubbard, 2011), which is based on responses from 1,047 certified organic growers representing approximately 10% of US certified organic growers, found that on average, 52% of vegetable growers (survey question 5) and 72% of field crop growers (survey question 9) were using organic seed. The largest potential users of organic seed by volume were found to be the large scale baby lettuce and spinach leaf growers. However, respondents to our interviews in this group indicated that they were reluctant to move toward compliance with the organic seed rule because their seed costs comprise a relatively high percentage of their total expenses, related to high seeding rates and planting cycle frequency (Grower interviews, 2007-2011). As a result, this group of growers has been requesting and securing regular exceptions from their certifiers. Even when organic seed for their standard crop varieties is available, they have an incentive to represent to their certifiers that the seed is not available (at all, or in sufficient quantity or on time), or that they have different requirements than the traits offered by commercially available organic seed varieties (Grower interviews, 2007-2011). Exceptions are sanctioned in part because certifiers are not confident in judging commercial availability (as stated above). Also, they are not aware of the planning time required for a grower to commit to contract organic production and to secure supply of large volumes of seed in a timely manner (Grower and Seed company interviews, 2007-2013).

Paradoxically, the growers we interviewed also revealed that while some growers perceived many impediments to the implementation of the organic seed regulation, they saw several positive developments as a result of the open nature of the regulation's interpretation. Growers claimed to have become more aware of their varietal requirements and of their current and potential role in the organic seed chain. They have been actively engaged in performing on-farm trials to compare available organic varieties to their conventional untreated standards. To support growing demand, regional organic seed production cooperatives have also been established to fulfil seed requirements and provide growers with an additional income stream.

What is at stake for organic food buyers?

The NOSB recommendations emphasized the significance of the role of organic buyers, defined as buyers of raw organic food products for the fresh and processing food markets, in the enforcement of the seed regulation. They proposed that commercial buyers of organic products should also be subject to the organic seed requirement. Buyers whose organisations were certified as organic handlers, therefore, should require their suppliers of certified organic raw materials to use organic seed when commercially available. If the varieties were not available in organic form, the buyers should comply with the same documentation requirements as those required of a grower. Moreover, buyers who required their supplier to use a specific variety (proprietary or otherwise) should ensure that variety was available as 'certified organic' or assist in its production in organic form. However, in our study, the interviews with organic food crop buyers (n= 5) revealed that they were reluctant to become co-enforcers of the organic seed regulation because this role would impose an additional administrative cost (Food buyer interviews, 2009). Their greatest concern was that they could not readily access information about the range of available organic seed varieties. The SOS survey found that in 2010, 28% of grower respondents did not use organic seed because their buyers required that, for product consistency reasons, they use a variety not available in organic form (Dillon & Hubbard, 2011). In our study, it was noted during a presentation on organic seed held at a national organic conference (Ecofarm, Pacific Grove, CA, 2011), food buyers in the audience stated that they wanted to be better informed about seed issues and availability (principal author's meeting notes, 2011). In another instance recorded in our study, Organic Valley, a Midwest US-based dairy cooperative, announced that its suppliers were expected by 2015 to prove use of organic seed for all feed crops, and to supply certification that no genetically modified organisms (GMOs) had been detected (principal author's meeting notes, 2010). Organic Valley further announced it would contribute financially to the launch of an organic, conventional, non-GMO field crop seed-sourcing database in collaboration with the Association of Official Seed Certifying Agencies (AOSCA) to support their suppliers in identifying appropriate seed sources (ASTA Meeting, Huntington Beach, CA, 2011).

What is at stake for the formal seed sector?

The interviews with stakeholders in the formal seed sector (n=10) revealed that they thought the organic seed rule enforcement could pose considerable problems for the development of the organic seed sector. Their primary contention was that the market was not prepared for enforcement because there was an insufficient supply of organic seed. The NOSB recommendations noted that a major factor limiting wider use of organic seed was "an emerging organic seed industry that may, in certain cases, lack the diversity, quality, and quantity of organically grown seed to meet the needs of the organic production sector" (NOSB, 2008c). This conclusion was supported by the SOS survey which found that grower respondents ranked their reasons for not using organic seed as: (1) specific variety not available (77 %), (2) insufficient quantity of seed (50 %), (3) lack of desirable traits (46%), and (4) price (40%) (Dillon and Hubbard, 2011).

Currently, many seed companies still supply organic farmers with conventionally produced but post-harvest untreated seed. If the organic seed rule were to be consistently enforced, seed companies would need to produce their most requested varieties in organic form. Seed company respondents, however, indicated that if they were to invest in organically produced seed, it was in their interest that the rule be strictly enforced, without exceptions. Since then the on-going discussions and inconsistent enforcement of the organic seed regulation has stimulated differing responses by seed companies. Respondents working for companies that had invested in producing proprietary conventional varieties in organic form (n=3) in order to support the 'equivalent' variety requirement, reported that they were in fact losing sales to lower-priced conventional varieties because of the lack of enforcement of the organic seed rule (Seed company interviews, 2007-2013). Members of companies that had decided to stay out of the organic seed market (n= 3) indicated that the market was not large enough for them to consider and potentially conflicted with other aspects of their business (e.g. because their business was associated with genetic engineering research or they had a chemical agriculture division).

A respondent working for one seed company stated there was widespread dissatisfaction within the seed industry with the consequences of the continuing lack of formal endorsement of the recommended regulation for technical decision-making such as how to produce organic seed, how to avoid seed-borne diseases without chemical treatments, how to manage weed competition without chemical herbicides, how to avoid lower yields in seed production, and how to select varieties appropriate for organic production systems (Seed company interview, 2009). Four of the 10 companies interviewed are recognized experts in conventional seed production. These respondents noted that not all conventional seed production norms are directly transferable to organic. For instance, parent lines used to produce seed varieties may perform differently under organically managed soil conditions (e.g. with respect to flowering time), and the chemical tools used to enhance conventional seed yield and to control pests are not accepted in organic production systems (Seed company interviews, 2007-2009).

Seed companies wishing to remain or become competitive in the organic market for their part face challenges regarding varietal availability, seed quality, seed quantity, and pricing. Respondents stressed that the seed market is now locked in a situation in which unpredictable exceptions to the organic seed regulation are stalling the evolution of the commercial organic seed market, though they emphasised differing aspects of this dilemma. The American Seed Trade Association (ASTA), the industry group representing the mainstream and predominantly conventional seed sector, initially assumed that the desired market evolution could be achieved by funding an organic seed database. By 2004 ASTA was seeking to clarify the regulation, reporting that it had formally requested the NOP to endorse 100% closure to conventional seed exceptions in order for a viable market driven organic seed sector to develop (ASTA interview, 2008). Individual seed company respondents had mixed views on the necessity of the database. One indicated satisfaction with the sales volume the company had achieved despite the lack of a database (Seed company interview, 2008). Another indicated that by supporting the database the company would, by default, become responsible for enforcement of the organic seed rule (Seed company interview, 2009).

2.3.3 Emergent organisations and networks

As organic seed sector stakeholders struggle to reach agreement on the interpretation and enforcement of an organic seed regulation, new organisations and networks have emerged to promote their interests and drive the process. Certifiers, growers, food buyers and seed companies have been drawn into organic seed rule enforcement processes, and into networks of interest around issues of seed availability, quality, quantity, and pricing. Table 1.3 lists the chronology and main functions of various organizations that have emerged in the changing context. Based on our interviews and participant observations the groups have been clustered in terms of those who: (1) track the issues that evolve with the changing regulatory landscape, (2) access information on organic seed availability, (3) ensure that organic values shape the emergent policy and practice, (4) develop the market sector, (5) support the development of a diverse organic varietal assortment to meet organic grower needs, and (6) ensure the issue of organic seed remains at the forefront of policy and research discussions. All of these issues were considered by the respondents as integral to organic seed sector development, findings with respect to three of these clusters, (based on the high importance assigned to these by the respondents), are described below.

Table 2.3 Summary of organizational developments in response to the organic seed regulation referenced in chapter

Project	Organization	Year Formed	Function
Public Seed Initiative	Cornell University	2001	Participatory Plant Breeding and Variety Trialing in the US
Organic Committee Formed	American Seed Trade Association	2003	Organic Seed Committee Formed
Restore Our Seed	Heritage Wheat Conservancy	2003	Participatory Plant Breeding and Selection – North East
Multiple	Organic Seed Alliance	2004	Organic Seed Education and Advocacy
Organic Seed Partnership	Cornell University	2004	Participatory Plant Breeding, Selection and On-Farm Trialing – National
Organic Seed Database	Organic Materials Review Institute	2005	Organic Seed Database
Save Our Seed	Carolina Family Farm Stewardship	2005	Organic Seed Database, Seed Production Training
Family Farmer Seed Cooperative	Organic Seed Alliance	2008	Organic Seed Production Farmer Enterprise Development
Northern Organic Vegetable Improvement Collaborative	Oregon State University	2009	Participatory Plant Breeding and Variety Trialing in Northern US States
Seed Matters	Clif Bar Family Foundation, Organic Seed Alliance, Center for Food Safety, Organic Farming Research Foundation	2010	Funding organic seed breeding and communication initiatives
State of Organic Seed Report	Organic Seed Alliance	2011	Report on State of Organic Seed in the US
Information Working Group	Organic Seed Alliance	2011	Developing national organic seed database through multi-stakeholder input process
Organic Seed Finder	Association of Official Seed Certifying Agencies	2012	Re-launch organic seed database

Sources: Stakeholder Interviews (2007-2011); Podoll (2009); Dillon & Hubbard (2011), Hubbard (2012)

Seed choices, organisational developments and unintended consequences

The respondents identified transparency in the registration of organic seed availability as a key concern because it impacts enforcement, on-farm genetic diversity and overall market development strategies. The lack of effective information tools to source organic seed was identified as a major impediment to achieving the desired transparency. In 2003, as the economic potential of the organic market became more apparent, the ASTA formed a committee to respond to the draft seed regulation (ASTA interview, 2008). A year later, the ASTA approached the Organic Material Review Institute (OMRI) with start-up funding to establish a national database of all available certified organic seed varieties (ASTA meeting minutes, 2004). The goal of the OMRI database was to provide a single commercial listing of suppliers and a comprehensive register of the availability of organic seeds and planting stock. It was proposed that organic seed companies wishing to be listed on the database pay a small, one-time fee to OMRI but that the database would be free to the public. It would be designed to be searchable by crop, variety or company. The lack of formal organic seed regulatory guidelines by the NOP, however, prevented the database from securing sufficient interest (OMRI interview, 2008 and 2011) and, as the ASTA funding ran out, this initiative ended as a limited-use list of 15 well-known organic seed sources and eventually closed in 2011. In 2005, the Carolina Farm Land Stewardship, an organic certification and education organization, funded the Save Our Seed project to create another database. The goal in this case was a free, publicly accessible list of available varieties that were certified organic, with supporting educational material for organic seed production. This initiative ceased toward the end of 2008 (Save Our Seed interview, 2008). In 2007, the Appropriate Technology Transfer for Rural Areas (ATTRA) service launched another database. It included 125 less commonly known sources of untreated, non-GMO and open-pollinated seed. In 2008, the OSA, too, launched a database listing 23 suppliers of organic seed (Colley and Baker, 2010). Still more databases were developed by certifiers, including California Certified Organic Farmers (CCOF) that prepared a database of 29 organic seed suppliers to support their own grower clients.

None of the databases were completely comprehensive nor were officially sanctioned by the NOP, and none fulfilled the NOSB recommendation for a 'two-way database', although they did represent sincere stakeholder efforts to promote transparency in organic seed supply. The most recent effort has been facilitated by OSA's Information Working Group which focuses on organic seed availability, production and information sharing (Dillon and Hubbard, 2011). The working group invited broad stakeholder participation (representing eight diverse organic organizations, members of the private sector and growers) to develop the database. In collaboration with the Association of Official Seed Certifying Agencies (AOSCA), the "Organic Seed Finder," a national organic seed database which is funded by participant use and donations was launched in October 2012 (Hubbard, 2012).

Organizations supporting organic seed production

Organic seed production has become better structured as a range of new organisations emerge to produce seed for commercial use (Adam, 2005; MacDougall, 2005). One instance is the Family Farmers Seed Cooperative (FFSC) which was formed in 2008 as a farmer-owned enterprise working to improve varietal availability and quality to preserve open-pollinated (OP) varieties suited to organic production systems, and to develop capacity for quality maintenance and breeding of OP varieties. Another is the Saving Our Seed project, founded in 2003, as a seed production organization that focuses on conservation and training southeastern US farmers and extension agents in the production of organic and heirloom seed. Others include a coordinated programme of research and seed production training among a network of Southern organic farming organizations, crop improvement associations, foundation seed producers, small seed companies and growers. They are working together to increase the availability of regionally adapted, open-pollinated, certified organic seed, and to establish a well-functioning Southern seed network. These examples illustrate how a range of seed production and enterprise development initiatives have evolved to build the capacity of organic farmers to produce their own seed, develop small seed enterprises, develop regionally bred and adapted varieties, and ensure that their interests are met in the organic seed systems.

Organizations supporting on-farm trials and breeding for organic variety development

The OSA was established in 2004 and focuses on grower education and training and is the first organization dedicated exclusively to grower advocacy in the US organic seed sector. Other similar grant funded initiatives include the Public

Seed Initiative (2001), Restoring Our Seeds (2003), Organic Seed Partnership (2004) and Northern Organic Variety Improvement Coalition (2009). In 2010, Seed Matters, an industry-led foundation was set up to fund graduate research in organic plant breeding and associated breeding and organic seed education initiatives. The common purpose among these initiatives lies in training growers for a range of diverse agro-ecosystems and crops, and in on-farm breeding and organic seed production. Skills development includes management of variety trials, dissemination of organically available germplasm to new regions, training growers in on-farm breeding, developing new, organically-bred varieties through participatory plant breeding, and developing unique variety release mechanisms for the organic varieties bred through participatory processes. For a thorough review of US organic seed initiatives focusing on participatory approaches to organic plant breeding and varietal identification, see Podoll, (2009).

2.3.4 Resource mobilization

The diverse respondents consistently reported that the continuing regulatory ambiguity has hindered the growth of the organic seed sector. Because the regulatory process has remained open for interpretation and enforcement, many stakeholders indicated that they had either not participated in the evolution of the organic seed sector nor had mobilised resources to support development of the sector. Others have taken a pro-active role. For instance, the establishment of the OSA and the launch of the Seed Matters initiative were intended to guide developments which optimised organic values. In order to demonstrate the level of resources mobilized within the sector (and to identify opportunities for future funding), the OSA and Seed Matters inventoried organic seed funding initiatives. The resultant SOS report estimated that between 2002-2011 there had been 57 public initiatives in support of organic seed and breeding, funded to the sum of over $9,100,000, either through government or foundation grants (some project funding estimated through 2014). The report categorized these initiatives as follows: 30 breeding and variety trials ($6,800,000), 5 enterprise development projects ($288,000), 11 seed production research and education projects ($640,000), 5 systems development projects ($220,000), and 6 multi-topic projects ($1,118,000) (Dillon and Hubbard, 2011). The majority were initiated by universities, non-profit organizations and farmer groups, but the major part of the funding came from government sources, namely in the form of grants from the USDA's Organic Research and Education Initiative (OREI) and the Sustainable Agriculture Research and Education (SARE). The major part of the funding was used to support breeding and variety trials. The results of the SOS Report and this study's findings indicate that substantial funding has also supported the development of the various databases discussed above.

The mobilisation of over $9 million may seem like a large sum, but it is valuable to note that it is estimated that the USDA funds conventional breeding initiatives at more than six times this level (Policy representative interview, 2012). Much of the funding for the organic sector has come from various divisions of the USDA (but not the NOP). That is, while it is the USDA NOP that mandates organic seed regulation and recommends an organic seed database, other organizations and divisions within the USDA are funding the regulatory execution. The majority of the funding is allocated for breeding and variety trials, processes typically performed by the private sector in the conventional seed sector.

2.4 Discussion and conclusions

Over time, whether through commitment to the integrity of organic principles and processes or through recognition of the economic potential of the sector or both new stakeholders have opted to engage in the process of interpreting and implementing the emergent regulatory regime and, through their active participation, to construct the *de facto* regulatory framework under which the industry is developing. Reganold et al. (2011) suggest in reference to the anticipated changes to the upcoming US Farm Bill that "technical obstacles are not the greatest barrier (to agricultural innovation). Change is rather hindered by the market structures, policy incentives, and uneven development and availability of scientific information that guide farmers' decisions." This judgment maps well the evolution of organic seed regulation in the US. The interdependence of market structures, policy and science, in the absence of regulatory clarity, has inhibited both technical capacity and market development in the sector. Organic seed regulation has been driven by a growing inter-dependence among initially independent protagonists such as the organic certifiers, small- and large scale growers, organic food buyers, seed production and breeding companies, non-profit organizations and government bodies engaged in the sector. Klein and Winickoff (2011) also note that the organic regulatory process overall (not just seed) is drawing in an increasing number of stakeholders initially each in pursuit of their own agenda. Through their engagement their roles and expertise, the resulting regulatory procedures and structures are becoming legitimised and normalised in the ways that May and Finch (2009) describe their theory of normalization processes. These perspectives are considered in the next section in greater detail, and thereafter a review of lessons learned for future considerations.

2.4.1 Coalitions, governance and the rules of the game

DeLeon and DeLeon (2002) describe how in the process of policy implementation, coalitions of interest and influence emerge as governance networks in industrialized societies. These coalitions may be described as co-evolving relationships among stakeholders (Kickert et al., 1997) who are connected by exchanges of resources (such as technical guides on organic seed production in this case) and information (such as the organic seed database) which are mobilised because individually the stakeholders cannot attain their own goals without orchestrating collective action. These coalitions have been seen by some (e.g. Rhodes, 1996) as competing with and weakening the authority of the government, yet by others (e.g. Peters and Pierre, 1998) as providing the government with additional capacity for governance (as demonstrated in this case by multi-stakeholder initiatives to develop regional varietal testing networks). In this latter view, the government would continue to play a strong but new role: that of meta-governor of the 'rules of the game' that guide and guard the functioning and legitimacy of the networks. That is, the actions of governance networks are not independent of the state, they are circumscribed by and draw upon state power and resources. While networks might pursue some of their goals through private, non-governmental means, typically networks are attentive to the opportunities for accessing governmental funding and legitimacy (Meuleman, 2008). The US government's position with respect to the organic seed regulation appears to be somewhat reliant on the expectation that the organic sector will self-organize around its interpretation, and be driven by, coalitions of interest, and thereby enhance the overall governance of the sector.

However, our study indicates that the creation and stability of self-organizing governance networks is a challenging task, not least because the stakeholders each tend to seek through the networks the means primarily to achieve their own interests. Their commitment to shared goals for the sector as a whole can be weak, conditional and or change over time. The central question remains as to whether there is clarity as to who or what is driving regulatory closure. Some stakeholders risk losing the resources they have invested in contributing to organic seed related emergent governance networks because others have not fulfilled their commitments as expected. This dynamic is at play at various points in the processes described in this chapter such as when seed companies' revealed frustration as organic growers continue to buy conventional untreated seed when an organic seed supply is available. The heavy involvement of non-governmental stakeholders in the organic seed discourse, combined with the stalled formalization of the organic seed regulation, has created some confusion. A level playing field has not yet been achieved such as the sub-optimal allocation of risk that primarily rests on the certifiers' interpretive responsibility. Considerable duplication of efforts remain demonstrated by the multiple unsatisfactory databases attempted. After more than ten years the final NOP guidance has not brought sufficient regulatory clarity and closure has not been achieved.

On the basis of this study, the situation is interpreted as follows. Grower and seed sector stakeholder interests remain divergent driven by differences in market opportunity and their varying prioritization of profit, enterprise development, and biodiversity goals. The main tensions which divide stakeholders are: (1) organic versus commercial values, (2) consensus-building versus protest, and (3) market-led versus conservation and biodiversity concerns. Similar tensions are described also by Luttikholt (2007) with reference to the process of formulating IFOAM's basic principles. The differences between stakeholders' perspectives and interests have made it difficult to drive regulatory closure on the basis of a market-led business model, while the lack of closure constrains the willingness of commercial seed producers to make investment commitments. Waterman and Meier (1998) note that when stakeholders' goals are not aligned, policy-making tends to drift toward extended policymaker passivity. This may explain the NOP's reluctance to formally endorse a clear regulatory framework and drive regulatory closure, suggesting that the government has not (yet) opted to take on the role of meta-governor.

On the other hand, we note that while no single stakeholder, not even the government, can impose or control governance networks (Rhodes 1996), a government can seek to actively manage network governance, for instance, by creating institutions that facilitate interaction or lower the costs of engaging in network governance. A government also may develop various procedural and substantive instruments to support the particular policy process at hand. Procedural instruments, i.e. step-by-step processes to achieve an outcome or result, typically seek to manipulate the type, number, and relationships among networks, as well as the procedures for interacting with the government [such as the 'Expert Groups' used in the EU to determine allowance of exceptions to the use of organic seed (Döring et al., 2012). Substantive instruments outline what the government intends to do through stated plans of action, which are designed to influence the mix of goods and services provided through manipulating the behaviour of individual network actors (rather than that of the networks themselves). These instruments may include provision of incentives (e.g. taxes, grants), licenses, regulations, and information (e.g. via communication tools, education, training). Substantive instruments may have significant effects on how networks behave. For instance, the wording of a regulation may shape the preferences of stakeholders and the actions that they choose to collaborate on. Poor drafting of such instruments, as evidenced in the non-specific wording of the US organic seed regulation and the lack of clear definitions for equivalency and commercial availability, also may shape preferences and action, giving rise to unintended outcomes. Information-based instruments can strengthen shared norms and shape how objectives are formulated (e.g. by providing training manuals on organic seed production). Our research findings elucidate a comprehensive lack of governance to deploy sufficiently effective procedural and substantive instruments in a timely fashion and a failure to discover an effective mix of instruments for regulating the organic seed sector. The outcome does not meet expectation, and does not satisfy the aspirations or interests of the majority of the stakeholders. Our research indicates that the sector remains somewhat internally divided and the key stakeholders do not perceive themselves to share an overriding common interest to compel them to act in complete concert to develop an optimized organic seed sector, and arrive at regulatory closure.

2.4.2 Future considerations

Development of an organic seed sector is necessary to support the claims of organic agriculture and the realization of sustainable food systems. In the US case, important technical and institutional challenges remain. This study demonstrates that while access to a diverse assortment of organic varieties in sufficient volume, quality and at a competitive price is a major, shared concern among a diverse group of stakeholders, their markedly different interests in this objective have not always converged. The impetus to further the development of a broad assortment of organic varieties and a thriving organic seed market has stagnated in the absence of regulatory clarity. No individual stakeholder, organisation or network currently is capable of leading the process towards regulatory closure.

This study suggests that the priority regulatory areas that need to be addressed to achieve closure would include: (1) clear, formally endorsed NOP guidance that communicates detailed criteria for enforcement and an appropriate allocation of responsibility among stakeholders in the interpretation and enforcement of the organic seed clause which includes set deadlines, measurable targets and reporting requirements, (2) modification and harmonization of the NOP definitions of *equivalency* and *commercial availability* criteria in order to enable certifiers to make better decisions regarding exceptions, (3) clarity on the sector-wide procedures for granting exceptions, and the steps required to move toward 100% crop-specific closure (for EU provisions, see Döring et al., 2012), (4) clarity on NOP-endorsed database requirements, funding and management, (5) subsidies and grant funding to support capacity-building for the informal and formal seed sector in organic seed production and breeding [as Stolze and Lampkin (2009) describe for the EU organic sector as a whole] and, (6) identification of an organic seed sector specific governance body with authority to inform the NOSB and NOP of the needs of the diverse organic seed sector stakeholders who are in support of overall sector development and clear regulatory interpretation.

Further challenges and opportunities lie ahead for the US organic seed sector in relation to its major organic trade partners. The EU for instance is progressing toward closing exceptions for use of conventional seed in specific crops across its member states, driven by a mix of well-chosen procedural and substantive instruments such as clear regulatory language, mandatory member state databases, expert groups to oversee and guide exception allowances and funding schemes to stimulate organic seed production and breeding (Döring et al., 2012). Most recently, guidelines for organic variety development have been developed for those breeders that aim to distinguish themselves in the market that list breeding techniques that are considered to be non-compliant with organic values, e.g. *in-vitro* techniques and cytoplasmic male sterility derived through protoplast fusion (IFOAM, 2012). The advancement towards regulatory clarity, coordinated governance and organisation of the capacity of the organic seed sector in the EU, compared to the US, would give rise to a new trade issue between the EU, the U.S. and other jurisdictions if organic growers in the U.S. continue to be allowed to use conventional seed (Renaud et al., 2014). This issue is emerging as a shared regulatory concern.

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Chapter 3

Comparative Analysis of Organic Seed Regulation in the United States, European Union and Mexico

Comparative Analysis of Organic Seed Regulation in the United States, European Union and Mexico

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(submitted)

Abstract

The governance of seed in agriculture is a challenging global issue. This article analyses the evolution of organic seed regulation in the United States, the European Union and Mexico as model cases of how these challenges are being addressed, based on a study conducted between 2007 and 2013. It highlights how growth of the organic sector is hindered by regulatory imbalances and trade incompatibilities arising from divergent stakeholder interests along the organic seed value chain, and the varying capacity for self-organising governance of the seed sector in relation to the state's regulatory role. Progress toward regulatory harmonisation in the organic seed sector among the three cases has been slow. The article concludes with an assessment of the regulatory processes described including what the regions may learn from each other and lessons for key areas of regulatory policy and practice.

Keywords

Organic agriculture, organic seed regulation, harmonisation of standards, trade incompatibilities, United States (US), European Union (EU), Mexico

3.1 Introduction

In the context of a rapidly growing global organic market, estimated at $63 billion in 2011 (Willer and Kilcher, 2013) regulators have taken steps to bring order to the organic sector. This article deals specifically with the regulation of organic seed, a significant component of organic production systems. Although organic values and norms require organic farmers to use seeds that originate from organic production, the sector continues to depend largely on conventionally produced seed. Certified organic seed is defined by the International Federation for Organic Agriculture Movements (IFOAM) as seed from cultivars that may be derived from conventional breeding programs (excluding genetic engineering) and that are produced under organic farming conditions for one growing season for annual crop species, and two growing seasons for perennial and biannual crop species (IFOAM, 2012). Organic seed production is a challenge because use of synthetic chemical herbicides and pesticides are not allowed, and therefore adjustments to cultural techniques to achieve good quality seed are required. Evolving standards for organic agriculture worldwide are pushing the organic sector toward restricted use of conventional seed in favour of certified organic seed. Market recognition that the integrity of organic production systems begin with organic seed has caused organic seed production and seed sales to increase annually and new players in seed provision to enter the market (Döring et al., 2012).

However, progress toward organic seed sector development has been slow to overcome both technical and institutional obstacles. An appropriate assortment in sufficient quantity of organic seed is not yet available. A procedure to allow continued use of conventionally produced seed is needed as a result (Groot et al., 2004, MacDougall, 2005). Many countries, including the United States (US) and the Europe Union (EU), have implemented a regulation to govern the production and use of organic seed. However, the regulations differ in the ways in which they support the development of the organic seed sector and in their procedures for obtaining exceptions for the use of organic seed. This article focuses on how divergent practices and interpretations among stakeholders of organic seed regulations in three jurisdictions have created new risks in seed supply and in international trade, that potentially limit further expansion of the sector within and between them. The importance of harmonization of organic seed regulations between the US and EU is significant due to on-going trade negotiations between the regions. The three cases that are compared and contrasted are the US, EU and Mexico building on the work of Thommen et al., (2007) and Lammerts van Bueren et al., (2008) for the EU, and Renaud et al., (2014) for the US.

The reasons why these three regions have been selected are first because demand for organic products in the US and the EU together account for 97% of the global revenue in organic products. The agricultural area under organic production is 2.0 million hectares in the US, 9.3 million hectares in the EU (Willer and Kilcher, 2013), and approximately 500,000 hectares in Mexico (Guzman Contro, 2009, Salcido, 2011). Mexico is included for three main reasons: (1) it depends to a large extent on import of organic seed from these two regions, (2) over 80% of Mexican organic exports are destined for the US market (Salcido, 2011), where consumer demand for organic products is growing at a rate of 9% annually (OTA, 2013), and (3) because Mexico might benefit from the experience of others while in the process of developing its own federal organic regulation.

The US formalized its national organic standard in 2002, the EU in 1991, and Mexico in 2006 (USDA AMS, 2002, EU, 1991, 2007, SAGARPA, 2006). The EU first sought to achieve harmonization at member state level in a 2007 regulatory revision (Michelson, 2009). The US and the EU harmonized their general organic standards in 2012 in order to enhance transatlantic trade and align practices (Haumann, 2012), while Mexico is still in the process of formalizing its domestic regulations (SAGARPA, 2013). The current organic regulations in the three cases each include a clause that requires organic seed usage in certified organic farming systems but they have not (yet) been able to establish a level playing field. An international task force on harmonization and equivalence in organic agriculture (UNCTAD et al., 2009) has examined select technical components of domestic regulatory and trade regimes. Other researchers have carried out cross-country comparison of organic farming policies among EU member state (e.g. Michelson, 2009, Moschitz and Stolze, 2009), and of the trade impacts of non-harmonization (e.g. De Frahan and Vancouteren, 2006, Disdier et al., 2008). However, these studies do not provide insight into the regulatory processes at work or address the differences in regulatory regimes governing organic seed.

Regulation is about determining priorities and avoiding undesired trade-offs in relation to the formulation, interpretation and enforcement of standards and practices that balance public and private interests. Studies based on economic models of the regulatory trade-offs in self-organising markets tend to focus on questions of efficiency, firm size or pricing, such as the work of Cuniberti et al., (2000), while sociological studies tend to focus on analysis of the values expressed by particular markets (e.g. Reynolds, 2000). Trade theorists, for their part, are interested in issues such as science-informed risk management in trade relations, the transaction costs of a regulatory practice, the discovery of legitimate standards that are the least trade-distorting, and dispute settlement (e.g. Josling et al., 2004). Such models have not yet been related to the field of international organic seed trade. However, the concerns of this study are more pragmatic: to reveal and analyse the processes that create or remove obstacles to harmonization in organic seed use in, and trade relations among, the three jurisdictions treated in this chapter, through empirical observation of evolving regulatory standards and interpretations.

May and Finch (2009) explain such processes of 'implementing, embedding and integration' of policy regulation in terms of 'normalization process theory' that emphasizes the contingent and normative factors that promote or inhibit enactment of complex interventions in a field of practice. This study provides the opportunity to contrast the 'normalization' experiences of the organic seed sector in the US, EU and Mexico and to identify where the differences are creating new barriers to international trade in organic seed. To deepen the understanding of the findings, the chapter examines the interactions between the ethical principles espoused by the organic sector, and the norms that in practice are shaping and steering the regulatory process, through the lens of meta-governance. The discussion continues in the light of the academic literature on governance (e.g. Peters and Pierre, 1998, Meuleman, 2008, Bell and Hindmoor, 2009) that outlines the role of self-organizing networks in meta-governance. Whether such networks compete with or are independent of the state, and whether there are contexts in which the state might seek to impose or manage governance networks or to work collaboratively with them by deploying appropriate policy instruments, is discussed. Lessons are drawn from the analysis and discussion that may advance the interests of the organic sector as a whole.

3.2 Methodology

The case material to support this research was collected from mid- 2007 through 2013. The description of the US organic seed sector builds on Renaud et al. (2014), which offers an in-depth analysis of the development of the sector. The US study was initiated by identification of stakeholder categories, the key stakeholders within each category, and the interests affected directly and indirectly by the evolving organic seed regulation (Reed et al., 2009). Interviews were conducted with individuals drawn from each stakeholder category to explore stakeholders' perceptions of the draft organic seed regulation, their respective role in the process, and their perceptions of opportunities for or constraints to regulatory development. Seventy-four in-depth interviews (Kvale, 1996) with individuals and representatives of organizations, identified by their high level of influence within each stakeholder category, were conducted. The stakeholder categories identified were organic certifiers (n=8), organic growers (n=40), organic food buyers (n=5), representatives of formal seed companies involved in organic and/or conventional seed production (n=10), administrative personnel (n=5), and non-profit organization representatives (n=6) with influence. The information from the interviews was recorded and analysed manually by means of qualitative analysis, by applying content analysis (Patton, 1980), and discourse analysis (Krippendorff, 2004). The findings from these analyses are presented here in narrative form, in order to reveal the unfolding processes and interests that are shaping the emergent regulatory outcomes in each case.

The material for analysis of the organic seed sector in the EU (drawing on Döring et al., 2012) and in Mexico is based also on interviews with selected stakeholders in the organic seed sector (in the EU, n=12; and in Mexico, n=15), who were identified through similar though less rigorous procedures as those outlined above for the US study. In all three jurisdictions, the respondents were asked to provide their perspectives on their respective organic seed regulations, and in the case of Mexico, also on the organic seed regulations in the country to which they export organic product. Responses were provided both in narrative form and, for specific questions, also on a rank order. The questions included: (1) What are the primary motivations for you(r) organization to support the development of the organic seed sector? Ranking options here were: ecological seed production, financial, farmer livelihood, biodiversity (genetic), imminent regulation enforcement, other. (2) What do you(r) organization perceive needs to be done to close the loop in organic seed usage in an organic agriculture system? Ranking options here were: clear regulatory enforcement, national organic variety trial program, crop group quota targets on organic seed use, sanctioned database, training in organic seed production, definition of equivalency, other, and (specifically for Mexico) allowance of untreated organic seed importation.

Relevant grey literature, expert reports and policy documents were reviewed for all three jurisdictions as no peer reviewed literature on organic seed regulation in the case study countries has been published. The first two authors participated, in varying roles as researchers and stakeholders, in key organic seed meetings held in the US, the EU and Mexico throughout the study period. The methodology emphasises the importance of within-case analysis and detailed process tracing. Finally, the case material from each jurisdiction is compared (George and Bennett, 2005).

3.3 Developments in organic seed regulation

3.3.1 The US case

In 2002 the United States Department of Agriculture (USDA) developed a domestic organic regulatory standard to govern the US organic sector, the National Organic Program (NOP). The standard includes a clause governing organic seed usage in certified organic farming systems (Section 205.204(a)) that prescribes the use of organic seed in organic production systems whenever such seed is commercially available (USDA AMS, 2002). Interpretations of the seed clause, and the development of monitoring tools for compliance, have evolved through successive guidance documents issued by a statutory authority charged with oversight of implementation, the National Organic Standards Board (NOSB), to the NOP. However, because after twenty years' of consultation and re-drafting of recommendations, no official endorsement by the NOP of the NOSB's recommendations has emerged, and because the framing legislation provides neither deadlines nor penalties for non-compliance, divergent interpretive practices have emerged. The main findings and analysis of these developments are discussed in detail in Renaud et al. (2014), and summarized briefly below. A chronology of the main events is outlined in Table 3.1.

Table 3.1 Summary of key events in the evolution US organic seed regulation 1990-present

Timeline	Regulatory Position Change	Outcome
November 28, 1990	OFPA signed into law as Title 21of the 1990 Farm Bill	US Organic Agriculture Law
December 22, 2000	USDA NOP standard published in the Federal Register	Proposed US Organic Agriculture Rule
March 7, 2001	Commercial Availability: Docket Number TMD-00-02-FR	Definition of Commercial Availability
October 22, 2002	USDA NOP standard approved	Approved US Organic Agriculture Standard
August 17, 2005	NOSB to NOP Recommendation: Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 1
November 30, 2007	NOSB to NOP Recommendation: Further Guidance on the Establishment of Commercial Availability Criteria	Organic Seed Guidance Document Version 2
April 3, 2008	NOSB JC & CAC Committee Recommendation: Further Guidance on Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 3
September 22, 2008	NOSB JC & CAC Committee Recommendation: Further Guidance on Commercial Availability of Organic Seed	Organic Seed Guidance Document Version 4
November 19, 2008	Formal Recommendation by the NOSB to the NOP: Commercial Availability of Organic Seeds	Submitted Organic Seed Guidance Document Version 5
June 13, 2011	NOP Guidance released for public comment	NOP Guidance proposal
March 4, 2013	NOP Guidance: Seeds, Annual Seedlings, and Planting Stock in Organic Crop Production	NOP Final Organic Seed Guidance

Source: Adapted from Renaud et al., 2014.

The NOP's standard and NOSB's guidelines assign primary responsibility for enforcement of the organic seed clause to organic certifiers (NOSB, 2008 a b c). The certifiers are required to ensure growers have attempted a rigorous organic seed sourcing process, and that growers increase their organic seed usage year-on-year. Growers for their part are assigned responsibility for demonstrating clearly the steps that they have taken to source organic seed, through on-farm variety trials, and by documenting why they might not have used organic seed. Growers' principal concerns relate to the availability of quality seed and of sufficient quantities of a diverse assortment of organic seed varieties. Growers are concerned also that in general certified organic seed costs more than conventional seed. Price, however, is not taken into account in the exemptions permitted by the regulation (USDA AMS, 2002). If growers use conventional instead of organic seed, they must justify in their Organic Systems Plan that the seed traits and characteristics of the conventional seed are not available in organic form. While data contained in the plans have the potential to inform the organization of organic seed supply, procedural differences among certifiers with respect to the review and enforcement of the plans has led to significant inconsistencies (Renaud et al. 2014). A residual level of regulatory enforcement responsibility has been allocated to organic food buyers, who are supposed to monitor the seed usage of their suppliers, particularly if the buyer's contract specifies a particular variety. According to our interviews, in practice such monitoring is considered by the buyers to be a costly administrative expense that is often avoided. In addition, food buyers may face a conflict of interest based on the varieties they want and the quality, characteristics, price or volume of the organic seed available to produce the variety (Dillon and Hubbard, 2011).

The lack of a comprehensive organic seed database lies at the heart of many of the tensions that have emerged. NOSB's guidance documents indicate that a database should list the availability of varieties aligned to certified organic growers' trait preferences, and the equivalent conventional seed options (in the case that an organic seed variety is not yet commercially available). At least eight organizations have created, or attempted to create, a database to ensure transparency in the claims made about organic seed varietal availability. To date (end 2013), none of the databases have achieved comprehensive coverage and none has been officially endorsed by the NOP. The Organic Material Review Institute's (OMRI) attempt was the most ambitious, aiming to provide a comprehensive national database for all growers and certifiers in the US. However, a lack of clarity about who should bear the cost of registering and organizing the information and, in the opinion of many stakeholders, because the initial fee for using the database was set too high, from the beginning OMRI's ability to mobilize long-term funding for the initiative was undermined. In 2012, drawing on OMRI's experience, a multi-stakeholder initiative to re-launch the database was coordinated by the Organic Seed Alliance (OSA) in collaboration with the database host organization Association of Official Seed Certifying Agencies (AOSCA) that emphasizes the importance of attaining NOP endorsement to ensure its success (Hubbard, 2012). All our respondents have recognized that without a fully endorsed and populated database requests for exceptions to the organic seed rule will persist and will discourage organic seed producers from meeting the demand, thereby sustaining the pressure to grant exemptions, an impasse that undermines the integrity and limits the potential growth of the US organic sector, see Table 3.2.

In the absence of a strong convergence of interests at the national level, new organizations with a regional focus have emerged to help manage local seed concerns. Their scope variously includes the testing of organic seed varieties with farmers, supporting participatory breeding (e.g. Organic Seed Alliance), the development of local organic seed production (e.g. Family Farmers Seed Cooperative), and the pursuit of funding for preparation and maintenance of organic seed lists or databases (e.g. OMRI, AOSCA). Although over 100 US seed production companies have developed niche markets in organic seed, the expansion of the seed sector remains challenged by the lack of reliable information about the requirements of organic growers for desired varieties. Nevertheless, several stakeholder groups have demonstrated a willingness to engage in the concerted development of the organic seed sector (Podoll, 2009, Renaud et al., 2014). Others, such as large-scale commercial baby lettuce leaf and spinach growers in California, where seed costs form a relatively large part of their cost structure, have less incentive to proceed toward compliance.

Table 3.2 US Stakeholder perspectives on an organic seed database (n=74)

Stakeholder category	Stakeholder type[1]	Stakeholder level of influence[1]	Perspective on Organic Seed Database
Organic Certifiers (n=8)	Key	High	-Valuable tool for certifiers to assist in the interpretation of a growers attempt at sourcing organic seed in the inspection process -An organic seed database would make assessing an organic growers attempt at sourcing organic seed more efficient and less costly
Small-Scale Organic Growers (n=26)	Primary	Low to High	-Valuable tool to identify possible organic seed sources commercially available that are unknown to the grower -Growers should not be limited to database sources for production operation use as many rare and unusual varieties are not available in organic form. Do not want to limit on-farm genetic diversity.
Large-Scale Organic Growers (n=14)	Primary	Low to High	-Valuable tool to identify possible organic seed sources commercially available that are unknown to the grower. -Growers should not be limited to database sources for production operations as many varieties used by commercial growers are not grown organically or are produced under longer term contracts.
Organic Food Buyer (n=5)	Intermediate	Low	-Potentially valuable tool to identify sources of organic seed to support contracts and ensure compliance of organic seed regulation guidance. -Do not want to be limited by varieties available on the database because the varieties may not meet contract requirements.
Formal Seed Companies (n=10)	Primary	Low to High	-Valuable tool if all companies with organic seed participate and keep availability updated. -Excellent nearly free marketing and promotion opportunity. -Potential to gather information on varieties that growers would like organically, but are not available. -Unnecessary costly and timely uploading process. -Do not want to participate if the company has a conventional untreated seed division as it will jeopardize their sales.
Non-Profit Organizations (n=6)	Intermediate	Low to High	-A two-way organic seed database is a stepping stone towards transparency of what varieties are available in organic form as well as those that are not available. -A needed tool in order to set derogations/exception by crop group and to set timelines. -Valuable to a broad stakeholder range in the organic seed chain.
Policy & Legislative Body (n=5)	Key	High	-Valuable tool to demonstrate availability and support organic certifiers, growers and food buyers in identifying availability. -Will include in guidelines, but not make it mandatory.

Sources: Stakeholder analysis (columns 1-3, 2007); stakeholder interviews and participant observation (column 4, 2007-2013). Adapted from Renaud et al., (2014).

[1]*Notes to Table 3.2:* Stakeholder categorization (Jiggins and Collins, 2003)

Stakeholder Type	Definition	Levels of Influence
Primary	Those who are directly affected, either positively or negatively	Low to High
Intermediate	The intermediaries in the delivery or execution of research, resource flows, and activities	Low to Intermediate
Key	Those with the power to influence or 'kill' activity	High

The spread of compliance responsibilities among growers, certifiers, and buyers remains contentious. The fact that the guidance recommendations have not achieved sufficient consensus and compliance to be endorsed by the NOP seems indicative that the government still expects this emerging economic sector to self-organize. The case study findings indicate that while an increasing number of private actors have come to the negotiating table to represent their various interests, the lack of a common agenda, and of policy instruments, such as an endorsed national organic seed database that would encourage advancement toward regulatory compliance at the national level, has allowed increasing dissent and fragmentation. In the absence of a central coordinating body with authority to drive toward compliance the diverse stakeholders in the organic sector, the conventional seed sector, and in the government, the interested parties continue to observe and act in response to each other (Renaud et al., 2014).

3.3.1 The EU case

The development of the organic seed sector in the EU differs significantly from the US experience. State actors have demarcated clearly stakeholders' roles and responsibilities, set deadlines for compliance, and established procedures for monitoring and for penalizing non-compliance. In 1991 the European Commission (EC) established an EU-wide organic standard, followed by revisions in 2009 (Council Regulation European Economic Community (EEC) No 834/2007). In 1999, an amended regulation was adopted, specifying that organic growers, with exceptions as outlined in Commission Regulation (No 1452/2003), by 31 December 2003 must use organic seed. The responsibility for enforcement lies with the national governments of each of the 27 EU member states, coordinated by government representatives of each member state in the Standing Committee Organic Farming (SCOF). The regulation further stipulates that governments must host an online database listing the available organic varieties and their suppliers, including the identification of exception allowances, and that they are responsible for supplying the EC with an annual report of the exceptions granted in the member state. The timeline for the chronology of events in the EU case is outlined in Table 3.4**.**

The European Seed Association (ESA) in 2002 carried out an assessment of seed companies' capacity to deliver the requisite quantities of organic seed by the end of the following year, concluding that it should be possible for seed companies to do so. However, the assessment also showed that despite overall availability, and in the quantities required, organic growers of particular crops in certain regions would in fact not be able to access all of their seed requirements in organic form by the deadline. Thus the regulation was amended again to allow exceptions on request so that growers could use conventional seed provided the seed was not chemically treated and organic seed was not available. The perspective of different seed company stakeholder types on the potential for achieving 100% organic seed is outlined in Table 3.3**.** Most member states base exceptions on the following categories: (1) no exception for species and sub-species with enough acceptable assortment of varieties available in organic form, (2) case-by-case authorization for exceptions for those species and sub-species with some varieties available in organic form but not a sufficient assortment of the main varieties required in the organic sector, (3) general exception for species and sub-species without any (appropriate) varieties available in organic form (Thommen et al. 2007).

Several member states have supported regulatory implementation by developing tools for database development, communicating availability criteria, and encouraging closure to exceptions for certain crop groups (Thommen et al. 2007, Lammerts van Bueren et al., 2008, Döring et al., 2012). Some member states, such as The Netherlands and Denmark, use formalized expert groups to identify which species and (sub) species are allocated to each of the above-noted exception categories. Expert group advice in these countries, in combination with approval by their respective Ministries of Agriculture, informs exception approval or disapproval by the member state's certification body. The composition of expert groups, and the method of analysis used to evaluate exceptions, is unique to each member state. For example, some member states allow grower representatives to participate in expert groups together with seed producers and advisors. Others do not, believing growers may influence exception allowances in their favour. Still others, including Germany and

Switzerland (noting that Switzerland is not part of the EU but an associated European country), do not work with exception categories at all, preferring to consider all requests on a case-by-case basis, using publicly available variety equivalence lists for each species and (sub) species (Thommen et al., 2007).

Table 3.3 European seed company perspectives on prospects for regulatory closure in the EU (n=7)

Seed company category	Stakeholder type[1]	Stakeholder level of influence[1]	Key concerns relating to the organic seed market and prospects for achieving regulatory closure
Conventional seed companies (n=2)	Intermediate	Low	No commitment to support regulatory closure. Market is too small to invest in. See no added value in organically produced seed. Fear for loss of conventional seed sales. Conflicts with GMO and chemical agriculture divisions. No infrastructure to support organic certification requirements.
Conventional seed companies with an organic division (n=3)	Primary	Med to high	Market is evolving and professional organic growers require their professionally bred varieties. Regulatory enforcement and derogation rigor required. Harmonization among member states needed. More transparent access to grower varietal requirements. Fear for loss of conventional seed sales and trade-offs in profitability. Organic seed production and breeding capacity. Organic seed quality (seed borne diseases and vigour).
Organic seed companies (n=2)	Primary	High	Market opportunity is there. Market requires varieties bred for organic production systems. Regulatory enforcement and derogation rigor required. Harmonization among member states processes. Value of biodiversity needs to be considered in varietal assortment. Organic seed quality (seed borne diseases and vigour). Organic seed production and breeding capacity.

Sources: Stakeholder analysis (columns 1-3, 2007); Content analysis of stakeholder interviews (column 4, 2007-2013).[1] Stakeholder typology, definition and level of influence, see Table 1 Notes.

Encouraged by the rigour of the procedures for the granting and reporting of exceptions, there are several on-going efforts by both public and private actors to achieve 100% organic seed use, beginning with a limited range of crops. BioSuisse, a Swiss certification body, has created a fund to address the price difference between organic and conventional seed. If a grower needs to use conventional seed because there is no comparable variety in organic form, the grower pays the difference in the cost of the seed into a fund that supports organic seed-breeding and multiplication, such as variety trials (Thommen et al., 2007). In The Netherlands, a government-funded project has provided the opportunity for growers to organize in national crop groups and, for crops with low availability of organic seed, to communicate their organic variety needs to breeders and seed companies (Lammerts van Bueren et al., 2008). This initiative, in combination with yearly publication of varietal exception requests by the national organic certifier, has helped seed companies in The Netherlands to identify appropriate varieties for which a secure organic market exists (Raaijmakers and Ter Berg, 2012).

In the case of the EU, clear enforcement guidelines have accompanied organic seed regulation. As a result, various crops (such as cucumber and lettuce) in several member states, including Denmark, France, The Netherlands and Sweden, are now closed to exceptions. The most comprehensive movement toward 100% compliance has been achieved in the more affluent north-western member states; others remain challenged by domestic policies and trade imbalances (e.g. due to lack of a national vegetable seed industry) that continue to prevent access to organic seed for certain crops. Growers in some countries, including Portugal, Estonia and Bulgaria, continue to have limited access to organic seed that meets the volume, quality and varietal requirements for primary crop groups, and so they continue to use predominantly conventional seed (Alonso and Rundgren, 2011). According to our respondents, and a study by Döring et al. (2012), despite differences in progress among EU member states, the EU organic seed regulation has stimulated the organic seed sector through clear allocation of enforcement responsibility to the national governments of member states, by requiring that each member state maintain a national seed sourcing database, and by requiring the submission of an annual report on exceptions to a central coordinating authority. The EC Agriculture & Rural Development website (2013), which collates all EU databases, lists over 300 organic seed suppliers throughout the EU (e.g. 80 in Germany, 30 in The Netherlands, and 26 in France). Döring et al. (2012) note, however, that further effort is needed to harmonize annual reports, encourage wider recourse to appropriately constituted national expert groups, enhance communication and cooperation between member states in order to achieve a level playing field for exporters, and to develop cross-compliance with national and EU-wide legislation related to biodiversity conservation and the conservation of landraces (FSO, 2010).

Table 3.4 Summary of key decisions and events in the evolution of the European organic seed regulation

Timeline	Regulatory Position Change	Outcome
1991	Council Regulation (EEC) No 2092/91	EU Organic standard implemented
1999	Council Regulation (EC) No 1804/1999	EU standard amended with derogation to enforce organic seed usage by December 2003
2002	EU commission to perform organic seed evaluation	Reform of 1999 Council Regulation (EC) No 1804/1999
2003	Commission regulation (EC) No 1452/2003	Retracted December 2003 derogation closure date. Requirement for all EU countries to establish national organic seed databases and annual derogation granting report for full availability disclosure.
2003	Formation of the European Consortium for Organic Plant Breeding (ECO PB)	Organization formed with the goal to harmonize EU members processes on organic seed databases and annual reports
2004	EC Organic Seed Regime 2004	Started implementing the derogation regimes for organic seed
2007	EU project EEC 2092/91 Organic Revision	Project included a report with revisions to the original organic standard including the section on organic seed
2008	ECO PB Position Document on Cross Country Regional agreements on derogations	Set goal to identify 5 crops that in the coming 3-5 years to work towards reductions in derogations or in category 1 list
2008	Motion on banning protoplast fusion at the IFOAM General Assembly accepted	Proposed ban on varieties derived from and use of protoplast fusion in organics
2009	ECO-PB Position Document on protoplast fusion	Requested that national databases indicate varieties derived from protoplast fusion
2009	Council Regulation (EC) No 834/2007	Revised EU Organic Standard
2009	Council Regulation (EC) No 889/2008	Revised of organic seed regulation
2010	IFOAM Standards for Organic Breeding under consultation	IFOAM included standards for organic breeding and defined the breeding techniques compatible with organic values
2012	IFOAM Final Document	IFOAM definition of organic plant breeding finalised
2012	ECO PB Meeting	ECO PB met on EU organic seed expansion and developed strategic framework

Sources: Doring et al., 2012, EC, 2007; 2009, Gibbons, 2008, IFOAM, 2012, Lammerts van Bueren et al., 2007; 2008, Rey et al., 2009, Wilbois, 2006.

3.3.3 The Mexico case

Mexico first sought to regulate the organic sector in 1997, with the publication of an Official Standard NOM-037-FITO-1995. However, the regulations were not enforced and the standard was officially cancelled in 2010. In 2006, the government enacted the Organic Products Law that required all organic products to be certified in accordance with an international organic standard (SAGARPA, 2006). This laid the foundation for a series of draft regulations that have been negotiated with Mexico's main trading partners in organic products, such as the US and the EU, published on 1 April 2010, and subsequently approved by the Mexican Federal Commission of Regulatory Improvement (COFEMER, 2010). Following further approval of the drafts by the Sanitary, Food Safety and Food Quality National Service (SENASICA), Mexico's 'Guidelines for the Organic Operation of Agricultural and Animal Production Activities' were released in 2010. The guidelines required the use of organic seed in certified organic agriculture systems (Section 3, "SEED or PROPAGATION MATERIAL" Article 41-43). Notably, there was no provision for exception for the use of conventional untreated seed (SENASICA, 2010). The organic regulation was redrafted in 2012. It withdrew the 100% organic seed use requirement. The revised draft permitted the use of conventional treated seed if the chemical treatment was been "washed-off" (Article 35, SAGARPA, 2012b). The final Mexican Organic Regulations retained Article 35 and was published on 29 October 2013 (SAGARPA, 2013).

The stakeholder interviews and participant experience suggest that the US regulatory regime arguably has had greater impact on the organic sector in Mexico than the efforts to develop effective domestic law, because the major part of Mexico's organic crop production is exported to the US market and must therefore meet the requirements of the US organic regulation. Conventional seed treatments, for instance, are not permitted under either US (or EU) organic regulations. Mexican organic growers in fact face a unique challenge. In the US, organic growers have access to diverse organic seed sources and the opportunity to secure exceptions to the use of organic seed. In Mexico, there is a limited domestic supply of organic seed and the major part of the seed used in Mexico is supplied mainly by companies based in the US and the EU. The organic sector in Mexico has become dependent on the importation of organic seed from foreign companies and on seed regulation and certification standards in their main export markets.

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Further complications have arisen. The imported seed must be accompanied by an organic certificate issued by a certification agency recognized by Mexico's Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) (Sonnabend, 2010), as outlined in the Organic Products Law of 2010 (COFEMER, 2010). In addition, imported seed is subject to the phytosanitary requirements outlined in Mexico's Federal Phytosanitary Law (NOM-006-FITO-1995), that requires imported seed to be treated with a particular chemical seed treatment. Because such treatments are not permissible in organic systems, an alternative treatment has been proposed that complies with the letter and intention of Mexico's Federal Phytosanitary Law. However, the treatment is consistent neither with the phytosanitary requirements of Mexico's primary organic trading partners, nor proven effective as a blanket phytosanitary control for all crops or all diseases.

Considering the severity of restrictions placed on the Mexican organic sector by foreign organic seed regulations and the phytosanitary restrictions on seed importation, stakeholders have been encouraged to seek other ways forward. Exception grants from SAGARPA are available for growers who solicit a grower-specific importation permit, thus allowing them to import seed directly and avoid a seed distributor, and to work directly with the authorities to authenticate potential phytosanitary risks. This has resulted in inconsistent certification standards with respect to enforcement of the seed importation process. Mexican growers are also importing seed from their own supplier networks, encouraging use of seed that is not certified organic and of conventional seed treated chemically (that might or might not be washed off). Moreover, organic growers continue to receive exception to the seed rule even when organic seed is available. The testing of imported seed for acceptability also has numerous loopholes. For instance, inspectors might or might not divulge the test criteria, and might or might not choose to exercise their discretionary authority to label a seed lot as unacceptable (thus requiring that it be sent back to the country of origin at the grower's expense, or be surrendered to the inspector for destruction) (Dunkle, 2011). However, and even more significantly, industry stakeholders report the growing practice of furtive acquisition of conventional seed (for organic purposes) that might or might not be treated in accordance with phytosanitary requirements, resulting in the growing illegal movement of seed into and around Mexico.

We examine these points in more detail below, with reference to a particular case.

The Mexican company Horticola Camarillos S.A. de C.V. was certified as complying with the organic certification requirement of the US by producing an Organic Farm Plan that stated the farm's seed use. Upon review, the company was found to have used treated seed for one crop, to have insufficient documentation for another crop, and to have violated a USDA NOP rule for seed treatment and phytosanitary requirements applicable in the US. Organic grower Isidro Camarillo Zavallo, General Manager of Carmarillo, argued (in 2010 during his appeal against loss of certification status) that compliance with US regulations requires Mexican growers to break the laws of Mexico. He reported that practices routinely include purposefully deceptive packaging, absent or inaccurate labelling, and ambiguous responses to the different phytosanitary requirements of trade partners. He further stated that it was the company's effort to comply with US regulations that had caused their certification to come into question. The organic certifier, the Organic Crop Improvement Association (OCIA), denied the appeal and cancelled Camarillo's certification for three years, on the grounds that evidence was lacking that chemical treatment of imported seed is compulsory in Mexico, and that USDA NOP regulations may not be circumvented to meet organic regulatory requirements outside the US (USDA Marketing Service, APL-027-08).

The contradictions posed by differing phytosanitary requirements have been an issue between Mexico and the US for some time. Before 2009 Mexico had approved, on a restrictive basis, a limited number of alternative seed treatments for phytosanitary purposes that were also approved under the NOP. These included 'Natural II', an Agricoat product (approved in 2005), and importation of untreated organic seed that was accompanied by phytosanitary certification based on seed testing and post-entry quarantine inspections (approved in 2008). The Natural II allowance was cancelled in 2008, because the product had not been approved by the Mexican Federal Commission for the Protection Against Sanitary Risk (COFEPRIS), and because any new treatment proposed for use in organic agriculture requires prior COFEPRIS approval. US companies seeking COFEPRIS approval of seed treatments subsequently reported that the data submission requirements were unclear and that the approval process was a restraint to trade, being both cumbersome and long (seed company interview, 2010). Only in 2011 did SAGARPA accept that the approval of new organic seed treatment options no longer required the prior approval of COFEPRIS.

The option of allowing importation and use of untreated seed if accompanied by the appropriate certification was described in Article 89 of the original Mexican Organic Products Law (COFEMER, 2007). The law provided for an exception when a seed importer presented technical or scientific evidence demonstrating an alternative to the required chemical treatments. In 2009, a biological seed treatment called T-22 (*Trichoderma harzarianum*) was approved for organic seed and the option to import organic untreated seed was removed. Use of T-22 proved problematic from the start because the company that had exclusive manufacturing rights was unable to meet the initial demand. In addition, inconsistent enforcement of what counts as acceptable seed continued at Mexico's borders. The minimum dosage rates for seed treatment were set at a high level, not all crops were approved for T-22 treatment, some seed producers encountered germination problems, and research analyses found only limited evidence to support the claim that T-22 prevented seed-borne diseases (Cummings et al., 2009). Since 2009 the number of crops approved for T-22 treatment has expanded from the original list of just six crops (although some crops remain excluded). In 2012, two new organic seed treatments were approved by SAGARPA to support the entry of organic seed into Mexico (SAGARPA, 2012ac). However, these treatments were originally not commercialized for application on seed in the US and were not permitted on all crops. By the end of 2013, these seed treatments were allowed on a select group of crops (Actinovate: 14; Mycostop: 9). In Table 3.5 the key decisions and events in the evolution of the Mexico organic and phytosanitary regulations are summarized.

In summary, three preliminary comments on the organic regulatory situation in Mexico can be made. First, Mexican organic growers are burdened with the costs of multiple organic certifications, additional phytosanitary treatments, and of securing complex import permissions, that place them at significant disadvantage compared with US and EU growers, who produce for the same markets. Secondly, certifiers and sellers in Mexico, if they wish to stay in business, in practice are forced to break the laws of either or both the seed's country of origin and of the destination markets for organic products. This significantly reduces the potential for trade while significantly increasing the potential for movement of diseased seed within Mexico. Thirdly, Mexican organic production nonetheless continues to grow at a rate of 20-30% annually, involves more than 130,000 growers, and covers more than 500,000 hectares of land (Guzman Contro, 2009) despite the complications documented above.

Table 3.5 Summary of key decisions and events in the evolution of the Mexico organic and phytosanitary regulations

Timeline	Regulatory Position Change	Outcome
1995	Mexican Phytosanitary Regulation NOM-006-FITO-1995 published	Mandatory chemical seed treatment imposed
1997	Mexico official organic standard NOM-037-FITO-1995published	Mexico's first organic standard proposal
2005	Natural II an organic seed treatment approved	First organic treatment permitted for seed entry into Mexico
Feb 7, 2006	Organic Products Law published	Mexico Organic Product Law
June 2008	Approval of importation of organic untreated seed	Use of organic untreated seed allowed
2008	Approval for use of Nature II organic seed treatment retracted	Entry of organic seed treated with Natural II banned
2009	Allowance of importation of organic untreated seed retracted	Entry of organic untreated seed banned
2009	Approval of T-22 as only method for organic seed importation	Entry of organic seed with T-22 treatment approved
2009	Approval of hot water treatment for seed importation	Entry of six crops treated with hot water
2009	AMSAC Organic Seed Committee formed	Committee formed to identify new methods for organic seed entry
April 1, 2010	Organic Products Law approved by COFEMER	Mexico Organic Regulation approved
May 11, 2010	Cancellation of Mexico organic standard: NOM-0337-FITO-1995	Mexico's initial organic standards cancelled
May 25, 2010	Mexico Organic Regulations draft published by SENASICA	Draft Mexico Organic Regulations published (includes a requirement that growers use 100% organic seed)
June 2010	Dutch agricultural delegation met with SAGARPA	The Netherlands and Mexico seek a bilateral agreement on seed trade
July 2010	Organic certifiers organize a multi-stakeholder meeting on organic seed importation into Mexico	Multi-stakeholders share with government authorities the impact of conflicting organic and phytosanitary requirements on their operations.
Aug 2010	US government inter-agency group including the USDA (NOP, APHIS, FAS, AMS) and OTA meet in the US with SAGARPA to develop bilateral agreement on seed importation issue	US authorities seek to create a strategy for bilateral agreement on (organic) seed trade with Mexican authorities

Table 3.5 (continued)

Timeline	Regulatory Position Change	Outcome
Oct 2011	ASTA hosts multi-stakeholder meeting with US and Mexican government authorities to develop a strategy on seed importation	Authorities on agricultural trade brought together by ASTA to develop strategy for organic seed importation
Aug/Nov, 2012	Approval of Mycostop and Actinovate treatments for seed importation	Entry of organic seed with Mycostop and Actinovate seed treatments
Nov 14, 2012	SAGARPA submits revised draft of Mexico Organic Regulations to COFEMER for review after public comment	Revised draft of Mexico Organic Regulation submitted for review (includes requirement that growers use organic seed if commercially available or use of conventional treated seed with treatment washed off)
Nov 30, 2012	COFEMER provides response to SAGARPA's draft regulation	COFEMER requests clarification on organic seed section of regulation
Feb 8, 2013	AMSAC revitalizes Organic Seed Committee	Committee revitalized to develop strategy on organic seed issue
July 6, 2012	Approval of more crops treated with Mycostop and Actinovate	Mycostop and Actinovate approved for 9 and 14 species, respectively.
Oct 29, 2013	Mexican Organic Regulation recorded in the Federal Register	Approved Mexican Organic Regulations (retains requirement that growers use organic seed if commercially available or use of conventional treated seed with treatment washed off)

Sources: COFEMER, 2006, 2007, 2010, 2012, Dunkle, 2011, Guzman Contro, 2009,SAGARPA, 2009, 2010, 2012abc; 2013, SENASICA, 2012, Salcido, 2011, Sonnabend, 2010, Content analysis of policy documents (2007-2013).

3.4 Contrasts and comparisions

This section first reports and analyses the study findings concerning the evolution of the organic seed regulatory harmonization among EU member states. The US and EU regulatory processes then are compared. It is suggested that the US might learn from the EU process a number of important lessons. Finally, an analysis is made of how the Mexico organic regulatory process is stifled by conflicting phytosanitary requirements that impede development of the sector in relation to its main trade partners.

3.4.1 Challenges in the harmonization of organic seed regulation among EU member states

Achievement of a comprehensive EU-wide database for all crops and varieties for which sufficient organic seeds are available and exceptions are not permitted, is considered by all our respondents and participants in the meetings observed in this study to be a realisable objective. It remains a shared goal although differences in legal languages, eco-climate zones, and agricultural and cultural traditions continue to pose challenges. The emergent regulatory regime combines a strong, clear, enforceable framework at the level of the EU with flexibility in interpretation and implementation at the level of each member state. Additional initiatives undertaken to enable and encourage greater harmonization of interpretation are proving helpful. For instance, in 2004, the EC funded an inventory and analysis of member states' organic seed policies The report of this study (Thommen et al., 2007) highlighted variance in interpretation of the term 'non availability of an appropriate variety' as a criterion for exception to the organic seed rule. It further recommended the EU-wide use of a standard check-list to define the appropriateness of an assortment of varieties for a (sub) species, and this has been adopted.

The European Consortium for Organic Plant Breeding (ECO-PB) has evolved alongside the regulatory developments documented. Since 2003 it has assumed responsibility for organizing joint meetings of stakeholders from member states, approximately two times a year, to share experiences and develop regulatory recommendations and practices (Wilbos, 2006, Lammerts van Bueren et al., 2008, Rey et al., 2009). The authority of decisions made at ECO-PB meetings has been recognized by member state governments, and several SCOF members regularly attend, to better understand sector-wide problems and to collaborate on finding ways forward. The meetings serve to reinforce member states' commitment to achieving zero exceptions, while highlighting the lessons of experience, for example, that strict compliance with the seed regulation can be a barrier to access to newly marketed crop varieties. Although the EU regulation currently allows growers to use conventional seed to trial new varieties on a small scale, if the crop is listed in the 'no exception' category for annual crops, growers have to wait at least a year before the organic seed of the desired variety is produced and on the market. In order to follow-up new developments without delay, The Netherlands has introduced a 'flexibility rule' that allows their growers to use conventionally produced but chemically untreated seed of a new crop variety for one year for annual crops, or two years for biannual crops, provided that a seed producer agrees to start organic seed production of the requested variety (Lammerts van Bueren et al., 2008). The ECO-PB joint meetings have identified also the lack of interest of certain seed companies, which are primary seed suppliers for particular crops, in pursuing organic seed production. ECO-PB members have recommended in response that official organic seed variety trials should not include the varieties produced by companies that are not interested in pursuing organic seed production. It was argued that this also would stimulate growers to learn about the organic varieties that are offered by other companies more committed to organic seed supply (Lammerts van Bueren et al. 2008, Rey et al., 2009). The EU case suggests that progress toward regulatory harmonization among EU member states is a product not only of the bottom-up commitment of stakeholders in the organic sector to achieve a common goal, but also of strong support and direction from national authorities and the EC. ECO-PB members themselves draw the lesson that the EC should seek stricter and more coordinated management of exception criteria among member states, as well as a common format for the national reports on exceptions so that the reports can be used to compare progress in regulatory implementation and to improve trade (Lammerts van Bueren et al., 2008, Döring et al., 2012).

In describing collective action and policy compliance in the organic food industry, Lee (2009) suggests that complexity typically emerges at the level of self-organizing networks as they seek to mobilize their members toward compliance with a common goal to meet regulatory requirements. Lee further suggests that those responsible for meta-governance of the regulatory regime on the other hand seek uniformity and a level playing field among the interested parties. The EU case suggests that it is the willingness to engage in and provide support for learning from experience that has assisted the process of normalizing regulatory requirements among member states. The EU's experience further suggests the importance, and perhaps the necessity of a central body that takes responsibility for developing and applying appropriate substantive and procedural policy instruments that provide incentives, penalties and support for compliance. We suggest in the next section that the regional example of harmonization amongst member states in the EU offers lessons that potentially might have larger policy impact worldwide.

3.4.2 The US and EU compared

In both the EU and the US there are numerous stakeholders, with diverse interests, who none the less want to ensure that the principles of organic agriculture are considered in the process of developing and implementing an effective regulatory regime (Klein and Winekoff, 2009). In the EU the normalization of these principles into regulatory practice was assigned to member states (Padel et al., 2009), operating within common, clear and enforceable regulatory standards. In the US, responsibility for enforcing compliance with organic principles has been spread among stakeholder categories (organic certifiers, growers, buyers), thereby creating potential for conflicts of interest and diverse interpretation of principle into practice.

Because the EU chose to regulate the use of organic seed through a formal amendment to its existing organic standard, accompanied by a deadline for compliance, the processes of implementing, embedding and integrating seed regulation into organic practices (assisted, for instance, by the databases and expert groups) has been able to move at a faster pace and with broader stakeholder compliance than in the US. We have identified in the content and discourse analyses five main contributing factors: (1) Most US respondents recognized the necessity for the information that only a database can provide. The database initiatives have been funded and organized by diverse coalitions of stakeholders rather than by a governmental authority such as the NOP. The reliance by the state on self-organizing initiatives has resulted in multiple databases using different criteria and serving different clients, thereby reinforcing fragmentation rather than the harmonization of the sector. (2) Maintenance of the US databases is currently reliant on the continuation of grants, and the uploading of varieties into a database is reliant on the willingness of companies to pay for inclusion. This has resulted in competition for financial support and market advantage. (3) The EC requires that each member state submit on time national annual reports on organic seed exceptions. The US regime makes no such provision for reporting, thus monitoring of progress toward regulatory compliance is not possible. (4) EU member states have developed common guidelines for types of exception and for the practices and procedures of exception review committees. The US has no appropriate procedural instruments in place for formal monitoring of exceptions and organic seed usage. The onus is placed primarily on the interpretation of independent certifiers, growers and buyers. (5) Several EU member states have developed Expert Groups to advise regulatory bodies and certifiers in their decision-making regarding exceptions. The US relies completely on stakeholders to oversee the integrity of the exception procedure. Overall, our analysis suggests that the US, in the near to medium term, will not be able to approach 100% compliance with the organic seed regulation for any crop group, while this is in prospect for many crop groups within the EU.

3.4.3 Mexico, US and EU experience compared

The disharmony between the phytosanitary standards of Mexico and the US places significant non-tariff barriers to trade on seed companies as well as on growers who directly import seed. Compliance with Mexico's current regulations not only requires an investment in a seed treatment with limited phytosanitary capacity but may actually be contributing to the movement and use of inferior and/or diseased seed. As awareness of Mexico's regulatory dilemma spreads, international organic certifying bodies are responding by imposing more frequent and stricter inspections, increasing the risk that Mexican growers will lose the certification that allows them to produce for their main markets. State authorities within Mexico have engaged with the development of organic seed regulations but have failed to harmonize their respective efforts, resulting in a regulatory confusion that hinders rather than supports the evolution of the sector. Self-organizing networks have emerged to exploit the opportunities for production and trade within and across state borders but they operate in the margins of legality, dampening the future growth prospects of individual producers and the sector as a whole. An overview of Mexican organic seed system stakeholder category types, their level of influence and their key concerns are identified in Table 3.6.

Mexico also remains in default of its obligations as a signatory of the International Plant Protection Convention (IPPC) of the Food and Agriculture Organization (FAO). The IPPC regulations require partner countries/regions to uphold phytosanitary standards compliant with trade standards. Recognized national phytosanitary services under the IPPC include phytosanitary controls such as field inspections, seed testing, seed treatments, and phytosanitary certification on the basis that procedures are compliant with IPPC regulations. The organic seed rules and standards of most EU member states and the US comply with the IPPC standards (IPPC, 1952); Mexico remains one of only three countries in the world that requires a blanket chemical treatment under its phytosanitary regulation of imported seed.

Table 3.6 Mexican organic seed system stakeholder categories: their type, level of influence and key concerns 2007-2013 (n=15)

Stakeholder category	Stakeholder type[1]	Stakeholder level of influence[1]	Key concerns relating to the organic seed regulation, availability and the sector overall
Organic certifiers (n=3)	Key	High	Restrictive importation processes that result in lack of available certified organic seed for growers. Lack of 'fair process' in the development of federal organic regulation resulting in short public comment processes and re-drafting. Dependency of Mexico on foreign owned seed supply companies due to lack of domestic seed production capacity. Capacity for large-scale commercial organic growers to attain organic seed through questionable means, while smaller-scale growers have more limited genetic resources. Restrictive importation processes on organic seed entry contributes to the increase the illegal movement of potentially diseased seed.
Organic growers (n=5)	Primary	Low to High	Restrictive importation processes that result in lack of available seed variety needs and increases costs. Capacity for large-scale commercial organic growers to attain organic seed through questionable means, while smaller-scale growers have more limited genetic resources. Seed treatment requirements for organic seed importation increase costs for growers, potentially decrease seed viability and require long delays in seed acquisition process. Organic certifiers representing foreign export market locations hold Mexican organic growers to the same or higher standards than growers in export country e.g. US. And concern of high price for organic seed.
Seed companies (n=3)	Primary	Low to High	Restrictive importation processes that result in lack of available organic varieties for growers. Seed treatment requirements for organic seed importation increase costs for seed companies, potentially decrease seed viability and require long delays in movement of seed. Limited to no collated market data on organic production acreage and varietal requirements for organic growers. Capacity for commercial organic growers to attain seed importation exceptions, but professional seed companies cannot. Proposed Federal Organic Law includes confusing and inconsistent language on organic seed use allowances. Access to information on which organic certifiers are working in Mexico and the consistency in their inspection processes around organic seed are unclear.
Policy & legislative bodies (n=4)	Key	High	Ensure movement of potentially diseased seed is managed under rigorous phytosanitary laws and procedures. Development of clear federal guidelines for organic seed through the Mexican organic law. Develop bilateral agreements with the US and EU to mitigate the risk of movement of seed borne diseases and ensure that supply of organic seed to growers. Work with seed treatment companies to identify new organic products to mitigate potential phytosanitary issues. Develop procedures for growers and seed companies to import organic seed through a risk analysis.

Sources: Stakeholder identification process (columns 1-3, 2008); stakeholder interviews and participate observation (column 4, 2007-2013). [1]Stakeholder typology, definition and level of influence, see Table 3.2 Notes.

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The prospects for harmonization of organic policies and regulatory regimes between the EU and the US on the other hand are influenced by the fact that the EU acknowledges UPOV '91 (the International Convention for the Protection of New Plant Varieties, 1991) that governs and protects breeders' rights worldwide. The EU's interpretation of the Convention's requirements has led to a common catalogue containing each marketed variety in the EU that has met the criteria of Distinctness, Uniformity and Stability (DUS) and that has been tested to assess the variety's Value for Cultivation and Use (VCU). The compulsory registration and release system in the EU set up to provide protection to farmers against the potential purchase of poor quality seed of questionable varieties, makes illegal the marketing of seeds from unregistered varieties, including seeds grown and traded amongst farmers. In contrast the US' strict seed labelling and testing laws prescribe that seed packaging labels include information on the crop, variety name, percentage germination and purity. It does not enforce such strict varietal testing and registration procedures as in the EU case (Chable et al., 2012). In consequence of these differences, EU seed companies tend to handle fewer varieties than their US counterparts, who are able to release and market varieties more easily. The more limited assortment of registered varieties available to growers in the EU, combined with more rigorous organic seed standards, has forced organic growers to learn how to cope with a smaller, more regulated assortment than continued use of conventional untreated seed would allow (Bocci, 2009). By contrast, the organic sector in the US continues to operate under light regulatory guidance that has allowed more frequent and continued recourse to conventional untreated seed, in a context in which a large portfolio of varieties is available and new varieties are brought easily to market. These conditions in themselves impose significant barriers to development of a single US-wide organic database. In the absence of stronger state involvement in the development and enforcement of the regulatory framework, and a clearer allocation of authority and responsibility in partnership with the various self-organizing networks that have emerged, it seems likely that the US will not be able to deploy appropriate procedural and substantial regulatory instruments to compete on level terms with the EU organic sector for some time.

The regulatory differences that now exist between the EU and the US raises the question of how trade relations between the two continents might develop. For instance, what are the implications for trade in organic products if the EU achieves 100% organic seed for certain crops and the US does not? On the one hand, organic growers in the US would be able to produce crops at lower cost by not having to use organic seed and would have a broader genetic diversity to choose from. Growers in the EU would continue to pay more for their seed than their US counterparts but also have access to a greater variety of organic seed. Because the integrity of the organic value chain is what safeguards its market position, US growers might find an increasing number of markets closed to them.

There is no certainty that market-led competition would be sufficient to drive the regulatory regimes of the US, the EU and Mexico toward convergence (Ogus, 1995) and there is no overarching governance body that could compel harmonization. The stakeholders in our study nonetheless are attempting to formulate a better-coordinated response to the dilemmas highlighted in this article. The Mexican Seed Trade Association (AMSAC) in 2009 set up its own task force to identify legitimate ways for organic untreated seed to be imported into Mexico. The American Seed Trade Association's (ASTA) organic committee has been working with the Animal and Plant Health Inspection Service (APHIS) under the USDA to identify priority crops and potential seed-borne disease risks, testing procedures and treatments, as the basis for proposing to SAGARPA a risk assessment procedure that could secure entry of untreated seed of sufficient phytosanitary quality (ASTA, 2011), and form the basis of a bi-lateral trade agreement. The Dutch government in 2010 sent a broadly composed organic stakeholder delegation to Mexico to discuss trade-related issues and determine next steps. The Dutch stakeholders carried out a risk analysis of potential seed-borne diseases and treatments of the major organic export crops, in order to demonstrate to SAGARPA that Dutch seed intended for export to Mexico meets international phytosanitary standards and to develop a bilateral agreement for organic seed importation. A*d hoc* groups of growers and other stakeholders have met in both Mexico and the US to facilitate progress on these issues. Could multilateral institutions evolve to take into consideration the compatibility of global organic and phytosanitary standards? The signing of an organic equivalency arrangement between the EU and the US (15 Feb 2012) might offer new opportunities for resolving the tensions in organic seed regulation (Haumann, 2012), although phytosanitary issues fall outside this agreement and into the realm of the North American Plant Protection Organization (NAPPO).

An overview of the comparative progress that each jurisdiction has achieved in regards to instrument development as of the end of 2013 is outlined in Table 3.7.

Table 3.7 Instruments influencing the success of achieving 100% organic seed usage, and their status in the US, EU & Mexico[1] (2013).

Instruments influencing organic seed sector development	Stakeholders' perception of level of influence	US	EU	Mexico
National (or regional) Organic Standard	High	✓	✓	✓
Organic Seed Regulation	High	✓	✓	✓
Interpretive Seed Regulatory Guidelines	High	✓	✓	--
Organic Seed Database	High	In process	✓	--
Deadline for Compliance	High	--	✓	--
Derogation or Exception Process	Medium	--	✓	--
Expert Groups	Medium	--	✓	--
Annual National Reports	Medium	--	✓	--
Phytosanitary Restrictions	Medium	NA	NA	✓
Organic Seed Production Activities	Med-High	✓	✓	--
Organic Plant Breeding Program	Medium	✓	✓	--
Compulsory Variety Registration Process	Low	NA	✓	NA

Sources: Content analysis of stakeholder interviews (n=96) and document analysis and participant observation (2007-2013).

Notes:
✓ instrument is in force in particular region; In process – instrument is under development in particular region; -- instrument is not yet in process in particular region; NA – instrument does not apply to particular region
[1] Mexico organic regulations published October 29, 2013 with scheduled enforcement April 29, 2014.

3.5 Conclusions

Developing an organic seed market is an iterative process that requires time. Clear governance of the processes that lead towards regulatory closure has the potential to hasten the transition rate and increase the chances of success. Trade-distorting practices and procedures that have emerged in and between the regulatory regimes addressed in this article are weakening the prospects of achieving the goal of 100% organic seed usage in the organic sector's major markets. Stakeholders in the US are locked in an institutional impasse that perpetuates inconsistent regulatory interpretation and enforcement among stakeholders who have not been able to organize among themselves an effective form of meta-governance. In the EU, member state governments under the overall guidance of the EC have assumed responsibility for defining, enforcing, communicating and supporting a clearly-defined regulatory policy that is achieving significant if not yet universal progress through an effective form of meta-governance. A commitment to learning from experience and incremental adoption of emergent best practice is helping stakeholders to address the remaining challenges. In Mexico the net effect of disparate initiatives by stakeholders has been to restrict access to organic seed, increase production costs, encourage the illegal movement of potentially diseased seed, and increase the risks of loss of certification and the potential to trade with the US and the EU. The lack of harmonization among regulatory standards and enforcement in different jurisdictions is a problem that affects the organic agriculture sector worldwide. In the absence of change in regulatory performance, there are likely to be more violations of organic standards, increased underground trade in potentially diseased seed, and an overall lack of appropriate varieties for organic farmers.

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Chapter 4

Broccoli cultivar performance under organic and conventional management systems and implications for crop improvement

Broccoli cultivar performance under organic and conventional management systems and implications for crop improvement

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Abstract

To determine if present commercial broccoli cultivars meet the diverse needs of organic management systems such as adaptation to low nitrogen input, mechanical weed management and no chemical pesticide use, and to propose the selection environments for crop improvement for organic production, we compared horticultural trait performance of 23 broccoli (*Brassica oleracea* L. ssp. *italica*) cultivars (G) under two management (M) systems (organic and conventional) in two regions of the USA (Oregon and Maine), including spring and fall trials. In our trials, location and season had the largest effect on broccoli head weight with Oregon outperforming Maine and fall trials outperforming spring plantings. M main effects and G × M interactions were often small but G × M × E (location and season) were large. Cultivars with both greater head weight and stability under conventional conditions generally had high head weight and stability under organic growing conditions, although there were exceptions in cultivar rank between management systems. Larger genotypic variances and somewhat increased error variances observed in organic compared to conventional management systems led to repeatability for head weight and other horticultural traits that were similar or even higher in organic compared to conventional conditions. The ratio of correlated response (predicting performance under organic conditions when evaluated in conventional conditions) to direct response (predicted performance in organic when evaluated under organic conditions) for all traits was close to but less than 1.0 with the exception of bead uniformity. This would imply that in most cases, direct selection in an organic environment could result in a more rapid genetic gain than indirect selection in a conventional environment.

Keywords

Crop growth and development, other crop management, plant and environment interactions, sustainable agriculture, crop genetics

4.1 Introduction

Continued growth in demand in the organic sector has spurred an increase in organic crop production area in the United States (US) with over two million hectares in 2011 (Willer and Kilcher, 2012). The seed industry is challenged to satisfy the demands of organic agriculture, and often does not understand the special requirements of an unfamiliar agricultural system that is characterized by a greater diversity of requirements and criteria compared to conventional management (Mäder et al., 2002). Organic farms often differ substantially from non-organic counterparts in the complexity of their crop rotations, number of crops, production area, and market outlets. Organic farmers refrain from using synthetically derived chemical inputs and rely largely on biological self-regulatory processes to maintain yield leaving fewer tools to manage crop production environments (Messmer et al., 2012; Wolfe et al., 2008). Thus, organic farmers need cultivars that are stable across a range of conditions, rather than varieties that are high yielding under optimal conditions, but prone to lose that yield advantage due to disease susceptibility or an inability to utilize available nutrients efficiently (Lammerts van Bueren et al., 2002).

Broccoli, a significant crop in organic agriculture due to its market demand as well as its nutritional contribution to the USA diet (Verkerk et al., 2009), was grown on 743,088 production acres (300,717 ha) and generated U.S. $47,629,515 in sales in 2011 (USDA NASS, 2012). The main conventional fresh market broccoli production areas in the USA are California and Arizona. Broccoli cultivars in the USA have been bred primarily for the agro-climatic requirements of these regions. Secondary commercial broccoli producing areas are Maine and Oregon which are characteristically cool continental and cool Mediterranean type climates, respectively and differ significantly from those of California and Arizona. Organic production in the USA is comprised of small acreages scattered across the country in a broad range of environments to service local and diverse food markets (USDA ERS, 2008; USDA NASS, 2012). These producers are dependent on the commercial cultivar assortment available that were developed predominantly for California and Arizona. The production environments for Oregon and Maine may be more representative of the growing conditions faced by organic growers located at higher latitudes on the east and west coasts.

Broccoli producers in the USA need cultivars that exhibit heat tolerance, head stability, and uniform maturation in the field, while others are seeking extended harvest from side-shoot development (Heather et al., 1992; Farnham et al., 2011a,b; Myers et al., 2012). Some desired traits in organic management are shared with conventional producers, such as drought tolerance, insect and disease resistance and high yield. Other cultivar characteristics that are more important to organic producers include vigorous early growth, waxy leaves, ability to perform in soils with potentially low or fluctuating nutrient mineralization rates, and the ability to compete with weeds (Lammerts van Bueren et al., 2002; Lammerts van Bueren and Myers, 2012; Lammerts van Bueren et al., 2012). This is particularly important in broccoli due to its relatively high nitrogen requirement and shallow fine root system, which limits its ability to take up water and nutrients (Pasakdee et al., 2005; Sajeemas et al., 2006; Myers et al., 2012). Most studies investigating traits needed for organic farming systems have focussed on field crops such as cereals (e.g. Murphy et al., 2007; Löschenberger et al., 2008; Prsystalski, 2008; Wolfe et al., 2008; Annicchiarico et al., 2010; Reid et al., 2009, 2011; Kirk et al., 2012; Koutis et al., 2012), with few conducted on vegetable crops (Osman et al., 2008; Lammerts van Bueren et al., 2012; Myers et al., 2012). None of these studies have evaluated commercial cultivars of broccoli across multiple regions or seasons for agronomic performance under organic conditions.

Some studies comparing performance of genotypes in organic and conventional management systems have shown that for certain traits, cultivar rank varies between the two management systems (e.g. for winter wheat: Murphy et al., 2007; Baresel et al., 2008; Kirk et al., 2012; for lentils: Vlachostergios and Roupakias, 2008; for maize: Goldstein et al., 2012), while others have shown no differences in ranking performance (for maize: Lorenzana & Bernardo, 2008; for cereals: Prsystalski, 2008; for onions: Lammerts van Bueren et al., 2012). The results of these studies have profound implications for organic variety selection and breeding strategies and raise questions as to the need for cultivars to be bred with broad adaptability or specific adaptation for the requirements of regional organic management. Two different outcomes have been identified. First, some studies showed cultivar performance varies between management systems with significant differences in ranking, and in some cases low genetic correlations for lower heritability traits (e.g. Kirk et al., 2012; Murphy et al., 2007), resulting in the recommendation that cultivars intended for organic agriculture should be selected only under organic conditions. Secondly, other studies indicated that rankings in cultivar performance between management systems were similar with high genetic correlations, suggesting that breeding can be conducted under conventional conditions, with the caveat that advanced breeding lines can be tested under organic conditions for less heritable traits (e.g. Löschenberger et al., 2008; Lorenzano and Bernardo, 2008).

The vegetable seed industry has not developed broccoli cultivars selected for performance in organic management systems. As a result, a collective of public breeders and organic growers have attempted to develop bioregionally bred broccoli cultivars for organic systems (see Northern Organic Vegetable Improvement Collaborative; www. http://eorganic.info/NOVIC). In the interim, this leaves no choice but for organic growers to use cultivars bred under conventional conditions for many crops (Lammerts van Bueren and Myers, 2012). While seeds of some cultivars are produced under organic conditions, the majority of organic producers are using conventionally produced and post-harvest untreated seeds (Dillon and Hubbard, 2011). With the private sector becoming more interested in breeding for the organic market, many questions arise as to what are the highest priority traits, what is their heritability under variable, sometimes low-input organic growing conditions, and what is the most appropriate selection environment. In order to better understand how and whether broccoli cultivars perform differently under organic conditions and to determine whether selection under organic growing conditions is necessary to service the needs of growers in diverse regions, a large genotype × environment × management (G × E × M) study with 16 field trials was established in Oregon and Maine to evaluate a diverse set of cultivars, trialled under organic and conventional management. The study aimed to address the following questions: (1) do currently available broccoli cultivars perform differently for head weight and other horticulture traits in organic compared to conventional management systems in different regions and different seasons; (2) is the relative ranking of cultivars the same under organic and conventional conditions; (3) does heritability differ for certain traits under organic conditions compared to conventional conditions; and (4) under which growing conditions and in what locations would selection for broccoli cultivars for organic agriculture be most effective?

4.2 Material & methods

4.2.1 Plant Material

Twenty-three broccoli cultivars including open pollinated (OP) cultivars, inbred lines, and F_1 hybrids were included in the field trials Table 4.1**)**. These cultivars were selected to encompass varietal diversity in the targeted trial regions by organic and conventional growers as well as to represent diverse genotypes and phenotypes that differed in their year of commercial introduction and the commercial seed company of origin.

4.2.2 Field Trial Locations

The cultivars were grown paired organic and conventional fields at two U.S. locations [Maine (ME)-Monmouth (Latitude 44.2386°N, Longitude 70.0356°W; elevation 61 masl); Oregon (OR)-Corvallis (Latitude 44.5647°N, Longitude123.2608°W; elevation 76 masl)] in fall and spring during 2006-07 and 2007-08 growing season. The paired organic and conventional fields within each location had similar soil types (ME: Woodbridge Fine Sandy Loam; OR organic: Malabon Silty Clay Loam, OR conventional: Chenalis Silt Loam) and comparable climatic conditions (one degree day or less between sites and negligible precipitation differences). In ME both the conventional and organic trials were at University of Maine Cooperative Extension, Highmoor Farms Research Station and adjacent to one another. The OR conventional field trials were located at the Oregon State University Vegetable Research Station and at a local organically managed commercial farm within 5 km and with a comparable elevation (<50 foot) for the organic field trials. Both organic trial sites had been managed organically for over five years and were mature organically managed production systems at the onset of the study.

4.2.3 Field Design

Field trials consisted of the 23 broccoli cultivars arranged in a randomized complete block design with three replicates under both organic and conventional management at ME and OR locations during 2007-08 growing season. An individual treatment plot contained 36 plants that were planted in three rows of 12 plants at 46 cm equidistant spacing within and between rows. In 2006, only 18 of the 23 cultivar entries were established in the OR and ME field trials, and there were only two replicates in the OR organic 2006 field trial.

Field trials were conducted during three consecutive years (2006-2008) over two growing seasons that included two fall (2006, 2007) and two spring trials (2007, 2008).

Table 4.1 Overview of broccoli cultivars, showing origin and main characteristics, included in paired organic - conventional field trials 2006-2008.

Cultivar	Abbreviation	Origin	Cultivar type†	Date of market entry	Maturity classification‡
Arcadia	ARC	Sakata	F_1	1985	L
B1 10	B11	Rogers	F_1	1988	M
Batavia	BAT	Bejo	F_1	2001	M
Beaumont	BEA	Bejo	F_1	2003	L
Belstar	BEL	Bejo	F_1	1997	L
Diplomat	DIP	Sakata	F_1	2004	L
Early Green	EGR	Seeds of Change	OP	1985	E
Everest	EVE	Rogers	F_1	1988	E
Fiesta	FIE	Bejo	F_1	1992	L
Green Goliath	GRG	Burpee	F_1	1981	M
Green Magic	GRM	Sakata	F_1	2003	M
Gypsy	GYP	Sakata	F_1	2004	M
Imperial	IMP	Sakata	F_1	2005	L
Marathon	MAR	Sakata	F_1	1985	L
Maximo	MAX	Sakata	F_1	2004	L
Nutribud	NUT	Seeds of Change	OP	1990	E
OSU OP	OSU	Jim Myers, OSU	OP	2005	E
Packman	PAC	Petoseed	F_1	1983	E
Patriot	PAT	Sakata	F_1	1991	M
Patron	PAN	Sakata	F_1	2000	M
Premium Crop	PRC	Takii	F_1	1975	E
USVL 048	U48	Mark Farnham, USVL	Inbred	not released	L
USVL 093	U93	Mark Farnham, USVL	Inbred	not released	M

† Cultivar Type: F1: hybrid; OP: Open Pollinated; Inbred.
‡ Maturity Classification: E: Early; M: Mid; L: Late.

4.2.4 Field Management

The primary management differences between the organic and conventional field trial sites are outlined in Table 4.2, which describes the management system and regionally appropriate fertility application tools, and the applied supplemental irrigation for the area of study. Cropping history and rotation are outlined per location. Mechanical and hand weed management were practiced for all sites. Baseline soil sampling for basic soil characteristics was performed as subsampling within plots, per trial site location prior to the start of each seasonal trial at the time of trial planting. Soils were analysed for pH, labile (available) N (ppm) and Particulate Organic Matter (POM), a measure of longer term available nitrogen taken pre-fertilization (N/kg soil). There were no pest control applications in organic fields. In the conventional trials diazinon was used for control of radish maggot and carbaryl (Sevin) was used for flea beetle control.

4.2.5 Weather

Weather data was collected from the two regional meteorological stations relative to the field experiments in Maine and Oregon to include maximum /minimum temperatures and precipitation per day for each trial duration. Growing degree days (GDD) were calculated per trial by taking the average of the daily maximum and minimum temperatures minus the base temperature for broccoli (4.4°C) across each trial period (Maynard and Hochmuth, 2007).

4.2.6 Field Data Collection

As plots approached maturity they were evaluated three times a week for broccoli heads that had reached commercial market maturity (approximately 10 to 12 cm in diameter for most of the cultivars while retaining firmness as an indicator of maturity) and were evaluated for quality traits. Field quality evaluations were measured on a 1 to 9 ordinal scale. Traits included head shape (1 = flat shape; 9 = high dome shape), head surface (1 = very uneven; 9 = smooth head), head color (1 = pale green; 9 = dark green), bead size (1 = large beads; 9 = small beads), bead uniformity (1 = not uniform; 9 = excellent uniformity), plant height (mean measurement of height of plant from base of stalk to tips of leaves in cm) and an overall plot quality rating (1 = poor overall performance; 9 = excellent overall performance) based on overall appearance, head quality and uniformity of the entire plot. Five broccoli heads were trimmed to a uniform length of 18 cm from the crown to stalk at maturity. For each of the five heads, head weight (g) and head diameter (cm) was measured. To determine average head weight (HW) the mean was taken of the sum of the five individual head weight measurements. Head diameter was measured on and averaged for five randomly harvested heads from each plot. Hollow stem was evaluated on a 1 to 9 scale (1 = many hollow stems to 9 = no hollow stems). Maturity was measured based on days to harvest (DTH) from the date seedlings were transplanted.

Table 4.2 Description of agronomic and environmental factors of the trial locations with paired organically and conventionally managed fields, 2006-2008.

Location	Season / Year	Planting date	Harvest end date	Preceeding crop	Field Management			
					Organic fertilizer		Conventional fertilizer	
					Type	Application	Type ($N-P_2O_5-K_2O$)	Application
Oregon	Fall 2006	28/Jul	13/Oct	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Fall 2006	1/Aug	19/Oct	Cucurbits	Manure Compost	26,900 kg ha	10-10- 10	560 kg/ha
Oregon	Spring 2007	10/May	23/Jul	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Spring 2007	31/May	22/Aug	Cucurbits	Manure Compost	26,900 kg ha	10-10- 10	560 kg/ha
Oregon	Fall 2007	7/Aug	20/Nov	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Fall 2007	14/Aug	20/Nov	Cucurbits	Manure Compost	26,900 kg ha	10-10- 10	560 kg/ha
Oregon	Spring 2008	14/May	21/Jul	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Spring 2008	18/Jun	10/Nov	Cucurbits	Manure Compost	26,900 kg ha	10-10- 10	560 kg/ha

Table 4.2 Description of agronomic and environmental factors of the trial locations with paired organically and conventionally managed fields, 2006-2008 (continued).

		Field Management		Soils						Climate			
Location	Season / Year	Supplemental Irrigation (mm)		pH		g POM-N/kg soil†		Available N (ppm)‡		Average Temp (°C)		Growing Degree Days¶	Precipitation§ (mm)
		Org	Conv	Org	Conv	Org	Conv	Org	Conv	Max	Min		
Oregon	Fall 2006	170.1	171.5	6.7	6.1	0.53	0.07	1.17	1.22	25.5	8.2	1741	48.3
Maine	Fall 2006	None	None	6.7	5.7	0.44	0.54	1.43	1.63	20.8	10.4	1611	279.4
Oregon	Spring 2007	131.9	135.4	6.4	6.5	0.35	0.06	1.14	1.48	24.2	9.0	1639	35.6
Maine	Spring 2007	None	None	6.2	5.4	0.48	0.50	1.83	1.99	24.8	13.6	2212	167.6
Oregon	Fall 2007	96.6	101.6	6.7	6.3	0.51	0.16	0.92	1.37	20.8	7.9	1823	274.3
Maine	Fall 2007	None	None	6.2	5.4	0.44	0.44	1.16	1.24	18.0	7.6	1573	370.8
Oregon	Spring 2008	157.2	156.5	6.9	6.4	0.64	0.11	1.55	1.75	24.1	9.2	1521	35.6
Maine	Spring 2008	None	None	6.4	5.5	0.47	0.43	1.53	1.53	21.0	11.1	3059	581.7

† g POM-N/kg soil: Particulate Organic Matter, a measure of longer term available nitrogen taken pre-fertilization.
‡ Available N (ppm): immediately available nitrogen at time of trial planting taken pre-fertilization.
¶ Growing Degree Days (GDD): average daily maximum and minimum temperatures across each trial period divided by base temperature for broccoli growth (4.4oC).
§ Total Precipitation during trial period per location, season not including irrigation.

4.2.7 Statistical Analysis

Various linear mixed models were used for the analysis of trait variation. Our approach was comparable to that of Lorenzana and Bernardo (2008). All linear mixed models were fitted in GenStat 15 (VSNi, 2012). The models can be formulated informally as:

Response = environment + replicate within environment + genotype + genotype by environment interaction + error

More formally we can write the general form of our mixed models as

$$y = E + R(E) + G + G \times E + e,$$

with the individual terms in the formal model corresponding to those in the informal model just above it. Depending on the analysis, the terms included in E (the environments) varied. For the most general analysis, E contained all main effects and interactions of Season (S), Location (L) and Management (M). Thus, in that case

$$E = S + L + S \times L + M + S \times M + L \times M + S \times L \times M \text{ and } G \times E = G \times S + G \times L + G \times S \times L + G \times M + G \times S \times M + G \times L \times M + G \times S \times L \times M,$$

where the combination of S, L and M defined individual trials. The term *S* (Season) contained a combination of year (2006, 2007, 2008) and season within year (spring, fall). Effectively, there were only four year by season within year combinations included: fall 2006, spring 2007, fall 2007, spring 2008). For convenience, in our general model, we fitted one factor 'Season' to cover the four trialing periods. However, other model formulations are possible. For example, we can define a factor 'Year' with two levels (level 1 = fall 2006 + spring 2007; level 2 = fall 2007 + spring 2008) and factor 'Season' with two levels (spring, fall). The main effects of these factors 'Year' and 'Season' plus their interaction covers the same variation as the original factor 'Season' with four levels. We used this second formulation in analysis per location to obtain a more fine grained interpretation of the variation.

All terms were assumed to be normally distributed with a proper variance. For ease of interpretation and to allow straightforward comparisons between traits, the variance components were reported as coefficients of variation, which is standard deviations as a percentage of the trait mean, i.e.,

$$CV=100\sqrt{V}\,/\,\bar{x},$$

with V the variance for a particular model term and $\overline{xx}$ the trait mean. Repeatability (analogous to broad sense heritability, but for unrelated genotypes) was calculated from the variance components as:

$$H = V_G \,/\, (V_G + V_{GL}/nL + V_{GS}/nS + V_{GM}/nM + V_{GLS}/(nL.nS) + V_{GLM}/(nL.nM) + V_{GSM}/(nS.nM) + V_{GLSM}/(nL.nS.nM) + V_e/(nL.nS.nM.nR),$$

where the variance components correspond to the terms in the mixed model above. The terms *nL, nS, nM* and *nR* represent the number of locations (2: Maine and Oregon), number of 'seasons' (4: Fall 2006, Spring 2007, Fall 2007, Spring 2008), management (2; organic and conventional), and replicates (2 or 3).

The above model and repeatability was simplified when performing analyses per location, or per management regime. For the first situation, analysis for Oregon and Maine separately, we omitted all terms that contain L. For the second situation, analysis for organic and conventional management separately, we omitted all terms containing M.

To calculate genotypic means across all conditions, the general model defined above was used, but the genotypic main effect was assumed to be fixed instead of random. Similarly, genotypic means per location and management system were obtained by assuming fixed genotypic main effects as well as the relevant environmental effects (L, M) and their interactions (G × L, G × M). These means were used to calculate correlations and for box plots and biplots (procedure *dbiplot* in GenStat). Pairwise comparisons between means were performed using GenStat procedure *VMCOMPARISON*. Correlations on the basis of genotypic means were referred to as genetic correlations.

To study correlations between conventional and organic conditions at the fine grained level of location by trialing period combinations, we used Spearman's rank correlations, because we were especially interested in rank changes.

A further comparison of conventional and organic conditions was performed by evaluating stability of performance versus mean performance for the set of varieties. Genotypic (in)stabilities under organic and conventional conditions were calculated as the variance for individual genotypes across all trials in the system.

Correlated Response theory (Falconer and Mackay, 1996) was used to assess the feasibility of selection for organic conditions (the target environment) under conventional conditions (the selection environment). The ratio of correlated response (for organic conditions using conventional conditions), CR, to direct response (for organic conditions in organic conditions), DR, can be used to decide whether it is possible to use selection under conventional conditions for improvement in organic systems; it was calculated as the product of the genetic correlation between organic and conventional systems (r_G) and the ratio of the roots of conventional and organic repeatabilities (and respectively):

$$CR/DR = r_G \, H_C \, / \, H_O.$$

Ratios smaller than 1 indicate that it is better to select under organic conditions when the aim is to improve the performance in organic conditions.

4.3 Results

4.3.1 Partitioning of variance components

We fitted variance components models for all traits, where we report these variance components as coefficients of variation (CV's). We do not report the significance of the variance components as almost all components were found to be significant by likelihood ratio tests, even for components that were close to zero. The information on the variation is best considered through the magnitude of the variance components and not through significance tests.

Table 4.3 Partitioning of variance components presented as coefficients of variance (%) for horticulture traits of 23 broccoli cultivars grown across eight pair combinations of location (Maine/Oregon), season (Fall/Spring) and management system (Conventional/Organic), 2006-2008.

	Location (L)	Season (S)	Management system (M)	L x S	L x M	S x M	L x S x M	L x S x M x Rep (R)	Genotype (G)
Head Weight (g)	17.58	34.34	1.52	17.45	0.01	0.01	10.71	4.33	12.91
Head Diameter (cm)	0.01	9.86	0.00	12.81	0.01	0.00	8.67	3.05	4.19
Maturity[†]	10.37	0.00	0.00	22.60	0.00	4.14	3.46	1.64	6.79
Head Shape[‡]	1.59	13.31	0.00	0.01	0.01	0.01	7.84	2.02	14.00
Head Surface[§]	0.01	0.01	1.71	15.60	2.15	0.01	4.59	2.56	5.53
Head Color[¶]	9.63	0.01	0.01	14.55	0.01	0.01	3.03	1.93	4.68
Bead Size[#]	0.00	16.47	0.02	3.85	0.01	3.18	3.39	0.82	13.65
Bead Uniformity[††]	1.09	0.01	2.38	12.87	2.69	0.01	1.93	1.45	2.76
Hollow Stem[‡‡]	20.63	22.39	0.01	12.82	0.01	2.90	7.39	6.59	4.78
Plant Height (cm)	30.08	0.00	1.24	26.88	0.01	0.01	5.68	2.96	4.50
Overall Quality[§§]	11.99	0.01	0.01	11.40	0.01	0.01	4.26	5.02	12.12

Table 4.3 Partitioning of variance components presented as coefficients of variance (%) for horticulture traits of 23 broccoli cultivars grown across eight pair combinations of location (Maine/Oregon), season (Fall/Spring) and management system (Conventional/Organic), 2006-2008. (continued)

	G x L	G x S	G x M	G x L x S	G x L x M	G x S x M	G x L x S x M	Residual
Head Weight (g)	13.72	9.03	4.25	7.56	0.01	0.01	10.70	13.87
Head Diameter (cm)	7.42	4.04	2.61	7.01	0.01	0.00	4.96	8.79
Maturity†	4.32	3.81	0.00	8.42	0.22	1.39	2.02	3.87
Head Shape‡	0.01	0.00	0.01	15.14	2.92	0.01	10.64	12.17
Head Surface§	7.40	0.76	0.00	14.72	0.01	0.02	9.19	13.55
Head Color¶	6.88	0.00	0.11	15.85	0.00	3.64	10.91	15.02
Bead Size#	1.51	0.01	3.86	17.27	0.01	0.01	15.10	13.05
Bead Uniformity††	3.40	0.00	0.01	13.01	0.01	0.01	11.52	13.98
Hollow Stem‡‡	10.86	0.00	0.01	11.88	0.01	0.01	12.05	17.83
Plant Height (cm)	9.62	9.70	0.00	7.28	0.01	6.03	2.05	8.12
Overall Quality§§	11.09	5.24	0.01	14.57	4.69	2.02	11.06	15.09

†Maturity: days from transplant to harvest (DTH);
‡Head Shape: (1-9 ranking with 1 = flat shape; 9 = high dome shape);
§Head Surface: (1-9 ranking with 1 = very uneven; 9 = smooth head);
¶Head Color: (1-9 ranking with 1 = pale green; 9 = dark green);
#Bead Size: (1-9 ranking with 1 = large beads; 9 = small beads);
††Bead Uniformity: (1-9 ranking with 1 = not uniform; 9 = excellent uniformity);
‡‡Hollow Stem: (1-9 ranking with 1 = many hollow stem; 9 = no hollow stem);
§§Overall quality: (1-9 ranking with 1 = poor overall performance; 9 = excellent overall performance).

For head weight across all trials in both locations (L, Oregon versus Maine), we found that at the environmental level Season (four trialing periods) described the largest portion of the total variance (34%), followed by L with a CV of 18% (Table 4.3**).** Management system (M, Organic versus Conventional) main effect was small (< 2%), but the three-way interaction (L×S×M) had a CV of about 11%. Genotype main effect (G) was 13%, and genotype interactions with L and S (14% and 9%, respectively), were larger sources of variation for head weight than G×M at 4%. The CV for the four-way interaction G×L×S×M was 11%. This large interaction was due to trial specific effects, because attempts to reduce the complexity of this interaction by ignoring years (so focussing on spring versus fall) or ignoring season within year (so focussing on year itself) failed (results not shown).

For days to maturity, the L×S interaction accounted for the largest source of variation (23%) followed by L and G main effects of 10 and 7%, and the three-way interaction G×L×S (8%). M main effect and its interaction with G was absent (0%), and other two- and three-way interactions were small. The largest source of variation for bead size was G as well as three- and four-way interactions (G×L×S and G×L×S×M). There was no L main effect for this trait. For the overall quality rating, sources of variation were distributed among G and L main effects and G, L and S interactions. For eight of 11 traits analysed the contribution of variation described by four-way interactions compared to other interaction terms in the model was relatively large. For this reason, we performed a partitioning of variance component analysis at each location and season within location to analyse the contribution of management system to variation at these trial levels (data not shown).

We performed variance components analyses for the separate locations Maine and Oregon to more closely examine the partitioning of the variation conditional on location. At the trial location level (Maine and Oregon), the partitioning of variance for head weight showed the same pattern as across all trials; trialing period was important as S contributed to the largest source of variation, followed by Y×S interactions (data not shown). For other traits such as bead size, again trialing period effects as S and Y effects were most important. For maturity, the Y effect in Maine accounted for the largest source of variation, but not in Oregon. With the higher means for head weight in Oregon (347 g) compared to Maine

(261 g) the genotypic effect for most traits was larger in Oregon compared to Maine. As with the overall analysis, the M main effect was zero or small. Among M interactions the largest source of variation was associated with G×Y×S×M in both Maine and Oregon, with variances generally larger in Oregon (data not shown). When trials were analysed by S and L separately, M main effect was also not significant for head weight and most traits; only in Maine Fall did the M have a large effect on plant height (data not shown). When trials were analysed at the paired trial level per L, S, and Y level, we found that the G × M interaction was often significant (53 of 72 interactions (74%) for nine traits x eight environments). For head weight, seven of eight trials showed significant G × M interaction, while all additional traits also showed significance in G × M interaction in five to seven of the eight trial combinations (data not shown).

4.3.2 Comparison of head weight and other horticulture traits over the environments

Location, Season, Management System Overall

Results across all S, L, and M system trials for Oregon showed a significantly higher overall head weight compared to Maine trials, (Figure 4.1a). Mean head weight of broccoli cultivars in the Fall trials was significantly higher than in the Spring trials for all L, S and M combinations (Fall 397 g; Spring 214 g), (Figure 4.1b). In the Fall, the magnitude of the difference in head weight between Oregon (474 g) and Maine (321 g) were much larger than the difference in Spring (Oregon 225 g versus Maine 202 g). Organically produced broccoli (head weight overall 315 g) performed as well as conventionally produced broccoli (296 g) (Figure 4.1c). Head weight across all organic trials had a wider range and greater variance among cultivars compared to conventional trials. An overview of location and season mean head weight are presented in Figure 4.1d.

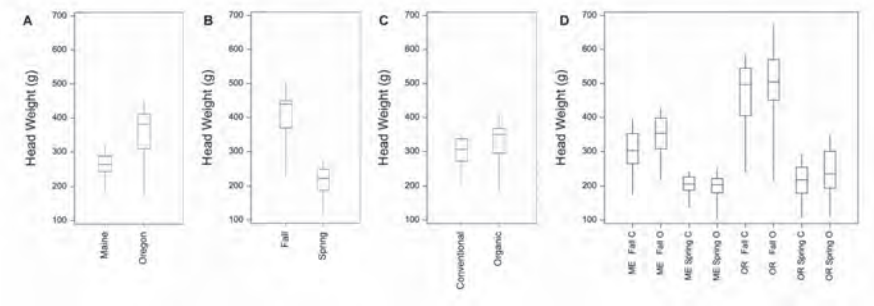

Figure 4.1 Comparison of broccoli cultivars for average head weight (g). A. grown across all trials in two trial locations (Maine & Oregon) (2006-2008). B. between seasons (Fall/Spring) across trials (2006-2008). C. between two management systems (Organic versus Conventional) across all trial locations and seasons (2006-2008), and D. comparing performance in (Maine/Oregon) across both seasons (Fall/Spring) and management systems (conventional/organic) and years (2006-2008).

Horticulture trait means

Head diameter demonstrated the same pattern as head weight with broccoli from Oregon Fall trials having significantly larger head size than those from Spring trials (Table 4.4). Days to maturity for broccoli cultivars grown in Fall trials in Oregon (average 76 days) were significantly longer than in Spring (average 58 days) trials, whereas in Maine the days to maturity for Fall (74 days) were comparable to Oregon while the results of the Spring trials for Maine (91 days) were longer than Oregon. Bead size ranking for Fall trials averaged 5.2 compared to 6.4 in Spring trials in both locations, indicating larger beads were observed in Fall trials compared to Spring in both Locations and Management systems. The same pattern was demonstrated for bead uniformity. Hollow stem had the highest incidence in Oregon Fall, while Oregon Spring and Maine trials were comparable. Plant height for broccoli cultivars grown in Oregon Fall trials were significantly taller than the Oregon Spring trials and Maine trials across Seasons, which agrees with the Oregon Fall head weight results (Table 4.4).

Table 4.4 Trait means of plant and head characteristics of 23 broccoli cultivars grown across four pair combinations of location (Maine/Oregon), season (Fall/Spring) two-years combined and management system (Conventional/Organic), 2006-2008[§§].

Horticulture Trait	Maine								Overall trait mean
	Fall				Spring				
	C	SE	O	SE	C	SE	O	SE	
Head Weight (g)	303.9 d	4.6	335.9 e	5.2	203.4 ab	3.8	198.1 a	3.9	260.3
Head Diameter (cm)	11.6 c	0.1	12.8 e	0.1	12.2 d	0.1	12.0 d	0.1	12.1
Maturity[†]	76.9 e	0.6	71.7 c	0.4	89.9 f	0.9	92.9 g	0.8	82.9
Head Shape[‡]	5.4 b	0.1	4.9 a	0.1	5.4 c	0.1	5.4 b	0.1	5.3
Head Surface[§]	5.2 b	0.1	5.2 a	0.1	5.0 a	0.1	4.9 a	0.1	5.1
Head Color[¶]	6.6 d	0.1	6.3 c	0.1	5.7 c	0.1	5.9 c	0.1	6.1
Bead Size[#]	5.2 a	0.1	5.3 de	0.1	6.5 de	0.1	6.7 e	0.1	5.9
Bead Uniformity[††]	6.4 e	0.1	6.2 de	0.1	6.0 c	0.1	6.0 c	0.1	6.1
Hollow Stem[‡‡]	7.9 c	0.2	7.3 b	0.1	8.4 d	0.1	8.8 e	0.0	8.1
Plant Height (cm)	28.7 a	0.3	36.7 b	0.3	38.4 c	0.3	39.6 d	0.3	35.8
Overall Quality[§§]	5.6 d	0.1	6.0 e	0.1	5.7 d	0.1	5.6 d	0.1	5.7

Horticulture Trait	Oregon								Overall trait mean
	Fall				Spring				
	C	SE	O	SE	C	SE	O	SE	
Head Weight (g)	462.5 f	8.3	478.8 f	8.5	212.4 b	3.3	238.7 c	4.5	348.1
Head Diameter (cm)	14.6 f	0.2	14.8 f	0.2	10.5 a	0.1	10.8 b	0.1	12.7
Maturity[†]	76.7 e	0.4	75.3 d	0.4	56.5 a	0.1	58.6 a	0.1	66.7
Head Shape[‡]	4.8 a	0.1	4.7 a	0.1	5.3 b	0.1	5.2 b	0.1	5.0
Head Surface[§]	5.8 c	0.1	5.2 b	0.1	5.6 c	0.1	5.2 ab	0.1	5.4
Head Color[¶]	4.8 a	0.1	5.1 ab	0.2	5.4 b	0.1	5.3 b	0.1	5.2
Bead Size[#]	5.0 a	0.2	5.7 b	0.2	6.3 cd	0.1	6.1 c	0.1	5.8
Bead Uniformity[††]	5.1 b	0.2	4.4 a	0.2	6.4 e	0.1	6.0 cd	0.1	5.5
Hollow Stem[‡‡]	4.3 a	0.2	4.6 a	0.3	7.8 c	0.1	7.6 bc	0.2	6.1
Plant Height (cm)	72.7 g	0.7	70.2 g	1.3	44.6 e	0.4	48.1 f	0.4	58.9
Overall Quality[§§]	5.2 c	0.1	4.9 bc	0.1	4.6 ab	0.1	4.3 a	0.1	4.7

[†]Maturity: days from transplant to harvest (DTH); [‡]Head Shape: (1-9 ranking with 1 = flat shape; 9 = high dome shape); [§]Head Surface: (1-9 ranking with 1 = very uneven; 9 = smooth head); [¶]Head Color: (1-9 ranking with 1 = pale green; 9 = dark green); [#]Bead Size: (1-9 ranking with 1 = large beads; 9 = small beads); [††]Bead Uniformity: (1-9 ranking with 1 = not uniform; 9 = excellent uniformity); [‡‡]Hollow Stem: (1-9 ranking with 1 = many hollow stem; 9 = no hollow stem); [§§]Overall quality: (1-9 ranking with 1 = poor overall performance; 9 = excellent overall performance).

[§§] Means followed by the same letter in the same row are not significantly different at the $P < 0.05$ level.

4.3.3 Repeatability and genetic correlations

The repeatabilities for head weight, head diameter, hollow stem and overall quality ratings were higher for organic compared to conventional across trials (Table 4.5). For maturity, head color and head surface, repeatability levels in organic were equal or near equal to those in conventional. For head shape, bead size, bead uniformity and plant height repeatabilities were higher in conventional compared to organic. The genetic correlations between organic and conventional for most traits were generally high with the exception of bead uniformity, which showed the lowest genetic correlation (0.66). The ratio of correlated response to direct response for all traits was below 1 with the exception again of bead uniformity. When repeatabilities were calculated for F_1 hybrids only, repeatabilities and correlated response were smaller in most cases, but the trends were similar (with the exception of overall and head diameter).

4.3.4 Comparison of cultivar rankings for head weight and other traits per cultivar

Spearman's Rank Correlation

We wanted to investigate the comparison between organic and conventional at the most fine grained level and looked at correlations between the genotypic means for the eight location by trialing period combinations. For head weight, conventional and organic genotypic means were highly correlated. However, when the F_1 hybrid genotype class was analyzed separately (minus the OPs and inbred lines), most M pairs were not significant, indicating change in rank between M in any given Y, L, S. Genotype rank was significantly correlated between management systems in Maine Spring 2008, and Oregon Spring 2007 and 2008 but genotypic rank was not correlated in fall environments (Table 4.6).

Table 4.5 Repeatabilities (H), genetic correlations (r_A) and ratio of correlated response to direct response (CR_{org}/R_{org}) for broccoli horticulture traits comparing organic versus conventional management systems over all trial season/location combinations (all cultivars and F_1 hybrids only), 2006-2008.

	All cultivars (F_1s, OPs and inbreds)				F1 hybrids only			
	Repeatability (H)		r_A[¶¶]	CR_{org}/R_{org}	Repeatability (H)		r_A[¶¶]	CR_{org}/R_{org}
	C	O			C	O		
Head Weight (g)	0.78	0.85	0.91	0.87	0.60	0.68	0.73	0.69
Head Diameter (cm)	0.61	0.75	0.81	0.73	0.14	0.00	0.22	>1
Maturity[†]	0.79	0.80	0.98	0.97	0.81	0.86	0.98	0.95
Head Shape[‡]	0.47	0.37	0.73	0.83	0.72	0.69	0.87	0.89
Head Surface[§]	0.81	0.77	0.90	0.92	0.46	0.53	0.85	0.79
Head Color[¶]	0.51	0.48	0.83	0.85	0.29	0.46	0.74	0.59
Bead Size[#]	0.77	0.67	0.82	0.88	0.69	0.64	0.71	0.73
Bead Uniformity[††]	0.24	0.03	0.66	>1	0.09	0.23	0.65	0.42
Hollow Stem[‡‡]	0.40	0.57	0.84	0.70	0.49	0.67	0.88	0.75
Plant Height (cm)	0.77	0.69	0.93	0.98	0.72	0.65	0.95	0.99
Overall Quality[§§]	0.72	0.77	0.89	0.86	0.17	0.48	0.63	0.38

[†]Maturity: days from transplant to harvest (DTH).
[‡]Head Shape: (1-9 ranking with 1 = flat shape; 9 = high dome shape).
[§]Head Surface: (1-9 ranking with 1 = very uneven; 9 = smooth head).
[¶]Head Color: (1-9 ranking with 1 = pale green; 9 = dark green).
[#]Bead Size: (1-9 ranking with 1 = large beads; 9 = small beads).
[††]Bead Uniformity: (1-9 ranking with 1 = not uniform; 9 = excellent uniformity).
[‡‡]Hollow Stem: (1-9 ranking with 1 = many hollow stem; 9 = no hollow stem).
[§§]Overall quality: (1-9 ranking with 1 = poor overall performance; 9 = excellent overall performance).
[¶¶]r_A: average genetic correlation between conventional and organic production systems across locations.

Table 4.6 Spearman's rank correlation for head weight between paired conventional and organic sites within a location, season and year for the F_1 hybrid subset (n=18) of broccoli cultivars.

Year	Maine			Oregon		
	Fall	Spring		Fall	Spring	
2006	0.51			0.42		
2007	0.24	0.15		0.33	0.69	***
2008		0.69	***		0.54	*

* Significant at P < 0.05; *** significant at P < 0.001.

We visualized the rank correlations of the individual cultivars between conventional and organic conditions at the location by season trial level in Table 4.7a and b**.** The ranking of cultivars for head weight between Locations and Seasons differed by cultivar, cultivar type and maturity classification. Between the paired management system trials, some cultivars showed the same ranking while others varied in rank. The open pollinated cultivars consistently ranked at the bottom, while a group of F_1 cultivars displayed the greatest head weight across Management systems.

In the Maine trials all cultivars from organic trials outperformed those grown in conventional trials for head weight. In the Fall trials four of the five top ranking cultivars were the same between the organic and conventional trials ('Packman', 'Fiesta', 'Everest' and 'Green Goliath'), see Table 4.7a**.** 'Green Magic' was the top performing cultivar in organic but ranked 10th in conventional with a significant head weight difference between Management systems. In the Maine organic Spring trials there were more rank changes. The top two performing cultivars ('Fiesta' and 'Green Magic'), were the 7th and 8th ranked cultivars in conventional, while 'Imperial' ranked 3rd in both systems. The best performing cultivars under conventional ('Marathon', 'Nutribud', 'Early Green') did not perform comparatively well under organic (rank 11, 12 and 18, respectively)

The results for the Oregon Fall trials for head weight indicated that three of the five top performing varieties in both organic and conventional systems were the same: 'Green Magic', 'Maximo' and 'Batavia'), see Table 4.7b. All three cultivars produced higher yields in the organic trials compared to the conventionally paired trial. 'Imperial' ranked #1 in conventional, while it ranked #6 in organic, and similar to the Maine trials, 'Marathon' ranked high in Oregon organic (#4) and much lower (#13) in conventional (significantly different than top two cultivars, 'Imperial' and 'Green Magic'), with a significant head weight difference in cultivar performance between management systems. Conventional 5th and 6th ranked cultivars, 'Belstar' and 'B1 10' dropped in rank to 9th and 11th in organic, respectively (significantly different from 'Green Magic', but not other cultivars in organic).

Table 4.7a Ranking of average head weight (g) of 23 cultivars of broccoli grown under organic (O) and conventional (C) conditions in Maine in two seasons (Fall and Spring) from 2006-2008 (Top 5 ranking per management system and rank performance in inverse system).

Maine											
Fall 2006-2007						Spring 2007-2008					
Rank	Cultivar	C	O	Culivar	Rank	Rank	Cultivar	C	O	Cultivar	Rank
1	Packman	369.1	431.6	Green Magic*	1	1	Marathon	243.2	251.2	Fiesta	1
2	Fiesta	365.8	424.5	Packman	2	2	Nutribud	243.0	251.0	Green Magic	2
3	Everest	360.6	400.8	Fiesta	3	3	Imperial	240.6	247.1	Imperial	3
4	Green Goliath	353.2	398.6	Everest	4	4	Early Green	240.0	240.5	B1 10	4
5	Belstar	346.4	397.7	Green Goliath	5	5	Batavia	232.2	228.1	Belstar	5
6	Batavia	344.1	392.9	Batavia	6	6	Belstar	226.6	222.0	Batavia	6
7	Diplomat	335.9	368.4	Belstar	7	7	Fiesta	224.2	217.0	Arcadia	7
8	Patriot	334.6	367.7	B1 10	8	8	Green Magic	219.1	212.1	Gypsy	8
9	B1 10	324.9	361.7	Marathon	9	9	B1 10	218.7	207.4	Green Goliath	9
10	Green Magic	324.5	352.9	Maximo	10	10	Maximo	215.0	205.3	Maximo	10
11	Nutribud	316.6	352.8	Patron	11	11	Premium Crop	211.5	204.9	Marathon	11
12	Patron	309.2	333.6	Patriot	12	12	OSU OP	202.6	202.5	Nutribud	12
13	Marathon	302.1	332.8	Early Green	13	13	Patriot	200.3	201.7	Patriot	13
14	Maximo	291.9	324.9	Premium Crop	14	14	Green Goliath	199.1	195.3	OSU OP	14
15	Gypsy	272.6	322.0	Gypsy	15	15	Packman	190.3	191.1	Premium Crop	15
16	Premium Crop	270.8	317.6	Imperial	16	16	Beaumont	189.1	185.5	Beaumont	16
17	Early Green	264.8	307.5	Arcadia	17	17	Diplomat	187.5	180.0	Diplomat	17
18	Imperial	253.4	298.5	Nutribud	18	18	Everest	182.3	167.4	Early Green	18
19	Arcadia	252.4	288.5	Diplomat	19	19	Arcadia	180.5	167.1	Packman	19
20	USVL 093	232.2	265.5	USVL 048	20	20	Gypsy	177.6	166.3	Patron	20
21	OSU OP	211.7	258.0	Beaumont	21	21	Patron	163.9	157.0	Everest	21
22	USVL 048	200.3	219.3	USVL 093	22	22	USVL 093	156.5	146.8	USVL 048	22
23	Beaumont	110.7	218.3	OSU OP	23	23	USVL 048	139.0	103.3	USVL 093	23

* Significant at $P < 0.05$ level.

Table 4.7b Ranking of average head weight (g) of 23 cultivars of broccoli grown under organic (O) and conventional (C) conditions in Oregon in two seasons (Fall and Spring) from 2006-2008 (Top 5 ranking per management system and rank performance in inverse system).

Oregon											
Fall 2006-2007						Spring 2007-2008					
Rank	Cultivar	C	O	Cultivar	Rank	Rank	Cultivar	C	O	Cultivar	Rank
1	Imperial	604.6	685.8	Green Magic	1	1	Batavia	292.7	348.3	Batavia	1
2	Green Magic	585.4	636.4	Maximo	2	2	Green Goliath	271.9	321.1	Green Goliath	2
3	Maximo	580.7	624.9	Batavia	3	3	Belstar	270.2	311.2	Maximo	3
4	Batavia	571.6	608.0	Marathon*	4	4	B1 10	265.2	308.6	Marathon	4
5	B1 10	554.4	565.7	Patron	5	5	Maximo	264.8	305.0	Fiesta	5
6	Belstar	552.8	561.1	Imperial	6	6	Imperial	259.8	300.9	Gypsy	6
7	Green Goliath	535.5	559.5	Green Goliath	7	7	Fiesta	241.0	299.3	Patron	7
8	Everest	522.2	538.8	B1 10	8	8	USVL 048	240.0	290.5	Patriot	8
9	Patron	521.7	526.6	Belstar	9	9	Patron	235.2	290.0	B1 10	9
10	Arcadia	499.6	517.7	Beaumont	10	10	Gypsy	231.5	289.2	Green Magic	10
11	Gypsy	493.7	516.7	Gypsy	11	11	Patriot	218.5	284.7	Belstar	11
12	Diplomat	490.7	494.5	Everest	12	12	Marathon	217.2	235.4	Arcadia	12
13	Marathon	480.0	486.2	Packman	13	13	Beaumont	216.2	223.9	Premium Crop	13
14	Fiesta	474.8	485.5	Fiesta	14	14	Arcadia	211.0	221.1	USVL 048	14
15	Patriot	459.2	481.3	Arcadia	15	15	Green Magic	202.6	220.0	Imperial	15
16	Beaumont	449.4	467.6	Patriot	16	16	Premium Crop	197.2	208.7	Diplomat	16
17	Packman	421.7	430.8	Premium Crop	17	17	Everest	191.8	198.5	Packman	17
18	Premium Crop	390.9	428.6	Diplomat	18	18	Nutribud	176.3	195.0	Beaumont	18
19	USVL 048	380.6	357.8	USVL 048	19	19	Diplomat	169.6	162.0	Everest	19
20	Nutribud	343.9	302.8	Early Green	20	20	Packman	151.3	138.9	Nutribud	20
21	OSU OP	265.4	267.6	Nutribud	21	21	Early Green	146.2	127.4	Early Green	21
22	Early Green	242.3	217.4	USVL 093	22	22	OSU OP	111.1	107.5	USVL 093	22
23	USVL 093	235.1	213.5	OSU OP	23	23	USVL 093	104.1	106.6	OSU OP	23

* Significant at P < 0.05 level.

4.3.5 Stability of genotype performance

The results of the stability analysis of a cultivars capacity to perform comparably across trial locations, and seasons in the different management systems for head weight indicated that under both management systems, 'Belstar', 'Batavia', and 'Green Magic' were similar across environments (Figure 4.2a and b). 'Arcadia' was highly stable across organic trials (ranked 5th), but less stable across conventional trials (ranked 11th). Because we were interested in the broccoli cultivars that provide both an acceptable yield and displayed stability across environments, we combined the analysis of head weight ranking with stability across environments, using 300g as a minimum threshold for weight and 15 g^2 as a maximum threshold for stability (Figure 4.2a and b). In that quadrant the cultivars 'Batavia', 'Belstar' and 'Green Magic' had the highest combined stability and head weight across both management systems. In the top group of most productive and stable cultivars also 'B1 10' appeared in conventional trials (Figure 4.2a), and 'Arcadia' and 'Everest' in the organic trials (Figure 4.2b). The open pollinated and inbred cultivars 'OSU OP', 'Nutribud', 'Early Green' (OPs) and USVL 048 and 093 (inbreds) had the lowest head weight and least stability across trials. In the combined head weight and stability analysis, the F_1 hybrid cultivar 'Diplomat' was in the bottom performing group overall.

4.3.6 Correlation among horticulture traits

The correlation analysis between genotypic means across trials, separately for organic and conventional management system, shows that head weight was positively and highly correlated with head size, bead size, bead uniformity (conventional only), and overall quality (Table 4.8). Conversely, head weight was negatively correlated with head color, but it was not significant. There was a significant positive correlation for head shape and bead size in both systems. Overall quality was highly correlated across both management systems for head weight, head diameter, bead uniformity, head surface, and bead uniformity and in conventional systems for head shape and bead size.

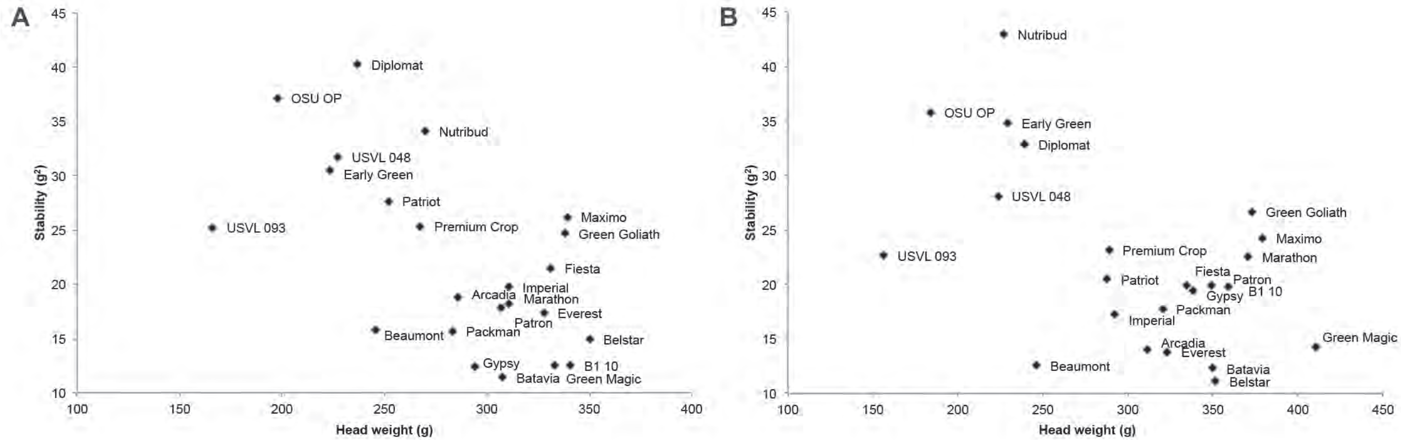

Figure 4.2 Broccoli cultivar (in)stability, expressed as the cultivar variance (g2), plotted against mean head weight (g) across trials in Oregon and Maine, across seasons (Fall/Spring), 2006-2008. A. conventional, and B. organic management systems.

Table 4.8 Genetic correlation of broccoli horticulture traits across organic and conventional trials (upper right of diagonal, organic; lower left of diagonal, conventional).

Horticulture Traits	Head Weight	Head Diameter	Hollow Stem	Maturity	Head Color	Head Shape	Bead Size	Bead Uniformity	Head Surface	Plant Height	Overall Quality
Head Weight		0.83	-0.18	0.30	-0.25	0.32	0.49	0.38	0.17	0.32	0.74
Head Diameter	0.76		-0.16	-0.10	-0.20	-0.12	0.33	0.31	-0.09	0.54	0.73
Hollow Stem	-0.09	-0.05		0.01	-0.02	0.20	-0.01	0.12	0.07	-0.21	-0.03
Maturity	0.39	-0.06	0.16		-0.28	0.60	0.61	-0.09	0.07	-0.22	-0.04
Head Color	-0.31	-0.26	-0.32	-0.29		0.15	0.02	0.29	0.15	0.32	0.16
Head Shape	0.42	-0.08	0.22	0.65	0.12		0.54	0.39	0.61	-0.10	0.37
Bead Size	0.66	0.29	0.10	0.66	-0.25	0.64		0.30	-0.04	0.13	0.39
Bead Uniformity	0.46	0.46	-0.16	-0.16	0.06	0.12	0.35		0.42	0.32	0.73
Head Surface	0.13	-0.02	0.25	0.11	0.33	0.59	0.05	0.25		0.14	0.42
Plant Height	0.19	0.41	-0.30	-0.24	0.35	-0.11	0.12	0.64	0.09		0.63
Overall Quality	0.64	0.55	-0.10	0.09	0.21	0.46	0.53	0.69	0.52	0.61	

Values ≤ |0.40| are not significantly different from zero at the $P < 0.05$ level

4.4 Discussion

4.4.1 Relative importance of Management system, Location, and Season

Overall, our trials demonstrated that Location and Season, not Management System, are the largest source of environmental variation in broccoli cultivar performance. The significantly higher broccoli head weight from the Oregon trials compared to the Maine trials in both seasons as well as the overall higher broccoli head weight across all trials in the Fall compared to the Spring supported these findings. Higher head weight overall in the Oregon field trials could be explained by the climatic differences between Oregon and Maine with Oregon having more growing degree days than Maine in both Fall season trial years (Table 4.2). For many traits, Management system contributed only to variation at the three- and four-way interaction level, and these interactions constituted a large portion of the total variance in the model. Thus, genotype by management systems interactions did occur, but there were no overarching effects of management system apparent across locations and seasons.

One of the reasons for only the small magnitude of the Management system relative to other environmental factors on head weight could be the fact that on average over all trials, this trait did not significantly differ when cultivars were grown under organic and conventional conditions even though variances differed. This is in contrast with much of the literature [e.g. de Ponti et al. (2012) and Seufert et al. (2012)] who after reviewing comparative studies, concluded overall that organic yields were on average lower (reduction of 5-34%) compared to conventional. Their reviews suggested that when farms have been managed organically over a long period of time with consistent soil building practices, soil fertility increases due to higher levels of organic matter and improved water holding capacity and increased particulate organic matter (POM), can produce higher or comparable yields to conventionally produced crops. When comparing the soil quality of the Oregon and Maine trial locations, the soils at both of the conventional trial sites had higher levels of immediately available Nitrogen (N) compared to the organic sites at the time of trial implementation, but had lower POM levels indicating that their long term available N was less compared to the organic sites (Table 4.2). Our results in Oregon and Maine demonstrated that organic is not *per se* lower yielding compared to conventional. Broccoli grown under organic conditions in the spring, however, may be at more of a disadvantage due to slower nitrogen mineralization rates under cooler temperatures resulting in lower yields than conventional. This was shown in trials in Oregon where there were 100 fewer GDD in Spring 2008 compared to 2007 and where organic yields were lower than under conventional conditions (Table 4.2).

Despite comparable mean head weights between organic and conventional growing conditions, the overall range in head weight across cultivars was greater in organic than conventional across all trials, (Figure 4.1c) which represents a larger variance in organic compared to conventional. This difference in head weight variance was even more pronounced in the fall trials compared to the spring trials (Figure 4.1d). Ceccarelli (1994; 1996) in discussing barley breeding for marginal, low input and drought-prone environments indicated that such environments can be heterogeneous, and genetic variance can be greater compared to more homogeneous high input low stressed environments, and that by breeding solely under high input conditions, an opportunity to exploit genetic differences at lower input levels can be lost. While our organic trial locations were not necessarily representative of the type of abiotic stresses described by Ceccarelli, the locations did exhibit the unique stresses of an organically managed heterogeneous environment. Such characteristics that define an organic management system and were representative of our broccoli trials included slow release of nutrients, plant defence against insect predation (e.g. flea beetles and aphids) without insecticides, and the additional weed pressure typically found in an organic management system without the use of synthetic herbicides. Ceccarelli proposes also that the environment of selection affects the pattern of responses of genotypes to varying environmental conditions. Repeated cycles of selection in a given type of environment will reduce the frequency of lines specifically adapted to other environments. Most of the cultivars evaluated in our trials were commercial F_1 hybrids originally selected for and used in high input conventional agriculture systems, while the remainder were OPs selected under organic/low input conditions and inbreds selected in South Carolina. The combination of F_1 hybrids and OPs in the same trial may explain the broader range of variation observed for genotype performance when grown under organic conditions. Another aspect to be taken into account is that if hybrids alone are considered, the range of variation is narrowed as demonstrated in Table 4.6.

Our third major finding related to Management system is that only at the three- and four-way interaction level did Management system play a significant role. As such, it appeared that under our trial conditions there were G×M interactions within each trial combination but that organic management did not have a large impact on a seasonal or regional basis. In other words, there do not appear to be factors associated with organic systems that transcend regions and seasons, rather, each environment is different, and differences between organic and conventional systems are apparent on a local trial level. This observation is supported by the fact that when data were analysed within region and season, most paired trials at the individual Location, Season, Year level had Genotype by Management system interactions.

4.4.2 Cultivar ranking and stability in Management systems

Our trial results demonstrated that across all locations and seasons, overall cultivar rankings were comparable (with some exceptions) for head weight between organic and conventional trials. Østergård et al. (2005) proposed that not only yield as such but also yield stability across years and seasons are important breeding objectives for organic conditions. 'Batavia', 'Belstar' and 'Green Magic' had the highest combined head weight and head weight stability in both management systems, while 'Arcadia' was one of the top performing cultivars in organic, but not in conventional trials. Not all cultivars that performed well in head weight were stable, such as 'Maximo'. These examples demonstrate that some cultivars may be more tolerant to abiotic and biotic stress than others, and therefore more suitable for organic management systems. A strong positive correlation of top performing cultivars between management systems was also found by Burger et al. (2008) for maize who recommended as a result of these findings that cultivar performance under conventional conditions could provide a good prediction for the average cultivar performance under organic conditions in a breeding program. They also recommended that the use of organic test sites would increase the chances of identifying broadly adapted genotypes when aiming at cultivars for both systems.

To further examine the question of whether differences in ranking at the individual paired conventional and organic sites were significant, we performed Spearman's rank correlation on cultivar performance between paired conventional and organic environments. Correlation coefficients were large and statistically significant as would be expected when mean genotype ranking was similar between management systems (data not shown). However, when correlation was performed on F_1s only (leaving out the inherently lower yielding OPs and inbreds), significant correlation was observed in the trial combinations for Maine Spring 2008, and Oregon Spring 2007 and 2008, but not the other five trial combinations (Table 4.6). It is apparent that the significant correlations observed on the full set of cultivars was a function of hybrids always being higher yielding than OPs and inbreds, but a much weaker association was revealed within the hybrid sub-group. The weak correlation among hybrids is in agreement with the crossover interaction that was observed at a local level between management systems described above (Table 4.7a and b**).** Przystalski et al. (2008) analyzed performance of cereals grown under organic and conventional systems in multiple locations, and determined that despite high overall genetic correlation for yield and associated traits, there were exceptions on the individual cultivar ranking level that could be relevant to the selection process. For example, a cultivar that produced an average yield under conventional conditions could perform among the top under organic conditions due to better weed competitive ability. In order not to overlook the best performing cultivars for organic management systems, they advised combining the cultivar ranking results from trials from both management systems (see also Reid et al., 2009 and 2011).

In our trials the open pollinated cultivars were the lowest yielding and least stable across all trials. The small group of OPs in our trials tended to be early maturing and demonstrated a narrow harvest window at prime quality, which could have contributed to their lack of resilience to environmental variation. Duvick (2009) found that the heterosis in maize hybrids contributed to their overall vigour under stress conditions. However, the research of Ceccarelli (1996) and Pswarayi et al. (2008) in the case of barley indicated that modern cultivars were adapted to low stress, high yielding environments and did not always perform favourably in higher stress, marginal conditions. In the case of our trials, however, the organic management conditions were not necessarily low input stress conditions in the strictest sense, as mean head weights were comparable to conventional, and therefore high ranking hybrids were shared across environments with the exception of some that dropped their high ranking under organic conditions. We therefore must stress that we anticipate that results could be different when growing conditions are less favourable for crop growth.

4.4.3 Repeatability as affected by Management systems

Lammerts van Bueren et al. (2002) described organic growing conditions as heterogeneous and sometimes lower input environments compared to conventionally managed production environments where high levels of readily available nitrogen can mask variation in soil quality conditions. Higher variability in growing conditions under organic conditions may cause increased macro- and micro-environmental variance relative to the genotypic component, and result in lower heritabilities compared to more controlled conditions in high-input conventional farming conditions. In the present study, we were able to estimate the proportion of the genotypic variance relative to phenotypic variance, but because we did not have a genetically structured breeding population, could only estimate repeatability rather than broad sense heritability. The argument commonly used to support selecting in optimal environments is that heritabilities are higher in high input environments compared to poor environments (Ceccarelli, 1994; 1996). In our trials, repeatabilities for head weight, head diameter, hollow stem and overall quality were higher for organic compared to conventional, while for the traits of maturity, head color, and head surface, repeatability levels between management systems were equal or near equal. It is recognized that these coefficients combine additive and non-additive genetic variance, and it would be anticipated that they would be much lower if the additive component was partitioned out. For the traits of head shape, bead size, and bead uniformity, repeatabilities were higher in conventional compared to organic, which could be explained by a more variable organic management environment. The traits with repeatabilities larger or equal in organic systems were those generally associated with growth and productivity, and probably under similar genetic control, whereas those with repeatibilities lower in organic compared to conventional are probably under separate genetic control. Higher heritabilities under organic conditions were also found by Burger et al. (2008) and Goldstein et al. (2012) for maize and for faba bean (*Vicia faba*) (Link and Ghaouti, 2012). They supported their findings with the following justifications, which can also explain our results: (1) with heterogeneous soils found in organic management systems the precision of experiments may be more impaired under stress (slow nutrient release) than under conventional high input conditions; (2) genetic variance may be greater under stress conditions than non-stress conditions, and (3) the high genetic variance in organic trials compensated for the high experimental error which produced comparable heritabilities between organic and conventional trials.

Trait repeatabilities alone are not sufficient to determine the optimum selection environment. Both estimates of genetic variance and repeatabilities are useful in predicting the response to selection in organic and conventional management systems. Estimates of the genetic correlation between performance of traits in the organic and conventional management systems is an indicator for the extent of G $\times$ M interaction. In our broccoli trials the genetic correlations between organic and conventional trials for the traits head weight, maturity, head shape, and plant height were high (>0.90) indicating that a differential response of the genotypes to the two management systems was largely absent. The ratio of correlated response to direct response for all traits was close to but below 1.0 with the exception of bead uniformity. This would imply that in most cases, selection directly in an organic environment could result in more rapid genetic gain than indirect selection in a conventional environment, but because most repeatibilities were close to 1.0, indirect selection in a conventional environment would be nearly as effective as direct selection in an organic system. Also in our trials we found larger genetic variances (broader minimum-maximum ranges) compared to results under conventional management.

4.4.4 Breeding broccoli for organic systems

Determining whether broccoli cultivar development could better take place under organic or conventional management systems to develop cultivars optimized for organic agriculture is a complex proposition. Breeding in the target environment is most effective for organic systems, where G × E interaction, genetic diversity, and trait heritability are all taken into account (see e.g. Wolfe et al., 2008). Driven by the need for efficiency, commercial broccoli breeders often aim to reduce G × E interactions by selecting cultivars that are broadly adapted to the range of their target environments. However, from our data location and season and their interactions were the primary sources of variation identified for broccoli head weight and the other horticultural traits studied. This is supported by our observations that the general location- and season-specific trend for head weight interacted with the cultivar's maturity class designation, where mid-to-late season cultivars were the highest ranking in Oregon in the Fall, while in Maine early-to-mid season cultivars were the highest ranking. In the Spring, best performing cultivars in both Maine and Oregon were in the mid-to-late season maturing class. When comparing cultivar performance between seasons and locations, we observed that the best performing early-to-mid season cultivars in Spring trials and the mid-to-late season cultivars in Fall trials for Oregon were a different group of cultivars than those in Maine of the same maturity class.

Greater heterogeneity in organic management systems and G × M crossover interaction observed on a local scale supports the idea that direct selection (under organic management) of cultivars for organic agriculture would benefit from evaluation in organic systems, particularly if the intent of the breeder is to develop cultivars that support local adaptation. Annicchiarico et al. (2012) found that the performance of lucerne (*Medicago sativa*) populations bred in the location of intended use were better performers on organic farms in

Northern Italy compared to cultivars that were bred outside of the intended region. Annicchiarico et al. (2010) also found that when comparing G × M to G × L, the effect of wheat selected for a specific bioregion outweighed the effect of breeding for management system for direct selection of yield. Specific to broccoli, Crisp and Gray (1984) reported that to develop cultivars for a specific season, populations from different maturity groups should be used to take advantage of high heritability in heading characteristics, head color and time of maturity.

The stability between the organic and conventional trials across most trials, and comparable heritability between systems for most traits, would suggest that selection for broccoli for organic systems would best be carried out under organic conditions. Lorenzano and Bernardo (2008) suggest that breeding for adaptation to organic production environments could be conducted under conventional conditions due to high correlations, with the caveat that advanced breeding lines be tested under organic conditions for less heritable traits such as yield. However, in our trials, there was significant crossover interaction at the individual trial level as well as low rank correlation when genotypic classes were separated in the ranking analysis. Considering these findings (and without taking costs into account), a separate organic regional, seasonal breeding program for broccoli can be effective. This is further supported by the fact that the ratio of correlated response to direct response in our trials for most traits was close to but below 1.0 implying that selection directly in an organic environment could result in more rapid genetic gain than indirect selection in a conventional environment.

The large genotype variance observed in our organic trials relative to conventional trials indicated that the potential for breeding within an organic system may benefit cultivar development for both management systems. Because organic management systems do not use synthetic fertilizers and pesticides, the potential for a breeder to observe and select parent lines for nitrogen use efficiency, disease resistance and vigour, under organic systems may bring benefits to the breeding program. Due to the different management practices, locations and seasonal differences in organic farming across the US, such screening could provide additional information about breeding line performance, and support in determining which lines are most stable across environments and in organic conditions. Burger et al. (2008) found with maize selection, that trialing advanced lines under conventional management after determining superior lines selected in organic systems, could also enhance conventional breeding as lines that tolerate stress in an organic management system may carry this performance over to stress conditions that can also occur under conventional systems.

We want to stress that our study included predominantly modern broccoli cultivars selected for broad adaptability in conventional production systems, which does not fully show the potential of selection in breeding populations under organic management. Kirk et al. (2012) and Reid et al. (2011) both reported that direct selection in organically managed field conditions for genotypes targeted for organic agriculture offered advantages over indirect selection in conventionally managed field conditions for spring wheat because they found that breeding populations selected in organic environments had higher yields when grown organically, compared to conventionally selected populations that did not perform comparatively well. We therefore recommend that for further studies, early generation broccoli breeding lines and/or populations be compared to attain a better prediction of genetic correlations for organic, and to explore potential genetic changes that may occur when broccoli breeding lines are bred in the target environment from inception.

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Chapter 5

Variation in broccoli cultivar phytochemical content under organic and conventional management systems: Implications in breeding for nutrition

Variation in broccoli cultivar phytochemical content under organic and conventional management systems: Implications in breeding for nutrition

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Abstract

Organic agriculture requires cultivars that can adapt to organic crop management systems without the use of synthetic pesticides as well as genotypes with improved nutritional value. The aim of this study encompassing 16 experiments was to compare 23 broccoli cultivars for the content of phytochemicals associated with health promotion grown under organic and conventional management in spring and fall plantings in two broccoli growing regions in the US (Oregon and Maine). The phytochemicals quantified included: glucosinolates (glucoraphanin, glucobrassicin, neoglucobrassin), tocopherols (δ-, γ-, α-tocopherol) and carotenoids (lutein, zeaxanthin, β-carotene). For glucoraphanin (17.5%) and lutein (13%), genotype was the major source of total variation; for glucobrassicin, region (36%) and the interaction of location and season (27.5%); and for neoglucobrassicin, both genotype (36.8%) and its interactions (34.4%) with season were important. For δ- and γ- tocopherols, season played the largest role in the total variation followed by location and genotype; for total carotenoids, genotype (8.41-13.03%) was the largest source of variation and its interactions with location and season. Overall, phytochemicals were not significantly influenced by management system. We observed that the cultivars with the highest concentrations of glucoraphanin had the lowest for glucobrassicin and neoglucobrassicin. The genotypes with high concentrations of glucobrassicin and neoglucobrassicin were the same cultivars and were early maturing F_1 hybrids. Cultivars highest in tocopherols and carotenoids were open pollinated or early maturing F_1 hybrids. We identified distinct locations and seasons where phytochemical performance was higher for each compound. Correlations among horticulture traits and phytochemicals demonstrated that glucoraphanin was negatively correlated with the carotenoids and the carotenoids were correlated with one another. Little or no association between phytochemical concentration and date of cultivar release was observed, suggesting that modern breeding has not

negatively influenced the level of tested compounds. We found no significant differences among cultivars from different seed companies.

Keywords
Genotype × environment interaction, organic agriculture, *Brassica oleracea*, glucosinolates, tocopherols, carotenoids, breeding, health promotion

5.1 Introduction:

Organic food consumption is in part driven by consumer perception that organic foods are more nutritious and simultaneously less potentially harmful to human health (Saba and Messina, 2003; Stolz et al., 2011). Studies, such as Smith-Sprangler et al., (2012), have concluded that there is little evidence for differences in health benefits between organic and conventional products, but other studies have indicated that organic vegetables and fruits contain higher concentrations of certain plant phytochemicals associated with health promotion than those produced conventionally (Asami et al., 2003; Chassy et al., 2004; Brandt et al., 2011; Hunter et al., 2011; Koh et al., 2012). A number of these compounds are produced by plants in response to environmental stress or pathogen infection, providing a potential explanation of why concentrations of these compounds might be higher in plants grown in organic systems without application of pesticides (e.g. Crozier et al., 2006). In addition, higher phytochemical levels may be due to the effects that different fertilization practices have on plant metabolism. Synthetic fertilizers used in conventional agriculture are more readily available to plants than organic fertilizers (Bourn and Prescott, 2002). Nutrients derived from organic fertilizers need to be mineralized, and the availability of these nutrients depends on soil moisture, temperature and level of activity of soil organisms (Mäder et al., 2002). Conventional systems seek to maximize yields, resulting in a relative decrease of plant phytochemicals and secondary metabolites (Martinez-Ballaesta et al., 2008; Meyer and Adam, 2008; Mozafar, 1993; Zhao et al., 2006). Correspondingly, compounds such as phenolics, flavonoids, and indolyl glucosinolates may be induced by biotic or abiotic stress (Dixon and Paiva, 1995; Kim and Juvik, 2011).

Broccoli is an abundant source of nutrients, including provitamin A (β-carotene), vitamin C (ascorbate), and vitamin E (tocopherol) (USDA Nutrient Database, 2011). It is also a source of phytochemicals associated with health benefits and these include glucosinolates, carotenoids, tocopherols, and flavonoids (Brown et al., 2002; Kushad et al., 1999; Farnham et al., 2009). Verhoeven et al. (1996), Keck and Finley (2004) and Here and Büchler (2010), reported that diets rich in broccoli reduce cancer incidence in humans. Strong associations between consumption level and disease risk reduction exists for glucosinolates (anti-cancer), tocopherols (cardiovascular), and the carotenoids (eye-health) (Higdon et al., 2007).

Sulfur containing glucosinolates are found in the tissues of many species of the *Brassicaceae* family. When glucosinolates are consumed, they are hydrolyzed into isothiocyanates (ITC) and other products that up-regulate genes associated with carcinogen detoxification and elimination. Aliphatic glucoraphanin (up to 50% of total glucosinolates) and the indolylic glucosinolates, glucobrassicin and neoglucobrassicin are abundant in broccoli florets (Kushad et al., 1999; Brown et al., 2002; Schonhof et al., 2004). Glucoraphanin is hydrolyzed either by the endogenous plant enzyme myrosinase (Fenwick et al., 1983; Juge et al., 2007) or by gut microbes to produce sulforaphane, an ITC. The indole glucosinolates are tryptophan-derived in a similar but alternate biosynthetic pathway (Mithen et al., 2000). The health promoting effects of the indolyl glucosinolates are attributed to indole-3-carbinol, a hydrolysis product of glucobrassicin, N-methoxyindole-3-carbinol and neoascorbigen, hydrolysis products from neoglucobrassicin, and the catabolic products derived from alkyl glucosinolates. Clinical studies have shown that the glucosinolate hydrolysis products reduce the incidence of certain forms of cancer (e.g., prostate, intestinal, liver, lung, breast, bladder) (Wang et al., 2004; Hsu et al., 2007; Kirsh et al., 2007; Lam et al., 2010; Bosetti et al., 2012; Wu et al., 2012). The lipophilic phytonutrients found in broccoli include the carotenoids lutein, zeaxanthin, ß-carotene, and tocopherols (forms of vitamin E) (Kopsell and Kopsell, 2006; Ibrahim and Juvik, 2009). In addition to their role as vitamins, these compounds are powerful antioxidants (Kurilich et al., 1999; Kurilich and Juvik, 1999). Consumption of vegetables high in tocopherols and carotenoids has decreased the incidence of certain forms of cancer (Mayne, 1996). Lutein and zeaxanthin protect against development of cataracts and age-related macular degeneration (Krinsky et al., 2003). Tocopherols have also been associated with reduced risk of cardiovascular disease by preventing oxidative modification of low-density lipoproteins in blood vessels (Kritchevsky et al., 1999).

The genetic potential for high nutrient content has long been a concern of the organic industry in order to meet the expectations of organic consumers. This has often been manifested by questioning whether modern elite cultivars may have lower levels of nutritional content than older open pollinated cultivars. Indirect evidence supporting this argument comes from Davis et al. (2004), who compared USDA nutrient content data for 43 garden crops released between 1950 and 1999. Statistically significant decreases were noted for six nutrients (protein, calcium, potassium, iron, riboflavin, and ascorbic acid), with declines ranging from 6% for protein to 38% for riboflavin. Crop varieties in 1950 had been bred to be adapted to specific regions and a relatively low input agriculture system, but contemporary cultivars are selected for yield, disease resistance, broad adaptation to high input agriculture systems, and for increased 'shipability' and shelf life. Traka et al. (2013) recommend breeding with greater genetic diversity when the goal is enhanced phytochemical contentby exploiting wild crop relatives. The genotype is important in determining the level of nutrients in a crop cultivar (Munger, 1979; Welch and Graham, 2004; Troxell Alrich et al., 2010). What is unclear, however, is whether the nutritional content of a cultivar is associated with certain genotypic categorization, e.g. old versus modern, open pollinated versus F_1 hybrid cultivars. In addition, there is no clear differentiation as to what extent nutritional content in a crop is determined by genotypic or by field management factors or by the interaction of both. Some studies comparing performance of genotypes in organic and conventional production systems have shown that for certain agronomic traits, cultivars perform differently between the two production systems (e.g. for winter wheat: Murphy et al., 2007; Baresel et al., 2008; for lentils: Vlachostergios et al., 2008; for maize: Goldstein et al., 2012), while others have shown no differences in ranking performance (for maize: Lorenzana and Bernardo, 2008; for onions: Osman et al., 2008; for cereals: Prsystalski et al., 2008). The results of these studies have profound implications for organic cultivar selection and breeding strategies and raise questions as to the need for cultivars to be bred with broad adaptability or specific adaptation for the requirements of regional organic production and for designing breeding programs that optimize phytochemicals in an adapted management system.

Previous studies comparing organically versus conventionally grown broccoli for nutritional quality have been 'market basket' (off-the-shelf) studies (Wunderlich et al., 2008; Koh et al., 2009). Harker (2004) explained that the limitation of market basket studies is that they either have purchased the products from the store shelf and cannot relate differences to specific growing conditions or that the number of cultivars is too small to generalize the results. While other studies have compared cultivars from one production season time period to another, knowledge of the actual cultivar and production system (soil quality, temperature, rainfall) was not available (Benbrook, 2012; Davis et al., 2004). The concentrations and form of health-promoting nutrients in *Brassica* vegetables have been reported to vary significantly due to (1) genotype (cultivar and genotypic class) (Carlson et al., 1987; Kushad et al., 1999; Schonhof et al., 2004; Farnham et al., 2005; 2009; Ibrahim and Juvik, 2009; Wang et al., 2012; Traka et al., 2013), (2) environmental conditions such as season (Rosa et al., 2001; Vallejo et al., 2003ab; Charron et al., 2005ab; Aires et al., 2011), light (Brown et al., 2002), max/min temperature, irrigation (Pek et al., 2012; Schonhof et al., 2007), (3) genotype by environment interactions (Brown et al., 2002; Farnham et al., 2004; Björkman et al., 2011); (4) management system including soil fertility (Robbins et al., 2005; Xu et al., 2010), organic versus conventional (Meyer and Adams, 2008; Naguib et al., 2012; Picchi et al., 2012), days to harvest (Vallejo et al., 2003ab), and (5) post-harvest management (Hansen et al., 1995; Tiwari and Cummins, 2013). Identifying specific growing conditions and genotypes that produce cultivars with varying phytochemical content and putative disease-prevention activity could offer value-added commercial opportunities to the seed and food industry.

In addition to research conducted on how broccoli genotypes, management system and environment interact for horticultural traits (Renaud et al., 2014), we address in this chapter the question of how do genotypes, management system and environment interact to determine the nutritional contributions of broccoli to the human diet. We studied the relative importance and interaction among genotypes (cultivars, genotypic classes) and environment {management system [M: organic (O) or conventional (C)], season (S, a combination of year and season within year, i.e., fall 2006, spring 2007, fall 2007, spring 2008), location (E)} in a set of 23 broccoli cultivars for floret glucosinolate, tocopherol and carotenoid concentrations grown under organic and conventional production systems in two contrasting broccoli production regions of the US: Oregon and Maine. Specifically we addressed the following questions: (1) what is the impact of organic management system compared to the environmental factors including climatic region, season and their interactions [Genotype (G) x Environment (E) x Management System (M)]?, (2) is there a significant difference in phytochemical content between different genotypes and genotypic classes (old and modern cultivars; open pollinated and F_1 hybrid cultivars; early and late maturing cultivars; and between different commercial seed sources)?, (3) what is the best selection environment for a broccoli breeding program for enhanced phytochemical content?

5.2 Materials & methods:

5.2.1 Plant Material and Field Trial Locations

Twenty-three broccoli cultivars including open pollinated (OP) cultivars, inbred lines, and F_1 hybrids were included in field trials (Table 5.1**).** Cultivars were grown in a randomized complete block design with three replicates in Maine (ME)-Monmouth (Latitude 44.2386°N, Longitude 70.0356°W); and Oregon (OR)-Corvallis (Latitude 44.5647°N, Longitude123.2608°W)] with each location including organically (O) and conventionally (C) managed treatments. Plots contained 36 plants, planted in three rows of 12 plants at 46 cm equidistant spacing within and between rows. The 2006 trials had only 18 of the 23 entries, and the Oregon 2006 trial had only two replicates at the organic location. Field trials were conducted for three consecutive years with one production cycle in Fall 2006, two production cycles in Spring and Fall 2007 and one production cycle in Spring 2008. The primary management differences between the organic and conventional field trial sites are outlined in Supplemental Figure 5.1**,** which describes the production system, soils, fertility applications, the applied supplemental irrigation, and weather conditions for the area of study. Further details of the field design are reported in Renaud et al. (2014).

5.2.2 Field Data Collection

As plots approached maturity they were evaluated three times a week for field quality and broccoli heads that had reached commercial market maturity (approximately 10 to 12 cm in diameter for most of the cultivars while retaining firmness). Field quality traits evaluated on a 1 to 9 ordinal scale included head color, bead size, and bead uniformity. Average head weight was determined by taking the mean of the five individual heads per plot. Head diameter averaged for five heads at harvest maturity from each plot. Maturity was based on days to harvest from transplanting date. Detailed procedures and horticulture trait performance data are reported in Renaud et al. (2014).

Table 5.1 Overview of commercially available broccoli cultivars, showing origin, main characteristics, included in paired organic - conventional field trials 2006-2008.

Cultivar	Abbreviation	Origin	Cultivar Type[a]	Date of Market Entry	Maturity Classification[b]
Arcadia	ARC	Sakata	F_1	1985	L
B1 10	B11	Rogers	F_1	1988	M
Batavia	BAT	Bejo	F_1	2001	M
Beaumont	BEA	Bejo	F_1	2003	L
Belstar	BEL	Bejo	F_1	1997	L
Diplomat	DIP	Sakata	F_1	2004	L
Early Green	EGR	Seeds of Change	OP	1985	E
Everest	EVE	Rogers	F_1	1988	E
Fiesta	FIE	Bejo	F_1	1992	L
Green Goliath	GRG	Burpee	F_1	1981	M
Green Magic	GRM	Sakata	F_1	2003	M
Gypsy	GYP	Sakata	F_1	2004	M
Imperial	IMP	Sakata	F_1	2005	L
Marathon	MAR	Sakata	F_1	1985	L
Maximo	MAX	Sakata	F_1	2004	L
Nutribud	NUT	Seeds of Change	OP	1990	E
OSU OP	OSU	Jim Myers, OSU	OP	2005	E
Packman	PAC	Petoseed	F_1	1983	E
Patriot	PAT	Sakata	F_1	1991	M
Patron	PAN	Sakata	F_1	2000	M
Premium Crop	PRC	Takii	F_1	1975	E
USVL 048	U48	Mark Farnham, USVL	Inbred	not released	L
USVL 093	U93	Mark Farnham, USVL	Inbred	not released	M

[a] Cultivar Type: F_1: hybrid; OP: Open Pollinated; Inbred.
[b] Maturity Classification: E: Early; M: Mid; L: Late.

5.2.3 Broccoli Floret Samples and glucosinolate, tocopherol, and carotenoid analysis

In order to analyse nutritional compounds of the broccoli heads, the following procedure was followed: As plots approached maturity, five broccoli head tissue samples were harvested fresh from each subplot at each trial location and were composited into a single sample per replication. The samples were frozen at -20^{o}C and shipped in a frozen state to the University of Illinois, Urbana-Champaign where they were freeze-dried and assessed for nutritional phytochemicals. Each sample was analyzed for the glucosinolates (glucoraphanin, glucobrassicin and neoglucobrassicin), carotenoids (β-carotene, lutein, and zeaxanthin), and tocopherols (δ-, γ-, α- tocopherol) by high-performance liquid chromatography (HPLC) analysis using analytical protocols described in Brown et al. (2002) for glucosinolates, and Ibrahim and Juvik (2009) for tocopherols and carotenoids. Glucosinolates in lyophilized floret tissue samples were extracted and analysed by HPLC using a reverse phase C18 column. Three hundred mg samples of broccoli floret tissue were weighed out for extraction and the HPLC quantification of the tocopherols and carotenoids.

5.2.4 Statistical Analysis

Various linear mixed models were used for the analysis of trait variation. We followed the same methodology as described in Renaud et al. (2014), which was comparable to the approach followed by Lorenzana and Bernardo (2008). For fitting the linear mixed models, GenStat 15 (VSNi, 2012) was used. The models followed the set-up:

$$y = E + R(E) + G + G \times E + e.$$

Here y is the phytochemical response. Term E represents the environment in a very general sense, it includes all main effects and interactions of Season (S), Location (L) and Management (M). For analyses per location, the terms involving L were dropped. Similarly, for analyses regarding a specific management regime, the terms involving M were dropped. Term $R(E)$ is the effect of replicate within environment, and there were two or three replicates in individual trials. G and $G \times E$ are genotype and genotype by environment interaction effects, respectively. Finally e is a residual.

Variance components were reported as coefficients of variation, i.e.,

$$CV=100\sqrt{V}/\bar{x},$$

with V the variance corresponding to specific effects and $\bar{x}$ the trait mean. Repeatability was calculated from the variance components in its most general form as

$$H^2 = V_G / (V_G + V_{GL}/nL + V_{GS}/nS + V_{GM}/nM + V_{GLS}/(nL.nS) + V_{GLM}/(nL.nM) + V_{GSM}/(nS.nM) + V_{GLSM}/(nL.nS.nM) + V_e/(nL.nS.nM.nR)),$$

where the variance components correspond to the terms in the mixed model above. The terms *nL, nS, nM* and *nR* stand for the number of locations (2: Maine and Oregon), number of 'seasons' (4: Fall 2006, Spring 2007, Fall 2007, Spring 2008), management (2; organic and conventional), and replicates (2 or 3).

Genotypic means were calculated by taking genotypic main effects fixed instead of random in the mixed models above. Pairwise comparisons between genotypic means were performed using GenStat procedure *VMCOMPARISON*. Correlations on the basis of genotypic means were referred to as genetic correlations. Genotypic stabilities under organic and conventional conditions were calculated as the variance for individual genotypes across all trials in the system.

To assess the feasibility of selection for organic conditions (the target environment) under conventional conditions, we calculated the ratio of correlated response (for organic conditions using conventional conditions), CR, to direct response (for organic conditions in organic conditions), DR, as the product of the genetic correlation between organic and conventional systems (r_G) and the ratio of the roots of conventional and organic repeatabilities (and respectively):

$$CR/DR=r_G H_C / H_O.$$

A ratio smaller than 1 indicates that selection is better done directly under organic conditions when the aim is indeed to improve the performance in organic conditions.

5.3 Results

5.3.1 Comparison of phytochemicals means over the environments

Glucosinolates

Across all trials, glucoraphanin levels were comparable between locations and seasons but were more variable at the individual location and season trial analysis level (Table 5.2). Glucoraphanin, glucobrassicin and neoglucobrassicin levels were comparable between organic and conventional treatments. Comparisons of organic versus conventional by location and season for the glucosinolate phytochemicals are presented in Supplemental Figure 5.1A, B, and C. Comparable levels of glucosinolates were observed in the organic - conventional comparisons within locations and seasons.

Tocopherols

Across trials compared regionally, Oregon had higher levels of all three tocopherols compared to Maine (Table 5.2, Supplemental Figure 5.2A, B and C). The tocopherols δ- and γ- were higher in Fall compared to Spring (Supplemental Figure 5.2A and B), but not so for α-tocopherol (Supplemental Figure 5.2C). Organic and conventional levels for all tocopherol concentrations were in the same range and not significantly different. When the three tocopherols were analysed by organic versus conventional within location and season, there were no clear significant differences in management system across the season and location combinations (Table 5.2, Supplemental Figure 5.2 A, B and C).

Carotenoids

Overall, Oregon had higher levels of lutein and β-carotene compared to Maine (Table 5.2, Supplemental Figures 3A and 3C) and comparative levels of zeaxanthin (Table 5.2, Supplemental Figure 5.3B). Spring produced higher levels of all carotenoids compared to Fall levels in contrast to the glucosinolates and the δ- and γ- tocopherol concentrations. There were no significant differences between organic and conventional for any carotenoid measured. When carotenoids were analysed by management system within location and season, β-carotene showed significantly lower levels in Maine in the Fall compared to other location and season combinations (Supplemental Figure 5.3A, B and C).

Table 5.2 Trait means1 of phytochemicals of 23 broccoli cultivars grown across four pair combinations of location (Maine/Oregon), season (Fall/Spring) two-years combined and management system (Conventional/Organic), 2006-2008.

	Maine					Oregon				
	Fall		Spring			Fall		Spring		
	2006-2007 Combined		2007-2008 Combined		Mean	2006-2007 Combined		2007-2008 Combined		Mean
	C	O	C	O		C	O	C	O	
Glucoraphanin	5.31 e	3.77 bc	3.56 b	4.06 c	4.18	3.46 b	3.03 a	4.64 d	4.51 d	3.91
Glucobrassicin	1.06 b	0.90 a	1.45 c	1.33 c	1.19	5.14 f	5.51 g	2.24 d	2.70 e	3.90
Neoglucobrassicin	0.46 a	0.40 a	2.16 c	1.85 b	1.22	2.34 c	3.20 d	4.32 e	5.10 f	3.74
δ-Tocopherol	2.34 c	2.77 d	1.91 b	1.70 a	2.18	3.53 e	3.66 e	1.91 b	2.24 c	2.83
γ-Tocopherol	4.67 c	4.40 c	2.63 a	2.98 b	3.67	8.48 d	8.73 d	3.31 b	3.22 b	5.94
α-Tocopherol	25.83 a	27.33 a	38.61 b	40.51 bc	33.07	43.04 c	43.20 c	40.52 bc	42.25 c	42.25
Lutein	11.49 a	12.47 a	15.53 b	15.93 b	13.85	15.91 b	16.04 b	16.48 b	17.81 c	16.56
Zeaxanthin	0.81 a	0.83 ab	0.87 ab	0.88 b	0.85	0.83 ab	0.84 ab	1.02 c	1.02 c	0.93
β-Carotene	12.98 a	13.25 a	28.73 c	29.71 c	21.16	29.10 c	30.10 c	25.16 b	25.80 b	27.54

[1] Values in the table are means. Means of the same letter in the same row are not significantly different at the $P < 0.05$ level.

5.3.2 Partitioning of variance components

Glucosinolates

For glucoraphanin across all trials in both regions, Genotype (G) main effect accounted for the largest proportion of variance, followed by G×L×S interaction (Table 5.3). There was no Management (M) main effect, but M contributed to the three (L×S×M and G×S×M) and four-way interactions (G×L×S×M). In contrast to glucoraphanin, Location (L) had the largest effect for glucobrassicin and neoglucobrassicin across all trials in both regions, followed by the L×S interactions. For neoglucobrassicin the S and G main effect was more important than for glucobrassicin. When trials were further partitioned by location, a G and S main effect was apparent for neoglucobrassicin in both locations; for glucobrassicin the S main effects was only apparent in Oregon and not in Maine (Supplemental Table 5.2ab). There was M main effect for glucobrassicin and neoglucobrassicin, but not for glucoraphanin, and no G×M interaction for all glucosinolates.

Tocopherols

For δ- and γ-tocopherol across all trials in both regions, the Season (S) main effect accounted for the largest proportion of variance (Table 5.3). In contrast the proportion of the variation associated with S for α-tocopherol across all trials was minor. For all three tocopherols there was minor to no M effect, but a large L main effect, being the greatest for γ-tocopherol. The G main effect showed a similar pattern to L.

Carotenoids

For all three carotenoids across all trials in both regions, the G main effect described a significant component of total variance and was of largest influence for lutein (Table 5.3). The S main effect played an important role for zeaxanthin, and to a lesser extent for lutein but not for β-carotene. For all three carotenoids the L effect was minor, but the L x S interaction for β-carotene was relatively large and mostly associated with Maine (Supplemental Table 5.2a). There was no M main effect; only for β-carotene was there a small effect of the G × M interaction (mainly driven by Maine).

5.3.3 Repeatability, genetic correlation and ratio of correlated response to direct response

Organic versus conventional

In the present study, we were able to estimate the proportion of the genotypic variance relative to phenotypic variance, but because we did not have a genetically structured breeding population, we apply the term repeatability rather than broad sense heritability. Of the phytochemicals studied, repeatabilities for concentrations of seven of the nine were comparable or higher in organic compared to conventional systems (Table 5.4). Only for glucobrassicin and δ-tocopherol was repeatability under organic conditions lower than under conventional. In the analyses δ- and α-tocopherol had relatively low repeatabilities. The highest repeatabilities were for glucoraphanin (0.82-0.84), neoglucobrassicin (0.75-0.76), γ- tocopherol (0.72-0.75), lutein (0.83-0.85) and zeaxanthin (0.76-0.77). Genetic correlations were high between organic and conventional for the glucosinolates, γ-tocopherol and lutein (0.84-0.95), while δ-tocopherol, α-tocopherol, zeaxanthin and β-carotene were lower (0.63-0.77). The ratio of the correlated response to direct response for selection in the organic system was less than 1.0 for all traits.

Table 5.3. Partitioning of variance components (%) presented as coefficients of variation for phytochemicals of 23 broccoli cultivars grown across eight pair combinations of location (Maine/Oregon), season (Fall/Spring) and management system (Conventional/Organic), 2006-2008.

	Location (L)	Season (S)	Management (M)	L x S	L x M	S x M	L x S x M	L x S x M x R Rep (R)	Genotype (G)	G x L	G x S	G x M	G x L x S	G x L x M	G x S x M	G x L x S x M	Residual
Glucoraphanin	0.01	5.45	0.00	7.20	0.01	0.00	11.86	1.56	17.45	0.01	0.01	0.00	15.97	0.01	7.49	12.62	11.94
Glucobrassicin	36.00	0.00	0.00	27.51	5.58	4.18	1.34	1.86	9.42	7.77	0.01	0.00	13.84	0.00	0.00	10.63	10.91
Neoglucobrassicin	36.81	13.51	0.00	34.36	8.47	6.84	4.50	4.76	15.16	6.24	0.01	0.00	16.40	0.00	0.01	13.40	15.80
δ-Tocopherol	6.83	35.22	0.43	7.87	0.01	0.01	3.39	0.01	5.57	5.65	6.01	0.00	13.65	0.01	0.00	12.21	12.74
γ-Tocopherol	12.02	19.09	0.01	12.11	0.01	3.64	4.47	2.12	13.79	4.85	15.82	0.00	12.95	0.00	0.01	11.08	12.03
α-Tocopherol	6.73	0.01	0.28	10.20	0.01	0.01	0.01	1.29	2.79	3.42	0.01	0.97	10.07	0.00	0.00	8.18	8.92
Lutein	3.71	4.91	0.00	7.52	0.01	2.70	1.85	1.40	13.03	4.14	0.01	0.01	10.76	0.73	0.01	9.21	9.95
Zeaxanthin	1.97	11.55	0.01	3.99	0.01	0.00	0.01	0.00	8.44	3.18	0.01	1.05	6.91	0.01	0.83	8.52	11.36
β-Carotene	4.61	0.00	0.00	17.84	0.01	0.70	0.01	0.71	8.41	4.45	0.00	2.31	11.32	4.63	0.65	12.83	10.99

By location and season

For the glucosinolates, glucoraphanin and glucobrassicin repeatability at each location, season and treatment trial were comparable and generally high (0.83-0.97) between organic and conventional trials, while no clear trend for neoglucobrassicin repeatabilities was observed between organic and conventional aside from being much lower than glucoraphanin and glucobrassicin (Supplemental Table 5.3). For γ- and α-tocopherol, repeatabilities were comparable between organic and conventional, while for δ-tocopherol repeatabilities were comparable between systems or higher in conventional except for one paired trial. For the carotenoids, repeatabilities were comparable or higher in organic for all paired trials, while for lutein in seven of the eight paired trials organic was comparable or greater than conventional. Repeatabilities for zeaxanthin concentrations were comparable for six of the eight paired trials.

Table 5.4 Repeatabilities, genetic correlation and ratio of correlated response to direct response for broccoli phytochemicals comparing organic versus conventional management systems over all trial season/location combinations, 2006-2008.

	Repeatability (H)		r_A [a]	CR_{org}/R_{org} [b]
	C	O		
Glucoraphanin	0.84	0.82	0.84	0.83
Glucobrassicin	0.70	0.64	0.88	0.84
Neoglucobrassicin	0.75	0.76	0.94	0.94
δ-Tocopherol	0.50	0.42	0.73	0.66
γ-Tocopherol	0.75	0.72	0.95	0.93
α-Tocopherol	0.23	0.35	0.61	0.76
Lutein	0.83	0.85	0.93	0.94
Zeaxanthin	0.76	0.77	0.77	0.78
β-Carotene	0.62	0.72	0.63	0.68

[a] Average genetic correlation between conventional and organic production systems across locations.
[b] Ratio of correlated response to direct response.

5.3.4 Comparison of cultivar ranking for phytochemical concentration and stability across trials

To determine trends in cultivars with both the highest concentration of phytochemical groups most stable across locations, seasons and production systems, phytochemical concentrations were plotted against stability per genotype across trials. A group of cultivars were identified as both highest in concentration and most stable and are indicated in the highlighted 'red circle' per phytochemical (Figure 5.1A-I). For glucoraphanin, the same group of cultivars had both the highest concentrations and were the most stable across production systems (Figure 5.1A; Supplemental Table 5.4). While for glucobrassicin, a different set of cultivars had the highest concentrations across production systems (Figure 5.1B; Supplemental Table 5.5). Overall stability of all cultivars across production system was less related to cultivar mean concentrations for glucobrassicin than for glucoraphanin. None of the cultivars with the highest concentration for neoglucobrassicin were in the top quartile for stability across trials; all cultivars with the highest neoglucobrassicin content were in the bottom half for stability (Figure 5.1C; Supplemental Table 5.6). Linear regression revealed a statistically significant association between higher concentrations of glucoraphanin and greater stability (Figure 5.3), but no such pattern was seen for any other glucosinolates. Some but not all cultivars that had the highest concentrations of α-tocopherol were among the top group for δ- and/or γ-tocopherol. There was no relationship between δ-tocopherol concentrations and stability, but both γ- and α- tocopherols had higher concentrations associated with greater stability (Figure 5.1D-F; Supplemental Tables 4.7-4.9). Open pollinated and early maturing cultivars had the highest and most stable concentrations for all carotenoids (Figure 5.1G-I; Supplemental Tables 4.10-4.12).

5.3.5 Comparison of phytochemical concentration by genotype classification

The open pollinated and F_1 hybrid cultivars were compared across trials for each phytochemical analysed (Figure 5.2A). The levels of glucoraphanin in F_1 hybrids tended to be higher than the open pollinated cultivars. But the inverse trend was observed for glucobrassicin, which was supported by the ranking and stability analysis where the F_1 hybrids showed higher levels and more stability across trials than the open pollinated cultivars for glucoraphanin. The reverse was observed for glucobrassicin. For the carotenoids, the open pollinated cultivars had a significantly higher mean value of lutein and zeaxanthin and tended to be higher for β-carotene compared to the F_1 hybrids.

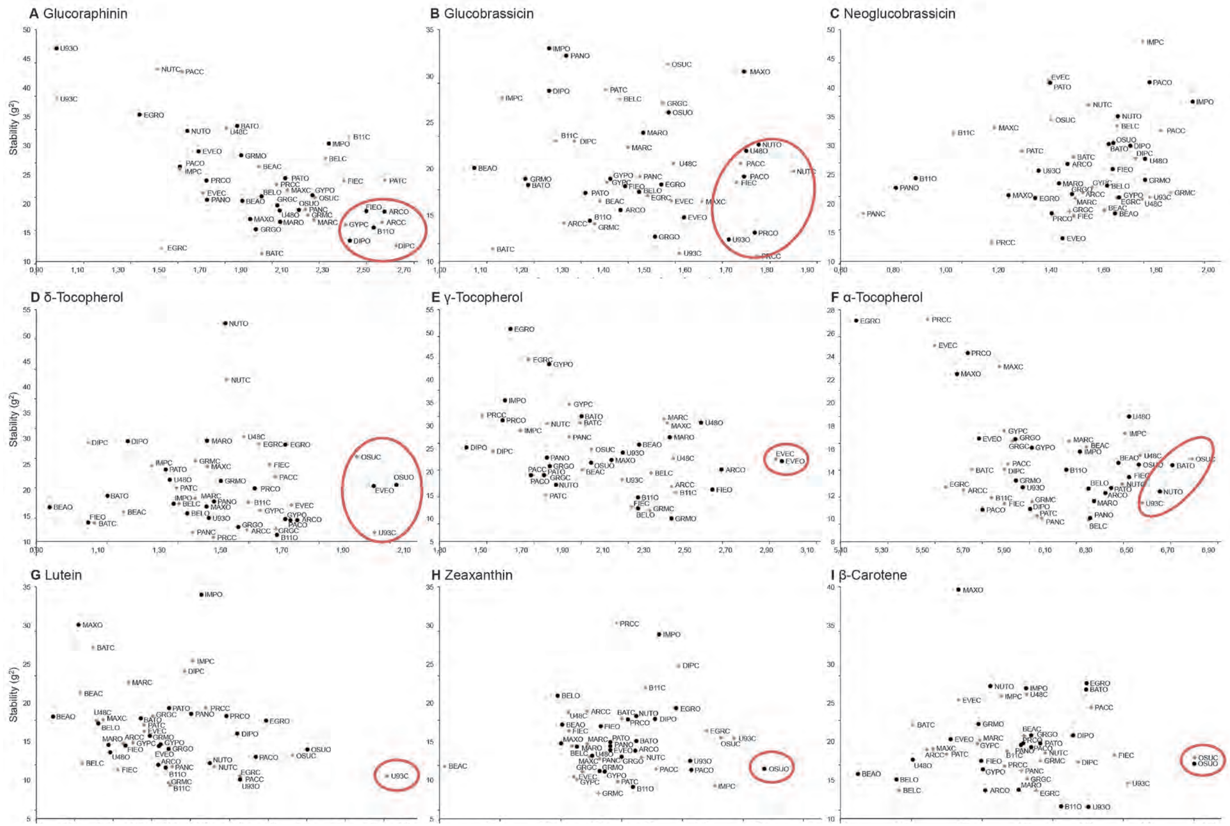

Figure 5.1 Broccoli cultivar stability from trials conducted in two locations over four seasons with two management systems plotted against phytochemical content. A. Glucoraphanin, B. Glucobrassicin, C. Neoglucobrassicin, D. δ-tocopherol, E. γ-tocopherol, F. α-tocopherol, G. Lutein, H. Zeaxanthin, I. β-carotene. See Table 5.1 for cultivar name abbreviations. The C or O at the end of the cultivar abbreviation indicates conventional or organic management system, respectively.

Based on the results of our field trials, the 23 cultivars of broccoli were grouped into three distinct maturity classes: Early (55-63 days); Mid (64-71 days); and Late (72-80 days) and analysed for the effect of the maturity class on phytochemical content (Figure 5.2B). For glucoraphanin, late maturing cultivars had significantly higher content levels, while for the carotenoids, early maturing cultivars tended to have higher concentrations and were significantly higher for lutein.

When cultivar performance between genetic material originating from two primary broccoli breeding companies was compared for phytochemical content there were no significant differences with the exception of lutein, where company 1's cultivars had significantly higher concentrations than those of company 2 (data not shown).

A negative correlation between the date of release and levels of glucobrassicin (R^2= 0.21; p=0.03) (Figure 5.3) was observed, but no significant correlations for any other phytochemical were seen when 21 cultivars (the total set minus the two inbred lines) were analysed by their date of commercial release (1975-2005).

5.3.6 Correlation analysis among phytochemicals and horticulture traits

Phytochemical correlation across trials

Correlation among phytochemicals indicated that glucoraphanin was significantly negatively correlated to glucobrassicin (Table 5.5). Correlations between the glucosinolates and the tocopherols were not significant. Glucoraphanin and neoglucobrassicin were negatively correlated to all carotenoids but only lutein and glucoraphanin were statistically significant. Glucobrassicin demonstrated a positive trend with all carotenoids. No statistically significant correlations were observed within tocopherols. Δ-tocopherol was positively correlated, while γ-tocopherol was negatively correlated to all carotenoids. There were no significant correlations for α-tocopherol with carotenoids. All carotenoids were highly positively correlated with one another.

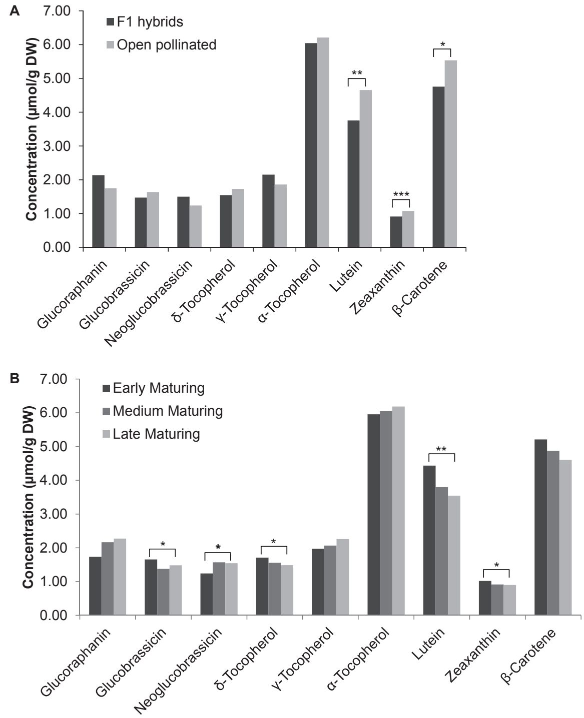

Figure 5.2 A. Mean phytochemical content of broccoli F1 hybrids versus open pollinated cultivars, and B. Mean phytochemical content of early, mid- and late-maturing cultivars grown across all trials at two locations (Maine and Oregon), in two seasons (Fall and Spring) and in two management systems (Conventional and Organic) and conventional management systems. See Table 1 for key to cultivar F1 hybrid versus open pollinated classification and maturity classification.

Significance (* = $P < 0.05$, ** = $P < 0.01$, *** = $P < 0.001$).

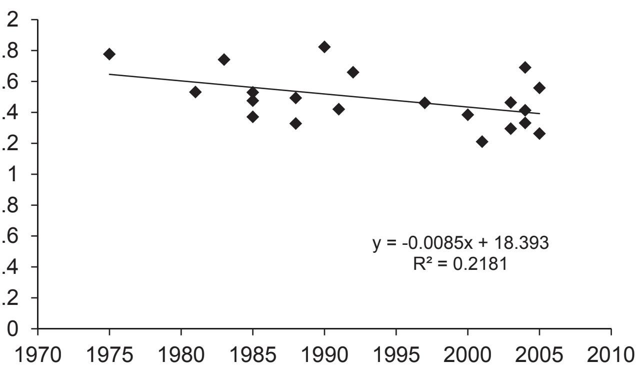

Figure 5.3 Regression of broccoli floret glucobrassicin concentrations on date of cultivar release for 23 cultivars grown across all trials in two locations (Maine and Oregon), in two seasons (Fall and Spring), in two management systems (Conventional and Organic), 2006-2008.

Phytochemical correlation to horticulture traits across trials

A correlation analysis was conducted for six horticulture traits, derived from the field study component of this research, Renaud et al. (2014), and the nine phytochemicals across trials. The results indicated that greater head weight and head diameter were significantly positively correlated with glucoraphanin and negatively correlated with glucobrassicin, δ-tocopherol and the carotenoids. Increasing days to maturity was positively correlated with glucoraphanin, and negatively correlated to carotenoids. Head color was significantly correlated with δ-tocopherol and the carotenoids, but not with glucosinolates or γ- and α-tocopherol. Bead size and bead uniformity were positively correlated with glucoraphanin, neoglucobrassicin and γ-tocopherol and negatively correlated with glucobrassicin and the carotenoids.

Table 5.5 Correlations coefficients (r) for six horticultural traits and nine phytochemicals, calculated using data standardized across trials. Correlation results include means from 23 cultivars, across eight pair combinations of location (Maine/Oregon), season (Fall/Spring) and management system (Conventional/Organic), 2006-2008[a].

	Head Weight	Head Diameter	Maturity	Head Color	Bead Size	Bead Uniformity	Glucoraphanin	Glucobrassicin	Neoglucobrassicin	δ-tocopherol	γ-tocopherol	α-tocopherol	Lutein	Zeaxanthin	β-Carotene
Head Weight															
Head Diameter	0.81														
Maturity															
Head Color															
Bead Size	0.63		0.69												
Bead Uniformity	0.49	0.48													
Glucoraphanin	0.47	0.44	0.43		0.63	0.51									
Glucobrassicin	-0.54	-0.50			-0.56	-0.64	-0.51								
Neoglucobrassicin			0.58		0.48										
δ-Tocopherol	-0.55			0.49											
γ-Tocopherol					0.43										
α-Tocopherol															
Lutein	-0.65		-0.70	0.56	-0.69		-0.41			0.55	-0.54				
Zeaxanthin	-0.68	-0.43	-0.62	0.49	-0.64					0.60	-0.42		0.95		
β-Carotene	-0.53		-0.54	0.59	-0.48					0.50	-0.43		0.90	0.90	

[a] For empty cells, r is not significantly different from zero (P < 0.05).

5.3.7 Principal component biplot analysis: correlation between phyto chemicals and cultivars by production system

In the principal component analysis the first PC axis accounted for similar amounts of the total variation in both conventional and organic production systems (43.5% vs. 39.6%). The second PC axis showed a similar trend with 17.02% for conventional and 16.93% for organic (Figure 5.4A and 4B). The first two PC axes together accounted for 60.53% and 56.57% of total variation for conventional and organic, respectively. The PCA biplot analysis supported our findings that carotenoids were highly associated across systems, while tocopherols were highly associated in conventional, but not in organic (tocopherols demonstrated the largest shift between production systems). Glucoraphanin and neoglucobrassicin were associated with one another, but not with glucobrassicin across production systems. Glucoraphanin was associated with α-tocopherol in organic, but not in conventional treatments. Glucobrassicin was associated with δ- and α- tocopherol in conventional, but not in organic treatments. δ-tocopherol had a higher association with the carotenoids in organic than conventional. The biplots show response of both cultivars and phytochemical traits to environment. Those cultivars close to the origin reveal little about the relationship of cultivars and trait vectors, whereas those located near the extremes of trait vectors are those with the highest (or lowest) values for those traits.

5.4 Discussion:

5.4.1 Impact of organic management system compared to environmental factors on phytochemical content

Few studies have specifically compared the levels of health promoting compounds in *Brassica* vegetable species grown under organic and conventional production systems (Meyer and Adam, 2008; Naguib et al., 2012; Picchi et al., 2012). To our knowledge, this investigation is the most comprehensive study with the broadest range of phytochemical compounds (9) and a diverse set of broccoli cultivars (23) over regions (2), and management systems (2), with Fall and Spring season trials (2 each). In this study organic versus conventional management systems contributed the smallest source of variation compared to genotype, region and season. Within the phytochemicals studied individual

5

compound concentrations responded differently. All compounds showed genetic variation, but also a substantial proportion of variance components were accounted for by high level interactions (Table 5.3; Supplemental Table 5.2). While M main effect was generally small, it had a substantial contribution in three- and four-way interactions. In particular, many G×L×S×M interactions were large relative to other variance components. This indicates that for the phytochemicals, M did have an influence on G, but that there were no consistent patterns across locations and seasons that would have shown up as significant G×M. Rather in each season and location, the paired organic and conventional environments differed significantly from one another but each situation was unique. In contrast to many comparisons between organic and conventional production systems (De Ponti et al., 2012), it should be noted that in our trials, yields averaged over the years did not differ significantly between the organic and conventional management systems (Renaud et al., 2014).

Among the nine compounds, glucoraphanin was the most strongly influenced by genotype followed by lutein: supporting the findings of several other broccoli studies where variation in concentrations for glucoraphanin (Brown et al., 2002; Farnham et al., 2004; Charron et al., 2005ab) and lutein (Farnham and Kopsell, 2009; Ibrahim and Juvik, 2009) was primarily due to genotype. For γ-tocopherol, genotype was a large source of variation, but this compound was equally influenced by location and season (also found by Ibrahim and Juvik, 2009). For glucobrassicin and neoglucobrassicin the location was the largest source of variation, but also L×S interaction was very influential, particularly for neoglucobrassicin, which is supported by Kushad et al. (1999) and Schonhof et al. (2004). Jasmonic acid, a signal transduction compound in plants, is up-regulated under conditions of plant stress, wounding, and herbivory. Increased endogenous levels or exogenous application of this compound (or methyl jasmonate) increases biosynthesis and transport of neoglucobrassicin to broccoli florets. This up-regulation was not observed for glucobrassicin biosynthesis (Kim and Juvik, 2011). This could explain why neoglucobrassicin was primarily under the control of Location and L×S interaction in our study. Season was the largest variance component for δ-tocopherol and zeaxanthin, which contrasts with the work of Ibrahim and Juvik (2009) who found genotype had the largest influence on these compounds, followed by genotype by environment interaction although this study was constrained by the fact that

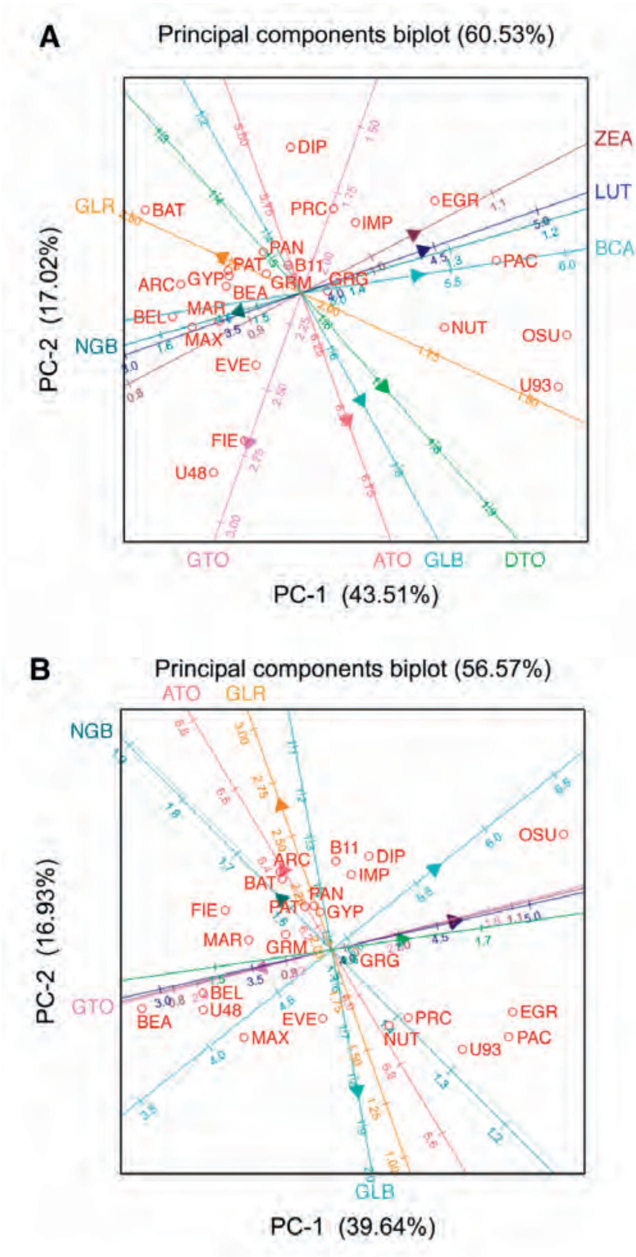

Figure 5.4 Principal components biplot of phytochemicals (vectors) and 23 cultivars (circles) grown in four seasons in Oregon and Maine. A. Biplot for conventional production, B. Biplot for organic production. See Table 1 for cultivar name abbreviations. Trait abbreviations: GLR: Glucoraphanin; GLB: Glucobrassicin; NGB: Neoglucobrassicin; DTO: δ-tocopherol; GTO: γ-tocopherol; ATO: α-tocopherol; LUT: Lutein; ZEA: Zeaxanthin; BCA: β-Carotene.

the experiment was conducted in only one location over two growing seasons. For the other compounds such as α-tocopherol and β-carotene, L×S and the G×L×S interactions were most important.

Overall we found high genetic correlations between glucosinolates in organic and conventional trials. When trial locations were analysed separately, M main effect was present for glucobrassicin and neoglucobrassicin. The mean concentrations of glucobrassicin and neoglucobrassicin in broccoli from Oregon organic trials had higher concentrations compared to Oregon conventional trials, while Maine trials were comparable between management systems (Table 5.2, Supplemental Figure 5.1A-C**)**. These results can be explained by the larger environment effect on glucobrassicin and genotype by environment effect on neoglucobrassicin found in the variance component analysis indicating sensitivity of these compounds to abiotic and/or biotic stresses. Our location specific findings are supported by those of Meyer and Adam (2008) who performed a comparative study of the glucosinolate content of store bought organic and conventional broccoli and determined that the indolyl glucosinolates, glucobrassicin and neoglucobrassicin were significantly higher in the organically grown versus the conventionally grown. Evaluation of 10 broccoli genotypes over two years by Brown et al. (2002) further supports our findings and those of Rosa and Rodrigues (2001), Vallejo et al. (2003), and Farnham et al. (2004), that variation in concentration for glucoraphanin was primarily due to genetic variation, while differences in glucobrassicin was due to environmental variation (e.g. season, temperature) and genotype by environment interaction. The significantly higher levels of glucobrassicin in Oregon in the Fall harvested trials compared to Maine could be attributed to the higher maximum temperatures and GDD in Oregon compared to Maine.

Compared to glucosinolates, there is substantially less research on the genotype by environment interaction of tocopherol and carotenoid phytochemical groups in broccoli, and no specific studies exploring the influence of organic production system. In our study, minor management system effect at the overall trial analysis level was observed for the tocopherols and for carotenoids, there was management system effect only for lutein in Oregon Spring trials. Picchi et al. (2012) also did not find differences in levels of carotenoids in cauliflower in organic versus conventional systems. In the tocopherols, there were no significant differences in location, but for δ- and γ- tocopherol concentration levels were higher in the fall compared to the spring, while for α-tocopherol, concentration levels were higher in the spring compared to the fall. For the carotenoids, there were no significant location differences, however there was a seasonal trend that all carotenoids were higher in spring compared to fall. Ibrahim and Juvik (2009) found significant environmental variation among 24 broccoli cultivars for carotenoids and tocopherols which they attributed to the stressful production environments. Factors explaining the genotype and genotype by environment interaction components of variation in the carotenoids and tocopherols could be clarified by the fact that environmental stimuli are both up- and down-regulating genes associated with carotenoid and tocopherol biosynthesis. There is evidence in the literature that there are coordinated responses of the carotenoid and tocopherol antioxidants *in vivo*. There was a reduction in rape seed (*Brassica napus*) tocopherol content in response to increased carotenoid levels due to over expression of the enzyme phytoene synthase (Shewmaker et al., 1999). This response could explain the negative correlation between γ- tocopherol concentration and the carotenoids observed in our trials.

5.4.2 Differences in phytochemical content between different genotypes and genotypic classes

The partitioning of variance indicated that genotype was an important source of variation for all glucosinolates. The cultivar ranking and rank correlation analysis demonstrated that there was a pattern in genotype content of glucosinolates where cultivars with the highest concentrations of glucoraphanin had the lowest levels for glucobrassicin (Supplemental Figure 5.1A-C). In our trials, the range in glucoraphanin concentrations across cultivars was (1.15-7.02 μmol/g DW, Supplemental Table 5.4), while glucobrassicin was 1.46-3.89 μmol/g DW, Supplemental Table 5.5). Several of the cultivars with the highest concentrations of neoglucobrassicin were those that had the highest concentrations of glucobrassicin. Range in neoglucobrassicin concentrations across cultivars was 0.68-4.54 μmol/g DW, Supplemental Table 5.6). In earlier studies, glucosinolate concentrations in broccoli have shown dramatic variation among different genotypes. Rosa et al. (2001) studied total glucosinolate levels in eleven cultivars of broccoli and found ranges from 15.2-59.3 μmol/g DW. Among 50 accessions of broccoli Kushad et al. (1999) found glucoraphanin content ranges from 0.8-

22 mmol/g DW with a mean concentration of 7.1µmol/g DW, while Wang et al. (2012) found glucoraphanin content of five commercial hybrids and 143 parent materials ranging from 1.57-5.95 µmol/g for the hybrids and 0.06-24.17 µmol/g in inbred lines and Charron et al. (2005a) found ranges from 6.4-14.9 µmol/g DW. While the means in our study are somewhat lower, they are within the range of other studies.

A genotype effect was observed for tocopherols, but predominantly for γ-tocopherol. The PCA biplots (Figure 5.4AB) and the correlation analysis (Table 5.5) demonstrated the high positive correlations between δ-tocopherol, α-tocopherol and the carotenoids (α-tocopherol and β-carotene were also highly correlated in the Kushad et al. (1999) study. The cultivar relationship to different phytochemicals was represented in the biplots as well as in the cultivar content and stability analysis (Figure 5.1). Many cultivars with the highest concentrations in the tocopherols and carotenoids were open pollinated cultivars, inbreds and early maturing, older F_1 hybrids. Many of this same group were also relatively high in glucobrassicin concentrations. Kurilich et al. (1999) found that carotenoid and tocopherol concentrations among 50 broccoli lines were highly variable and primarily genotype dependent. Specifically, levels of β-carotene ranged from 0.4-2.4 mg/100 g FW. Ibrahim and Juvik (2009) also found broad ranges for total carotenoid and tocopherol concentrations among 24 genotypes ranging from 55-154 mg/g DW and 35-99 mg/g DW, respectively. Farnham and Kopsell (2009) studied the carotenoid levels of nine double haploid lines of broccoli. Similar to our findings, lutein was the most abundant carotenoid in broccoli ranging from 65.3-139.6 µg/g DM. The sources of variation for lutein were predominantly genotype, followed by environment and GxE interaction, which also supports our findings. No genotypic differences were found for β-carotene in Farnham and Kopsell (2009), which is in contrast to our findings. Overall, they found that most of the carotenoids measured were positively and highly correlated to one another as was observed in our study (Table 5.5). Kopsell et al. (2004) found lutein levels in kale of 4.8–13.4 mg/100 g FW where the primary variance components for both lutein and β-carotene were also genotype and season.

Our research aimed also to address the question whether the phytochemical content of broccoli cultivars is associated with certain genotypic classes, e.g. open pollinated vs. F_1 hybrids; older vs. newer cultivar releases; and between commercial sources. Broccoli is typically a cross-pollinated, self-incompatible crop species and cultivars are either open pollinated and composed of heterogeneous genetically segregating individuals, or F_1 hybrids produced by crossing of two homozygous inbred lines, resulting in homogeneous populations of heterozygous individuals. In the 1960's virtually all broccoli grown was derived from OPs. By the 1990's almost all commercial cultivars were hybrids (Hale and Farnham, 2007).

In our trials with 18 F_1 hybrids (released between 1975-2005) and 3 open pollinated cultivars (released from 1985-2005), we found several interesting trends related to genotype and genotypic class performance as it related to the three groups of phytochemicals. When analysing F_1 hybrid and open pollinated cultivars, they also demonstrated different performance patterns depending upon the individual phytochemical or group of compounds analysed. When cultivars were ranked for content and stability per phytochemical, there were distinct trends for certain compounds such as late maturing, F_1 hybrids outperforming early maturing F_1 hybrids and open pollinated cultivars for glucoraphanin, while the inverse was found for glucobrassicin and all carotenoids studied. This analysis was further supported by the PCA biplots that showed a strong relationship for select cultivars to certain phytochemicals or groups of phytochemicals such as 'OSU OP' to the carotenoids. When the full set of cultivars was divided into F_1 hybrid and open pollinated groups and the means compared by phytochemical, the results further supported the individual cultivar analysis where F_1 hybrids had higher mean values for glucoraphanin than the open pollinated cultivars (Figure 5.2A). Clear cultivar performance differences were identified where early maturing versus late maturing cultivars performed differently depending upon the phytochemical (Figure 5.2B). We also found that late maturing cultivars had higher concentrations for glucoraphanin than early maturing lines (and the inverse for glucobrassicin and the carotenoids). Picchi et al. (2012) studied the quantity of glucosinolates of an early and late maturing cultivar of cauliflower grown in one conventional and three organic production systems, and found a significantly higher level of glucoraphanin in the later maturing cultivar compared to the early maturing cultivar in the organic production system. Another interesting trend was that cultivars with higher concentration levels for those phytochemicals whose expression is heavily influenced by environmental factors were not necessarily the most stable across trial environments; as was the case with neoglucobrassicin, δ- and γ-tocopherol in our study. For traits where genotype played a more significant role in contributing to variation, cultivars with a higher concentration level tended to also be those that were most stable across environments as was seen for lutein and glucoraphanin concentrations.

No significant differences were found for cultivar performance in phytochemical concentrations between genetic materials originating from two distinct commercial sources, with the exception of lutein (data not shown). When the full set of broccoli cultivars were analyzed for a correlation between date of release and mean level of phytochemical content across trials, no significant correlation was found with the exception of a negative trend for glucobrassicin (Figure 5.3**).** Our data does not support the idea that modern breeding for high yield performance and disease resistance necessarily leads to a trade-off in level of phytochemicals. Previous reports examining the relationship between year of release and performance had focussed on wheat vitamin and mineral content (Murphy et al., 2008); Hussain et al. (2010); Jones et al. (2010), and mineral content in broccoli (Farnham et al., 2011). However these authors did not study phytochemical content and their results were equivocal on the question on an innate biological trade-off between increased yield and nutritional content.

Not many studies have included two or more groups of phytochemicals. In our study with three phytochemical groups we found that phytochemicals demonstrating a negative correlation with one another (e.g. glucoraphanin with the carotenoids), showed an inverse cultivar response: e.g. cultivars with highest concentrations of glucoraphanin were the lowest in the carotenoids and vice versa. When both horticultural traits and phytochemicals were analysed for their phenotypic correlation, head weight was significantly and positively correlated with glucoraphanin and negatively correlated with δ- and α-tocopherol and the carotenoids. Farnham and Kopsell (2009) explained that negative correlations may occur as a result of increased biomass accumulation in a certain genotype that is not accompanied by increased carotenoid production, effectively lowering the carotenoid concentration in the immature broccoli florets when pigments are expressed. Comparatively, head color was highly correlated to the carotenoids and negatively correlated to the glucosinolates overall. The cultivar

'OSU OP' was explicitly bred for a dark green stem and head color, not only for a darker green dome surface but also for a dark green interior color between the florets of the dome and in the stem (personal communication, Jim Myers 2013). 'OSU OP' was the highest in overall carotenoid concentrations across trials as it is known that carotenoids are correlated with chlorophyll concentrations and the intensity of green pigmentation (Khoo et al., 2011).

5.4.3 Perspectives on breeding broccoli for enhanced phytochemical content specifically for organic agriculture

Our study included predominantly broccoli cultivars selected for broad adaptability in conventional production systems and not purposely bred for high phytochemical content nor for adaptation to organic agriculture. What we can conclude from our data is that there has been little change in levels of several phytochemicals over three decades of breeding. This may indicate genetic variation for phytochemicals is limited in elite germplasm, or it may be the result of the lack of selection tools for these traits. This may be changing with recent efforts to introgress high glucoraphanin from *B. villosa* to produce the high-glucoraphanin F_1 cultivar 'Beneforté' (Faulkner et al., 1998; Mithen et al., 2003; Traka et al., 2013). The seed industry needs to exploit known sources of variation in the genus *Brassica* to enhance levels of other health-promoting phytochemicals and to broaden the genetic diversity of commercial broccoli germplasm. Our finding of a strong correlation between dark green color and high carotenoid levels provides breeders with a simple and efficient means of increasing carotenoids. The three groups of phytochemicals studied contribute to health promotion in different ways. As these groups are related to different metabolic pathways selecting for one compound does not necessarily inadvertently improve the other compounds, and may even result in negative correlation as we have seen in our data between glucoraphanin and the carotenoids. Although these compounds belong to different metabolic pathways, their production may be coordinated through regulatory feedback loops, or the structural and/or regulatory genes controlling these pathways may be genetically linked.

Designing a breeding program for broccoli high in glucosinolates would require the following considerations generated from our research: (1) Glucoraphanin is a highly genetically determined compound with minor location and season main effects but with substantial G×L×S interaction., (2) Comparatively, glucobrassicin and neoglucobrassicin are more impacted by location and season and L×S interaction with highest glucobrassicin concentrations and largest range in our Oregon Fall trials and neoglucobrassicin highest in Oregon Spring trials., (3) Cultivar performance for glucoraphanin and glucobrassicin and neoglucobrassicin was negatively correlated indicating that there may be a trade-off between glucoraphanin on the one hand, and glucobrassicin and neoglucobrassicin on the other hand., (4) Selection for glucoraphanin without consideration of horticultural traits would probably result in larger headed and later maturing cultivars. Conversely, selection for smaller headed, early maturing cultivars would favor glucobrassicin and neoglucobrassicin at the expense of glucoraphanin.

A breeding program for broccoli for high tocopherol content would require: (1) Overall the tocopherols were more season, location and L×S dependent and had lower overall repeatabilities compared to the glucosinolates. In a structured genetic population where additive genetic variance could be partitioned, narrow sense heritability would likely be low, and increasing tocopherol content would best be conducted with breeding methods suited to low heritability traits., (2) δ- and γ-tocopherols were both season dependent and fall grown broccoli had higher concentrations of these compounds across trials and a wider range of content levels, whereas levels of α-tocopherol were higher in spring but the range was comparable under both seasons. Thus, fall would be the preferred environment for breeding for these compounds., (3) There were no significant differences for location for δ- or γ-tocopherol, but the average levels of α-tocopherol levels were significantly higher in Oregon than Maine, suggesting greater potential for genetic gain in the Oregon environment.

If the goal is to design a breeding program for broccoli enhancing the levels of carotenoids it would require the following considerations: (1) For all three carotenoids studied, genotypic variation, particularly for lutein, was relatively more important than location and season., (2) However, zeaxanthin exhibited a large S (spring) and L×S interaction. For both β-carotene and lutein, spring grown broccoli had significantly higher levels than fall produced. Thus, selection for carotenoids would probably be more effective in spring than in fall., (3) Early maturing and small headed cultivars had higher levels of carotenoids. Since most of the carotenoids are associated with the outer surfaces of the inflorescence, smaller broccoli heads with a greater surface area to volume ratio should show higher concentrations of these compounds., (4) Because carotenoids have high G main effect good germplasm sources as indicated in Figure 5.1 have high concentrations of carotenoids and demonstrated stability across environments. As all three carotenoids are highly correlated with one another, selecting for one should effectively select for all., (5) Selection for darker green colour more widely distributed throughout the tissues of the head should allow the breeder to relatively efficiently increase carotenoid content in broccoli.

In closing, we want to address the question of selecting in an organic or a conventional environment. The argument commonly used to support selecting in productive environments is that heritabilities are higher compared to resource poor environments (Ceccarelli, 1994; 1996). Organic is often considered a low-external input environment, resulting on average in 20% less yield compared to conventional production (De Ponti et al., 2012). Nevertheless, in our trials repeatabilities for some phytochemicals were higher or comparable to conventional (Table 5.3**).** Narrow sense heritabilities would be expected to be significantly lower. For those traits where repeatabilities were higher or comparable, direct selection under organic systems could enhance selection gain. In all cases, the ratio of correlated response to direct response was less than one suggesting that direct selection would allow more rapid progress than correlated selection. Our data on phytochemicals did not show a wider range of levels under organic conditions as we found for horticultural traits in the same trials (Renaud et al., 2014), however, in several cases, repeatabilities in organic production were higher than in conventional.

To maximize efficiency in a breeding program, commercial breeders may seek to combine breeding for both conventional and organic markets, and a combination of strategies can be proposed. Some studies that utilized highly heritable (agronomic) traits, where cultivar yield performance ranked similarly between organic and conventional management systems and which had high genetic correlations, suggested that early breeding be conducted under conventional conditions, with the caveat that advanced breeding lines be tested under organic conditions for less heritable traits (e.g. Löschenberger et al., 2008; Lorenzano and Bernardo, 2008). In studies where cultivar yield performance differed between management systems and there were significant differences in cultivar ranking, and in some cases low genetic correlations for lower heritability traits (e.g. Kirk et al., 2012; Murphy et al., 2007), these studies recommended that cultivars intended for organic agriculture be selected only under organic conditions. In our study of phytochemicals, we would recommend for organic purposes selection under organic conditions for the compounds where genetic correlations between organic and conventional were moderate.

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Supplemental Information

Supplemental Table 5.1 Description of agronomic and environmental factors of the trial locations with paired organically and conventionally managed fields, 2006-2008.

					Field Management			
Location	**Season / Year**	**Planting Date**	**Harvest End Date**	**Preceeding Crop**	**Organic Fertilizer**		**Conventional Fertilizer**	
					Type	**Application**	**Type ($N-P_2O_5-K_2O$)**	**Application**
Oregon	Fall 2006	28/Jul	13/Oct	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500 kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Fall 2006	1/Aug	19/Oct	Cucurbits	Manure Compost	26,900 kg ha	10-10-10	560 kg/ha
Oregon	Spring 2007	10/May	23/Jul	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500 kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Spring 2007	31/May	22/Aug	Cucurbits	Manure Compost	26,900 kg ha	10-10-10	560 kg/ha
Oregon	Fall 2007	7/Aug	20/Nov	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500 kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Fall 2007	14/Aug	20/Nov	Cucurbits	Manure Compost	26,900 kg ha	10-10-10	560 kg/ha
Oregon	Spring 2008	14/May	21/Jul	Lettuce	Chicken Manure; Oakleaf Compost; Gypsum	2,500 kg/ha; 22.200 kg/ha; 5,000kg/ha	12-29-10	504 kg/ha
Maine	Spring 2008	18/Jun	10/Nov	Cucurbits	Manure Compost	26,900 kg ha	10-10-10	560 kg/ha

Supplemental Table 5.1 Description of agronomic and environmental factors of the trial locations with paired organically and conventionally managed fields, 2006-2008 (continued).

		Field Management		Soils						Climate			
Location	Season / Year	Supplemental Irrigation (mm)		pH		g POM-N/kg soil[a]		Available N (ppm)[b]		Average Temp		Growing Degree Days[c]	Precipitation[d]
		Org	Conv	Org	Conv	Org	Conv	Org	Conv	Max (°C)	Min (°C)	(Base Temp 4.4°C)	(mm)
Oregon	Fall 2006	170.1	171.5	6.7	6.1	0.53	0.07	1.17	1.22	25.5	8.2	1741	48.3
Maine	Fall 2006	None	None	6.7	5.7	0.44	0.54	1.43	1.63	20.8	10.4	1611	279.4
Oregon	Spring 2007	131.9	135.4	6.4	6.5	0.35	0.06	1.14	1.48	24.2	9.0	1639	35.6
Maine	Spring 2007	None	None	6.2	5.4	0.48	0.50	1.83	1.99	24.8	13.6	2212	167.6
Oregon	Fall 2007	96.6	101.6	6.7	6.3	0.51	0.16	0.92	1.37	20.8	7.9	1823	274.3
Maine	Fall 2007	None	None	6.2	5.4	0.44	0.44	1.16	1.24	18.0	7.6	1573	370.8
Oregon	Spring 2008	157.2	156.5	6.9	6.4	0.64	0.11	1.55	1.75	24.1	9.2	1521	35.6
Maine	Spring 2008	None	None	6.4	5.5	0.47	0.43	1.53	1.53	21.0	11.1	3059	581.7

[a] g POM-N/kg soil: Particulate Organic Matter, a measure of longer term available nitrogen taken pre-fertilization.
[b] Available N (ppm): immediately available nitrogen at time of trial planting taken pre-fertilization.
[c] Growing Degree Days (GDD): average daily maximum and minimum temperatures across each trial period divided by base temperature for broccoli growth (4.4°C).
[d] Total Precipitation during trial period per location, season not including irrigation.

Supplemental Table 5.2a Partitioning (%) of variance components for various traits of 23 broccoli cultivars grown across four pair combinations in Maine, season (Fall/Spring) and management system (Conventional/Organic), 2006-2008. Variance components reported as coefficients of variation.

	Season (S)	Genotype (G)	Management (M)	S x M	S x M x Rep (R)	G x S	G x M	G x S x M	Residual
Glucoraphanin	10.89	14.15	0.00	15.35	0.73	19.82	0.00	17.44	12.35
Glucobrassicin	29.06	0.00	5.18	6.15	2.79	20.67	0.00	16.99	13.87
Neoglucobrassicin	66.18	10.67	6.10	7.01	6.32	21.51	0.01	14.19	17.74
δ-tocopherol	30.79	10.48	0.00	4.31	0.00	20.62	0.00	12.27	14.45
γ-tocopherol	13.49	5.74	0.00	9.18	2.40	20.60	0.00	12.49	13.01
α-tocopherol	15.58	3.60	0.00	0.01	1.54	8.74	0.00	9.99	9.38
Lutein	7.09	13.11	0.00	0.00	0.01	12.87	2.38	9.92	10.80
Zeaxanthin	13.05	7.77	0.01	0.00	0.00	7.97	0.00	8.59	11.06
β-Carotene	24.49	2.23	0.00	0.00	1.50	14.75	8.65	16.22	12.23

Supplemental Table 5.2b Partitioning (%) of variance components for various traits of 23 broccoli cultivars grown across four pair combinations in Oregon, season (Fall/Spring) and management system (Conventional/Organic), 2006-2008. Variance components reported as coefficients of variation

	Season (S)	Genotype (G)	Management (M)	S x M	S x M x Rep (R)	G x S	G x M	G x S x M	Residual
Glucoraphanin	8.71	17.80	0.00	5.52	2.16	13.82	0.00	11.39	11.49
Glucobrassicin	24.94	14.51	4.37	3.60	1.29	8.19	0.00	7.19	9.08
Neoglucobrassicin	18.66	17.25	7.14	8.42	3.92	13.31	0.00	12.33	14.14
δ-tocopherol	40.18	5.38	2.23	1.13	0.00	7.99	0.00	11.85	11.21
γ-tocopherol	27.58	18.18	0.00	0.01	1.77	19.52	0.01	9.85	11.21
α-tocopherol	0.01	5.13	0.00	0.01	1.00	10.67	0.00	6.72	8.51
Lutein	10.02	14.05	0.00	4.50	1.88	8.82	0.00	8.21	9.13
Zeaxanthin	11.28	10.08	0.01	0.00	0.68	5.84	2.41	8.29	11.58
β-Carotene	9.37	12.16	0.00	1.55	0.00	7.91	0.00	9.22	9.88

Supplemental Table 5.3 Repeatability for broccoli for phytochemicals and per trial of 23 broccoli cultivars grown across eight pair combinations of location (Maine/Oregon), season (Fall/Spring) and management system (Conventional/Organic), 2006-2008.

	Maine								Oregon							
	Fall				Spring				Fall				Spring			
	2006		2007		2007		2008		2006		2007		2007		2008	
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O
Glucoraphanin	0.88	0.86	0.99	0.97	0.92	0.88	0.97	0.95	0.93	0.92	0.94	0.93	0.91	0.94	0.96	0.92
Glucobrassicin	0.93	0.96	0.95	0.95	0.93	0.89	0.89	0.83	0.89	0.89	0.9	0.9	0.94	0.92	0.93	0.92
Neoglucobrassicin	0.87	0.52	0.91	0.93	0.81	0.92	0.85	0.74	0.88	0.95	0.88	0.87	0.9	0.92	0.93	0.75
δ-tocopherol	0.96	0.96	0.87	0.76	0.85	0.72	0.59	0.85	0.62	0.21	0.9	0.91	0.81	0.89	0.91	0.74
γ-tocopherol	0.91	0.93	0.98	0.96	0.76	0.73	0.53	0.89	0.96	0.91	0.98	0.98	0.87	0.88	0.94	0.93
α-tocopherol	0.89	0.86	0.83	0.94	0.69	0.78	0.86	0.89	0.98	0.93	0.9	0.88	0.75	0.81	0.77	0.7
Lutein	0.97	0.98	0.94	0.92	0.85	0.82	0.95	0.79	0.91	0.96	0.92	0.89	0.91	0.91	0.93	0.95
Zeaxanthin	0.91	0.97	0.88	0.76	0.69	0.75	0.79	0.85	0.9	0.75	0.88	0.85	0.8	0.79	0.83	0.87
β-Carotene	0.98	0.99	0.88	0.93	0.73	0.84	0.81	0.96	0.9	0.96	0.89	0.9	0.89	0.9	0.92	0.88

Supplemental Table 5.4 Glucoraphanin level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	6.05	5.07	15.12	9.12	5.92	8.56	1.60	7.06	8.83	5.05	5.80	6.42	8.09	7.03	6.06	6.50	7.02	7.19	6.85
B1 10	5.18	3.72	13.83	6.66	5.63	8.81	1.57	8.06	6.16	6.50	4.90	4.85	9.63	6.35	4.05	7.97	6.49	6.37	6.61
Batavia			4.92	2.13	2.49	4.69	8.95	4.14			2.31	2.58	5.84	6.19	1.70	2.38	4.03	4.37	3.69
Beaumont				5.93	4.88	3.28	2.42	2.89			3.17	2.40	6.97	7.33	3.09	1.55	3.99	4.11	3.90
Belstar	4.20	3.38	12.82	4.84	6.31	5.89	1.12	0.86	8.23	3.73	3.34	3.97	4.16	6.21	6.62	4.82	5.03	5.85	4.21
Diplomat			10.41	4.78	8.20	8.33	9.04	3.53			2.29	3.24	5.84	8.24	8.66	8.92	6.79	7.41	6.17
Early Green	2.88	3.80	2.99	0.82	1.94	2.54	1.56	1.67	2.02	1.18	1.29	1.69	3.98	2.43	2.20	2.43	2.21	2.36	2.07
Everest	2.41	5.03	4.58	0.40	3.26	5.50			2.09	1.64	1.43	2.12	4.79	5.26	2.84	2.57	3.14	3.06	3.22
Fiesta	4.60	4.43		5.81	5.80	5.61	3.75	9.22	5.69		4.61	5.04	12.22	8.54	5.38	6.28	6.21	6.01	6.42
Green Goliath	2.62	4.70	12.45	4.41	4.92	7.94	1.12	1.23	6.04	1.66	3.58	5.32	2.93	2.52	4.63	5.79	4.49	4.79	4.20
Green Magic	3.66	3.99	9.60	2.08	6.46	5.02	3.47	3.28	3.64	3.53	3.88	3.21	4.15	3.20	6.27	5.09	4.41	5.14	3.68
Gypsy	4.88	5.03	11.56	2.04	8.73	9.85	1.44	1.67	6.33	9.12	5.17	5.29	6.89	4.42	4.51	6.17	5.82	6.19	5.45
Imperial				5.33		10.13	0.31	2.40			2.81	3.42	3.99	5.39	4.76	7.68	4.62	2.97	5.73
Marathon	3.30	2.51	9.85	6.39	5.70	3.54	3.45	4.83	4.91	3.64	6.42	5.08	6.27	5.17	2.61	4.51	4.89	5.31	4.46
Maximo	2.35	2.36	9.42	4.64	7.79	6.82	1.89	1.97	3.10	2.47	4.39	4.19	7.31	6.13	2.91	3.14	4.43	4.90	3.97
Nutribud	3.40	4.01	3.28	1.10	2.37	5.73	2.62	1.97	2.15	2.25	1.71	1.97	2.17	2.33	0.81	3.33	2.58	2.31	2.84
OSU OP	10.25	10.64	3.55	1.86	5.92	7.05	6.59	2.43	2.64	2.35	4.65	5.16	6.72	7.23	2.70	4.59	5.27	5.38	5.16
Packman	3.40	4.08	2.25	1.36	3.61	4.48	2.88	1.51	1.01	1.36	2.27	4.62	4.89	2.73	1.53	1.74	2.73	2.73	2.73
Patriot			7.41	4.74	5.07	7.48	11.40	1.84			2.89	2.93	7.36	8.57	8.29	3.27	5.94	7.07	4.81
Patron	7.33	3.96	11.99	4.47	4.52	4.58	0.51	0.27	4.13	1.72	2.14	2.15	9.82	4.01	4.31	5.49	4.46	5.59	3.33
Premium Crop	6.52	6.15	5.51	1.39	7.39	7.01	1.84	1.03	3.84	1.99	1.46	1.92	5.50	2.96	4.43	4.14	3.94	4.56	3.32
USVL 048	3.25	4.16		10.52	3.80	4.66	1.88	1.56			5.27	5.38	2.58	2.40	3.83	4.28	4.12	3.43	4.71
USVL 093	0.10	0.30	0.67	0.55	1.12	2.91	1.96	1.27			0.47	0.43	1.44	0.64	2.30	1.99	1.15	1.15	1.16
																Mean	4.51	4.71	4.29

Supplemental Table 5.5 Glucobrassicin level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	0.47	0.38	2.19	1.54	1.99	1.55	0.35	1.45	5.25	6.72	3.05	3.93	1.02	1.51	1.46	2.04	2.18	1.81	2.39
B1 10	0.29	0.31	1.94	1.42	2.00	1.38	0.50	1.55	4.81	5.44	2.67	3.97	1.21	1.02	1.66	2.08	2.02	1.71	2.15
Batavia			0.87	0.62	1.13	1.15	1.16	1.24			2.98	2.72	1.17	1.54	0.80	2.07	1.46	1.35	1.56
Beaumont				2.32	1.68	1.85	0.59	0.74			3.35	2.73	2.04	2.00	2.68	3.51	2.13	2.07	2.19
Belstar	0.23	0.23	3.79	1.59	1.35	2.01	0.32	0.36	7.09	8.97	3.09	2.87	2.12	2.52	2.22	3.54	2.64	2.27	2.76
Diplomat			1.05	1.02	1.15	1.12	2.36	1.33			4.53	3.49	0.93	1.41	1.57	1.77	1.81	1.93	1.69
Early Green	1.28	1.14	1.55	0.74	1.74	2.42	1.38	0.57	4.99	4.14	3.70	5.51	2.18	2.58	2.44	4.49	2.55	2.28	2.70
Everest	0.44	0.34	1.07	0.63	2.21	2.15			5.48	5.94	3.69	5.07	2.51	2.83	3.75	3.86	2.86	2.45	2.97
Fiesta	0.40	0.42		2.36	2.29	1.97	1.57	1.80	8.44		4.60	4.43	3.56	1.32	3.05	3.97	2.87	3.04	2.32
Green Goliath	0.26	0.57	2.50	1.82	3.55	2.81	1.25	1.43	8.12	5.15	3.13	3.03	1.66	1.44	1.88	4.14	2.67	2.51	2.55
Green Magic	0.37	0.38	1.68	0.68	2.76	1.33	2.62	0.88	4.47	4.97	2.93	2.60	0.78	0.94	1.31	1.78	1.90	1.92	1.70
Gypsy	0.44	0.34	1.78	0.93	1.98	1.81	0.29	0.78	5.51	7.35	4.11	4.44	1.48	1.35	3.04	2.50	2.38	2.12	2.44
Imperial				1.48		1.30	0.45	0.52			2.65	2.79	1.28	1.87	1.40	2.21	1.60	1.44	1.70
Marathon	0.18	0.25	2.97	1.96	2.05	1.65	1.17	0.82	6.68	10.60	3.73	3.25	1.67	2.00	1.49	2.01	2.66	2.24	2.82
Maximo	0.24	0.43	4.02	1.74	2.44	2.71	0.42	0.45	8.32	10.21	6.46	6.31	2.37	4.05	2.13	3.79	3.51	2.96	3.71
Nutribud	0.91	0.88	3.23	0.76	3.25	3.62	0.59	0.46	8.84	8.02	5.79	6.69	4.28	3.14	4.68	7.09	3.89	3.61	3.83
OSU OP	1.36	0.90	0.90	0.49	2.17	2.71	1.47	0.43	4.93	6.67	3.87	4.63	3.67	3.93	2.43	3.33	2.74	2.46	2.89
Packman	2.07	1.20	1.40	1.05	2.91	1.95	0.48	0.46	5.55	7.71	4.56	7.71	6.56	4.15	3.31	4.72	3.49	3.21	3.62
Patriot			1.71	1.36	1.60	0.93	1.90	2.24			4.57	4.06	0.82	1.46	2.08	1.67	2.03	2.12	1.95
Patron	0.70	0.44	1.66	1.59	8.07	1.55	0.39	0.20	4.23	6.70	3.77	3.01	1.44	1.51	1.28	1.70	2.39	2.47	2.09
Premium Crop	1.55	2.16	2.77	0.91	4.05	3.84	0.51	0.24	9.43	11.01	4.42	4.67	2.47	2.75	3.38	4.65	3.68	3.35	3.78
USVL 048	0.39	0.80		5.00	1.80	3.46	0.81	0.46			6.31	5.65	3.91	4.00	4.30	4.90	3.21	2.56	3.47
USVL 093	0.31	0.69	2.11	2.59	2.86	2.59	0.66	0.75			5.99	5.87	3.99	4.37	4.61	6.35	3.13	2.61	3.32
																Mean	2.60	2.37	2.63

Supplemental Table 5.6 Neoglucobrassicin level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	0.27	0.18	1.53	0.67	5.29	4.07	0.37	1.31	3.49	6.66	1.66	3.75	5.57	4.33	4.67	5.08	3.06	2.86	3.26
B1 10	0.07	0.09	0.70	0.40	5.10	2.28	0.43	1.72	1.33	7.57	0.74	1.74	3.08	1.87	2.66	4.16	2.12	1.76	2.48
Batavia			0.97	0.74	4.96	2.98	1.07	0.90			4.12	4.39	6.01	3.91	3.09	8.66	3.48	3.37	3.60
Beaumont				1.38	3.87	3.05	0.70	0.64			1.10	1.45	6.17	9.16	7.63	7.30	3.86	3.89	3.83
Belstar	0.07	0.05	1.22	0.39	3.23	3.08	0.24	0.75	1.22	2.21	0.86	0.90	3.32	3.99	3.90	3.98	1.84	1.76	1.92
Diplomat			1.09	0.87	6.38	5.40	0.93	0.55			1.97	2.82	3.64	5.12	8.02	8.34	3.76	3.67	3.85
Early Green	0.32	0.31	0.73	0.39	2.87	1.83	2.03	1.03	2.63	3.66	1.90	3.45	4.97	1.53	1.87	9.00	2.41	2.17	2.65
Everest	0.18	0.16	0.48	0.68	2.97	3.25			4.25	4.29	1.30	3.77	3.22	3.26	3.94	6.83	2.76	2.33	3.18
Fiesta	0.10	0.16		0.86	3.61	4.02	1.29	1.14	1.97		1.43	1.90	7.32	4.54	8.53	7.92	3.20	3.46	2.93
Green Goliath	0.06	0.19	1.04	0.85	6.33	6.61	1.37	0.91	4.08	2.28	0.73	1.54	4.58	2.50	3.27	6.97	2.71	2.68	2.73
Green Magic	0.15	0.16	1.44	0.44	4.78	3.05	0.94	0.44	3.11	2.48	1.02	1.90	5.65	4.25	4.21	8.83	2.68	2.66	2.69
Gypsy	0.18	0.16	1.25	0.51	7.18	4.27	0.45	0.87	5.12	3.14	2.73	4.10	5.64	5.43	4.18	7.17	3.27	3.34	3.21
Imperial				1.08		3.86	0.40	0.66			1.22	1.65	4.40	4.61	4.48	6.63	2.90	2.63	3.08
Marathon	0.06	0.08	1.08	0.67	6.45	5.61	1.40	1.19	2.18	2.75	1.41	1.35	6.68	4.59	3.69	4.78	2.75	2.87	2.63
Maximo	0.11	0.15	1.13	1.22	7.37	4.67	0.45	0.38	5.15	8.32	2.21	2.92	5.05	4.68	2.86	5.12	3.24	3.04	3.43
Nutribud	0.13	0.10	0.71	0.10	1.95	1.54	0.94	0.34	3.31	1.39	0.73	1.06	1.03	0.77	0.99	2.31	1.09	1.22	0.95
OSU OP	0.28	0.29	0.43	0.24	2.86	4.60	1.34	0.51	3.79	3.06	1.63	2.51	2.74	2.52	1.95	5.62	2.15	1.88	2.42
Packman	0.10	0.04	0.14	0.12	0.99	0.33	0.28	0.33	1.04	1.40	0.35	0.91	0.88	1.67	0.51	1.81	0.68	0.54	0.83
Patriot			1.12	1.20	5.93	3.89	0.76	0.25			2.48	3.74	4.49	4.47	5.23	6.76	3.36	3.34	3.39
Patron	0.36	0.23	1.00	1.29	9.06	8.28	0.24	0.18	8.09	15.56	1.79	3.53	6.04	3.84	5.16	7.99	4.54	3.97	5.11
Premium Crop	0.44	0.49	1.32	0.15	6.27	3.68	0.32	0.73	3.39	8.12	2.12	2.63	4.99	6.08	2.21	4.71	2.98	2.63	3.32
USVL 048	0.10	0.21		1.59	5.17	4.61	0.79	0.25			1.26	2.25	10.73	11.52	10.71	9.40	4.51	4.79	4.26
USVL 093	0.14	0.53	1.08	1.23	8.33	4.73	0.35	0.58			1.48	1.54	6.23	8.22	6.99	6.95	3.46	3.51	3.40
																Mean	2.90	2.80	3.01

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Supplemental Table 5.7 δ-tocopherol level (μ mol/g DW) of 23 cultivars grown under organic (O) and conventional (C) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	4.66	3.37	1.19	1.58	1.59	1.47	1.73	2.59	6.09	6.77	1.69	1.60	1.94	7.67	2.94	2.11	3.06	2.73	3.40
B1 10	3.86	4.59	0.67	1.71	1.86	2.08	1.79	1.49	7.97	8.65	1.63	1.62	2.51	1.91	2.44	3.14	2.99	2.84	3.15
Batavia			0.73	0.84	1.69	0.95	1.33	1.13			0.98	0.98	2.17	1.92	0.58	2.14	1.29	1.25	1.33
Beaumont				0.57	1.34	1.33	1.74	1.32			0.82	2.12	1.89	1.75	1.35	2.95	1.56	1.43	1.67
Belstar	2.69	3.61	0.58	1.58	1.82	1.20	2.10	1.86	5.56	5.24	1.23	0.64	1.21	2.05	1.35	1.01	2.11	2.07	2.15
Diplomat			0.82	1.06	0.99	1.33	1.06	1.49			0.55	0.64	1.49	2.01	2.35	2.46	1.35	1.21	1.50
Early Green	6.91	8.43	1.07	1.97	3.12	3.12	1.43	1.44	7.54	8.14	0.74	0.81	1.53	1.66	2.38	1.95	3.26	3.09	3.44
Everest	9.08	10.38	1.38	1.20	1.25	2.85			7.87	8.70	2.12	2.90	1.30	2.29	2.02	3.38	4.05	3.57	4.53
Fiesta	3.42	2.26		0.78	1.16	1.27	1.95	0.47	8.08		1.93	2.58	3.22	1.26	1.64	2.65	2.33	3.06	1.61
Green Goliath	3.68	3.50	2.16	1.23	0.92	1.25	2.06	1.83	7.93	7.11	3.51	1.69	1.27	2.74	3.43	1.96	2.89	3.12	2.66
Green Magic	3.35	4.34	0.88	1.44	1.45	1.32	1.58	1.39	7.62	6.98	1.25	1.66	0.93	1.67	1.65	1.41	2.43	2.34	2.53
Gypsy	7.06	6.41	0.79	1.45	1.30	0.93	2.05	1.69	7.99	6.80	2.70	1.90	1.55	4.15	1.48	2.85	3.19	3.11	3.27
Imperial				2.18		1.95	1.37	1.07			1.20	1.21	2.39	3.62	1.68	1.40	1.81	1.66	1.91
Marathon	2.49	3.02	0.36	1.61	1.83	1.88	2.27	1.63	7.01	6.96	1.86	1.09	1.39	1.43	1.25	1.28	2.34	2.31	2.36
Maximo	2.10	1.25	0.75	1.18	3.37	1.94	1.74	3.92	6.15	6.26	1.08	1.14	1.66	1.83	1.94	1.29	2.35	2.35	2.35
Nutribud	2.84	3.70	1.49	1.35	3.69	1.96	2.11	1.56	7.47	6.21	0.86	1.08	1.32	1.25	1.19	3.07	2.57	2.62	2.52
OSU OP	14.64	21.86	0.76	1.87	2.40	2.51	3.99	3.42	9.31	6.79	0.95	1.87	1.71	1.85	3.97	3.23	5.07	4.72	5.42
Packman	8.98	6.80	1.58	1.57	1.41	3.86	1.66	1.85	6.10	7.19	1.75	0.94	1.45	1.54	2.96	3.10	3.30	3.24	3.36
Patriot			1.75	1.51	4.36	2.65	2.06	1.19			0.77	1.42	2.29	2.11	0.83	1.79	1.89	2.01	1.78
Patron	4.72	3.83	0.47	1.08	0.98	1.28	1.67	0.71	5.84	7.33	0.70	1.20	3.19	4.38	1.22	0.94	2.47	2.35	2.59
Premium Crop	3.04	7.38	0.70	0.72	1.92	1.65	1.97	1.46	6.74	7.66	0.89	1.48	1.60	1.72	2.71	2.38	2.75	2.45	3.06
USVL 048	2.52	2.44		1.16	2.90	1.76	1.83	1.87			1.34	0.64	4.04	3.52	2.71	1.78	2.19	2.56	1.88
USVL 093	2.46	2.75	2.00	2.17	8.63	1.52	2.58	2.03			1.35	1.77	2.69	2.86	2.87	2.03	2.69	3.22	2.16
																Mean	2.61	2.58	2.64

Supplemental Table 5.8 γ-tocopherol level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	5.78	5.59	10.05	5.60	2.85	3.67	2.45	8.03	14.53	14.54	12.05	10.17	2.33	11.90	3.40	2.26	7.20	6.68	7.72
B1 10	6.30	8.81	8.72	5.22	3.63	3.73	1.38	1.60	10.65	6.29	8.34	10.27	7.96	3.55	4.54	4.52	5.97	6.44	5.50
Batavia			4.07	2.99	2.56	3.22	2.46	5.19			7.84	6.55	6.86	5.43	1.77	1.61	4.21	4.26	4.17
Beaumont				8.96	1.51	2.38	1.67	3.50			13.77	14.39	5.63	3.50	1.93	2.53	5.43	4.90	5.88
Belstar	3.20	3.54	8.90	7.37	2.08	3.43	3.13	1.65	12.55	13.63	13.77	11.68	3.67	3.52	2.36	2.10	6.04	6.21	5.87
Diplomat			3.40	2.33	2.83	2.29	2.00	1.69			2.40	2.42	2.36	2.52	1.81	1.22	2.27	2.47	2.08
Early Green	2.60	3.51	1.58	0.95	2.52	3.23	2.67	1.71	5.25	5.87	3.95	2.16	3.85	2.89	2.44	2.68	2.99	3.11	2.88
Everest	4.01	9.35	8.21	3.94	3.19	4.59			13.89	14.26	16.65	16.75	6.02	4.08	13.71	14.13	9.49	9.38	9.59
Fiesta	4.49	3.76		8.69	2.23	2.59	5.25	4.23	15.30		12.76	12.27	8.11	4.08	2.88	3.04	6.40	7.29	5.52
Green Goliath	2.75	3.59	4.41	2.68	1.41	2.18	3.41	5.62	5.25	6.81	5.72	3.80	2.70	2.71	1.89	1.26	3.51	3.44	3.58
Green Magic	6.49	7.00	6.88	4.22	3.17	4.70	2.24	5.68	12.84	12.21	8.67	8.50	2.94	3.65	3.84	3.63	6.04	5.89	6.20
Gypsy	3.76	4.87	4.53	1.77	2.49	2.68	1.97	1.55	6.95	10.18	7.96	3.39	2.73	3.73	1.75	1.70	3.88	4.02	3.73
Imperial				3.60		2.91	3.20	4.46			3.30	2.37	4.42	1.72	1.18	1.35	2.85	3.02	2.73
Marathon	4.68	4.67	14.09	13.40	2.68	3.63	1.12	1.92	13.56	13.81	13.65	12.07	2.95	2.69	2.24	2.15	6.83	6.87	6.79
Maximo	3.02	3.97	16.92	2.35	3.80	4.89	1.53	1.65	4.41	4.73	14.70	12.01	5.33	8.07	4.20	2.68	5.89	6.74	5.04
Nutribud	2.05	3.57	1.94	0.99	3.25	3.21	2.60	2.62	15.49	14.46	2.37	2.32	2.32	2.98	1.92	2.58	4.04	3.99	4.09
OSU OP	6.79	6.53	1.82	2.47	5.10	4.17	1.95	2.71	6.62	6.23	4.39	4.78	4.76	5.71	3.55	2.10	4.35	4.37	4.34
Packman	3.40	2.82	1.89	1.18	4.83	5.10	2.60	1.82	5.32	8.87	2.79	2.40	2.27	2.04	2.04	2.71	3.26	3.14	3.37
Patriot			6.55	3.91	1.91	3.53	1.97	1.23			5.65	7.12	4.41	3.40	1.18	1.94	3.57	3.61	3.52
Patron	4.50	5.46	6.43	3.46	3.08	1.96	1.70	1.07	5.60	6.34	6.12	4.66	3.29	5.27	1.24	1.00	3.82	3.99	3.65
Premium Crop	3.83	7.98	1.31	1.30	1.94	1.93	2.22	1.05	6.03	4.60	1.43	2.24	1.66	1.58	1.32	2.52	2.68	2.47	2.90
USVL 048	5.97	6.31		5.40	3.79	5.70	1.71	2.82			15.21	17.64	9.33	6.49	4.04	5.78	6.94	6.67	7.16
USVL 093	2.84	3.96	9.87	8.93	6.63	3.06	1.52	1.92			12.52	17.04	3.00	3.03	2.06	1.95	5.60	5.49	5.70
																Mean	4.92	4.98	4.87

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Supplemental Table 5.9 α-tocopherol level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	18.52	19.92	28.67	28.13	43.15	47.18	12.59	30.50	40.93	55.38	44.89	44.77	34.17	66.58	47.56	45.04	38.00	33.81	42.19
B1 10	23.67	26.19	27.36	25.81	41.10	45.27	24.37	43.80	24.97	26.24	36.39	43.23	48.91	46.38	52.42	57.61	37.11	34.90	39.32
Batavia			19.65	27.47	46.74	50.09	25.87	54.55			33.54	45.69	45.65	53.48	30.93	43.18	39.74	33.73	45.74
Beaumont				28.42	35.67	39.85	29.98	34.53			53.97	68.30	50.45	38.24	31.64	46.12	41.56	40.34	42.58
Belstar	14.62	21.15	29.08	36.28	48.00	54.64	24.37	16.95	45.17	43.37	56.56	53.28	57.97	52.86	57.37	52.14	41.49	41.64	41.33
Diplomat			41.16	39.46	38.39	37.87	23.49	34.48			39.32	37.01	34.72	37.07	33.59	32.29	35.74	35.11	36.36
Early Green	24.48	15.78	30.61	21.60	37.11	37.56	24.85	15.30	20.82	26.32	40.70	30.57	41.46	36.52	35.83	36.69	29.76	31.98	27.54
Everest	26.94	30.43	29.22	13.72	39.32	77.94			21.30	25.16	33.13	40.31	34.59	21.35	33.61	41.11	33.44	31.16	35.72
Fiesta	16.47	18.40		56.59	55.60	48.71	34.03	49.81	89.67		58.23	47.37	42.82	54.48	38.82	30.01	45.79	47.95	43.62
Green Goliath	23.51	16.11	27.59	37.59	30.98	33.13	36.95	25.79	39.12	60.12	54.86	41.53	36.93	39.84	36.82	37.89	36.17	35.85	36.50
Green Magic	27.78	21.78	23.79	18.08	47.82	45.41	40.54	45.12	67.34	57.56	33.14	30.09	26.42	31.42	33.13	43.80	37.08	37.49	36.66
Gypsy	31.91	30.25	33.84	25.32	46.16	58.50	28.45	36.89	29.07	24.74	36.60	36.73	33.13	44.23	41.09	40.20	36.07	35.03	37.11
Imperial				58.29		44.18	56.93	43.53			53.28	40.87	42.16	32.59	21.47	21.62	41.49	43.46	40.18
Marathon	22.98	13.52	38.33	49.72	42.17	45.21	22.25	29.47	69.94	66.72	35.34	40.32	32.00	39.61	57.52	49.54	40.92	40.07	41.76
Maximo	10.92	11.94	32.54	39.54	66.55	47.05	15.34	27.80	46.30	27.18	37.68	28.83	39.80	48.12	44.86	35.62	35.01	36.75	33.26
Nutribud	22.49	38.06	42.63	24.61	59.01	47.49	28.24	26.71	93.31	98.27	34.03	38.92	33.74	44.61	39.24	53.00	45.27	44.09	46.46
OSU OP	35.23	26.34	32.10	36.92	57.25	66.58	50.10	33.70	66.48	44.81	42.01	54.53	48.22	54.54	45.35	34.13	45.52	47.09	43.94
Packman	25.77	19.16	25.85	22.34	60.87	70.22	36.81	23.02	19.54	27.27	42.79	31.85	37.82	37.13	38.64	50.80	35.62	36.01	35.22
Patriot			31.46	39.00	25.15	54.30	41.73	29.44			36.15	33.82	42.47	44.55	45.76	49.24	39.42	37.12	41.73
Patron	29.19	44.64	35.59	35.83	50.27	44.31	29.85	25.59	36.20	42.14	32.92	33.99	39.27	60.25	45.31	37.34	38.92	37.33	40.51
Premium Crop	17.26	31.04	22.40	22.24	36.48	38.58	31.55	23.73	42.71	30.12	29.90	39.09	31.73	41.07	36.12	39.20	32.08	31.02	33.13
USVL 048	15.47	11.36		34.50	58.46	60.23	33.38	48.83			39.84	51.39	68.83	49.07	55.43	55.08	44.76	45.24	44.35
USVL 093	23.15	20.77	47.91	57.67	83.61	42.22	33.09	25.87			46.59	52.54	45.96	28.70	33.60	31.30	40.93	44.84	37.01
																Mean	38.78	38.35	39.23

Supplemental Table 5.10 Lutein level (µ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

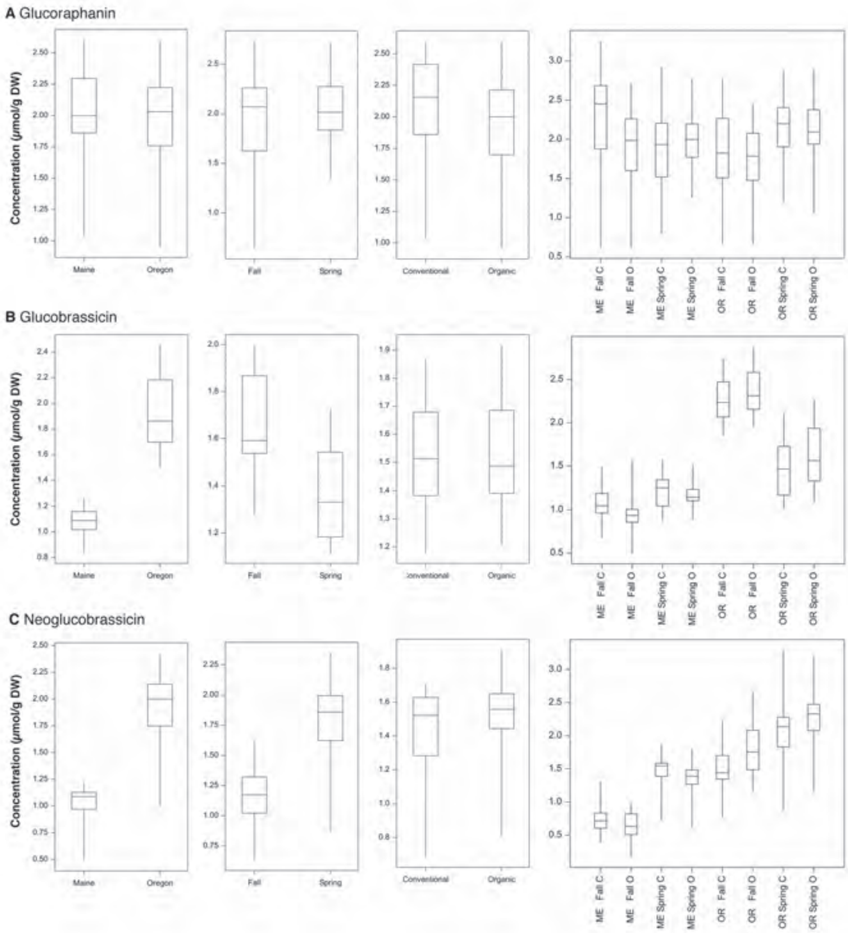
	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	10.03	8.00	9.46	11.63	12.18	16.09	16.02	12.04	20.50	17.44	10.06	12.98	4.45	25.14	18.35	14.97	13.71	12.63	14.79
B1 10	13.35	11.12	11.48	12.86	16.50	19.26	8.82	13.04	20.27	11.78	10.56	13.07	21.29	20.00	22.93	19.72	15.38	15.65	15.11
Batavia			7.07	9.17	14.68	18.31	9.84	12.64			6.65	10.92	12.72	14.63	12.23	14.65	11.96	10.53	13.39
Beaumont				5.71	7.82	5.55	5.07	8.23			9.80	12.83	6.67	6.01	22.26	11.97	9.27	10.33	8.38
Belstar	3.46	5.23	5.56	6.49	8.86	13.16	12.56	14.82	20.40	16.75	10.15	9.19	9.15	15.15	11.49	7.50	10.62	10.20	11.03
Diplomat			11.34	20.27	17.15	24.65	18.61	25.22			12.58	16.47	17.32	18.39	21.61	17.53	18.43	16.44	20.42
Early Green	15.72	25.27	19.66	13.87	21.52	20.06	5.77	13.59	29.16	32.53	21.97	18.99	22.77	26.39	34.98	35.67	22.37	21.44	23.30
Everest	15.25	22.95	13.70	8.59	12.37	18.59			19.10	14.81	10.30	11.72	10.04	9.76	14.52	17.30	14.21	13.61	14.82
Fiesta	5.54	4.50		12.50	11.17	13.61	13.42	15.67	15.64		10.98	13.59	14.56	14.23	12.74	13.90	12.29	12.00	12.57
Green Goliath	14.24	11.72	10.74	11.53	15.62	14.88	10.98	14.48	19.57	17.54	13.05	11.15	11.61	25.72	17.79	16.27	14.81	14.20	15.41
Green Magic	21.47	13.29	11.13	10.74	12.69	15.30	9.78	7.25	26.75	22.92	16.80	12.86	10.81	12.32	15.05	18.78	14.87	15.56	14.18
Gypsy	12.15	19.10	8.30	8.14	17.86	14.94	14.85	16.72	16.85	14.75	8.36	11.70	9.90	15.85	15.58	16.99	13.88	12.98	14.78
Imperial				16.57		24.93	17.05	18.95			12.99	12.51	24.30	25.12	14.14	9.70	17.63	17.12	17.96
Marathon	8.05	4.76	7.22	11.45	14.70	14.44	17.43	10.21	25.52	23.64	7.39	9.56	10.75	8.39	13.27	11.47	12.39	13.04	11.74
Maximo	4.90	4.17	6.57	8.58	21.38	15.22	4.60	6.72	23.13	17.01	7.91	6.91	8.38	8.82	18.90	11.95	10.95	11.97	9.93
Nutribud	21.48	21.78	14.34	12.70	22.15	17.45	17.70	7.21	15.76	17.07	10.45	14.98	22.60	29.03	25.82	31.12	18.85	18.79	18.92
OSU OP	26.90	24.28	19.71	26.38	18.60	26.96	22.09	20.61	35.10	34.87	19.93	22.05	28.34	27.99	31.92	28.90	25.91	25.32	26.51
Packman	22.20	18.72	18.10	14.26	18.47	20.78	17.23	16.18	21.54	24.71	12.26	16.32	28.17	28.71	29.08	39.61	21.65	20.88	22.41
Patriot			8.91	12.42	12.73	21.82	20.33	18.82			8.59	8.57	15.96	11.81	16.00	19.76	14.64	13.75	15.53
Patron	21.52	22.76	8.61	11.78	13.58	15.14	23.34	22.18	18.17	14.78	9.27	8.76	11.30	26.18	21.12	15.93	16.53	15.86	17.19
Premium Crop	20.99	36.03	10.94	15.52	24.11	18.83	19.97	11.57	24.30	17.87	8.90	15.41	16.04	18.70	20.95	25.80	19.12	18.28	19.97
USVL 048	3.60	2.34		19.49	26.00	11.36	20.14	29.02			5.95	6.67	7.41	14.91	7.81	5.71	12.34	11.82	12.78
USVL 093	22.46	10.41	15.92	17.93	44.40	25.06	24.82	19.53			21.82	24.99	21.06	24.25	29.62	23.79	23.29	25.73	20.85
																Mean	15.87	15.57	16.17

Supplemental Table 5.11 Zeaxanthin level (μ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) and conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

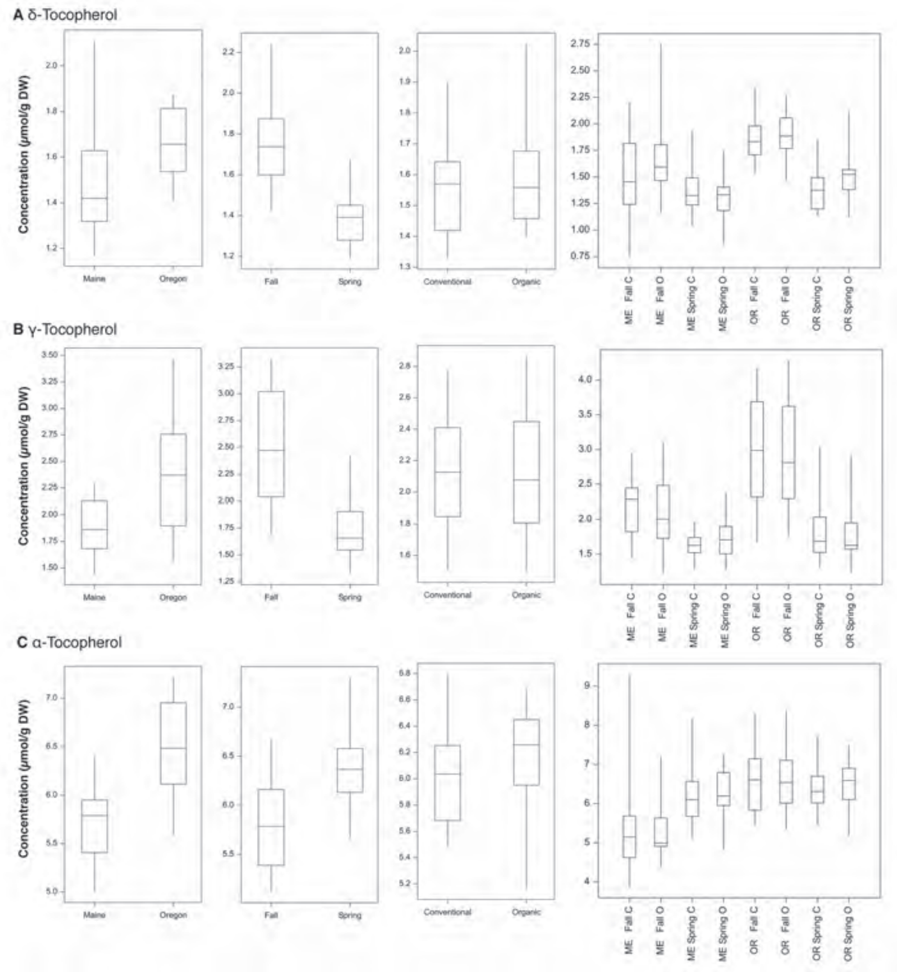
	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	0.49	0.46	1.09	1.10	0.80	0.98	0.80	0.68	0.63	0.62	1.05	0.94	0.44	2.40	1.06	0.87	0.90	0.80	1.01
B1 10	0.70	0.45	1.16	1.20	0.81	1.03	0.60	0.67	0.61	0.49	1.31	1.19	1.74	1.49	1.20	1.29	1.00	1.02	0.98
Batavia			0.73	0.93	1.71	0.92	0.67	0.81			0.63	1.01	1.06	1.15	0.76	0.89	0.94	0.93	0.95
Beaumont				0.67	0.97	0.50	0.64	0.52			1.00	1.13	0.80	0.62	1.42	0.81	0.83	0.97	0.71
Belstar	0.36	0.37	0.87	0.65	0.66	0.79	0.78	0.68	0.58	0.62	0.96	0.91	1.02	0.92	0.73	0.58	0.72	0.74	0.69
Diplomat			1.33	1.42	0.84	0.92	0.88	0.39			1.36	1.41	1.27	1.21	1.04	1.00	1.09	1.12	1.06
Early Green	0.82	0.96	1.82	1.22	1.02	1.18	0.51	0.55	0.74	0.76	1.94	1.26	1.32	1.22	2.19	1.93	1.22	1.30	1.13
Everest	0.66	0.97	1.22	0.95	0.73	1.36			0.58	0.53	0.79	0.87	0.41	0.47	0.87	1.01	0.81	0.75	0.88
Fiesta	0.38	0.39		1.14	0.73	0.83	0.82	0.78	0.61		0.81	0.86	1.01	1.18	0.73	0.72	0.78	0.73	0.84
Green Goliath	0.51	0.48	1.22	1.15	0.67	0.89	0.69	1.00	0.62	0.64	1.22	1.02	0.44	1.28	0.90	0.85	0.85	0.78	0.91
Green Magic	0.77	0.77	0.96	0.99	0.67	0.66	0.67	0.58	0.80	0.71	1.02	1.04	0.85	0.79	0.81	1.07	0.82	0.82	0.83
Gypsy	0.60	0.75	0.86	0.90	0.89	0.73	0.87	0.90	0.51	0.52	0.77	1.02	0.63	1.02	0.86	0.92	0.80	0.75	0.84
Imperial				1.52		1.15	0.76	0.82			1.18	1.11	2.06	0.96	1.21	0.73	1.15	1.30	1.05
Marathon	0.43	0.41	0.92	1.07	0.84	0.91	0.88	0.69	0.74	0.68	0.86	0.92	0.80	0.62	0.81	0.73	0.77	0.79	0.75
Maximo	0.37	0.35	0.95	1.01	1.49	1.05	0.51	0.57	0.66	0.57	0.84	0.71	0.75	0.72	0.93	0.68	0.76	0.81	0.71
Nutribud	0.57	0.59	1.34	1.24	1.09	0.86	0.96	0.59	0.58	0.54	1.03	1.45	1.08	1.24	1.24	1.37	0.99	0.99	0.98
OSU OP	0.88	1.68	1.62	1.81	0.97	1.98	1.62	1.08	0.91	0.75	1.60	1.78	1.54	1.75	1.33	1.30	1.41	1.31	1.51
Packman	0.84	0.78	1.67	1.31	0.89	1.51	0.62	0.99	0.62	0.68	1.06	1.41	1.37	1.13	1.37	1.69	1.12	1.05	1.19
Patriot			1.00	1.04	0.64	0.74	0.81	0.85			0.83	0.83	1.03	0.66	1.00	1.05	0.87	0.89	0.86
Patron	0.74	0.52	0.91	1.00	0.76	0.84	0.99	0.98	0.49	0.55	0.87	0.78	0.74	1.44	1.12	0.89	0.85	0.83	0.88
Premium Crop	0.62	0.83	1.08	0.97	0.97	0.97	0.91	0.57	0.72	0.63	0.88	1.41	0.88	0.85	1.00	1.27	0.91	0.88	0.94
USVL 048	0.37	0.36		0.80	0.92	0.70	1.02	1.97			0.71	0.81	0.64	0.67	0.71	0.61	0.79	0.73	0.85
USVL 093	0.49	0.50	1.48	1.50	1.73	1.00	1.44	1.06			1.66	1.78	1.24	1.12	1.66	1.39	1.29	1.39	1.19
																Mean	0.94	0.94	0.95

Supplemental Table 5.12 β-carotene level (µ mol/g DW) of 23 cultivars grown under conventional (C) and organic (O) conditions in two locations (Maine and Oregon) in two seasons (Fall and Spring) from 2006-2008.

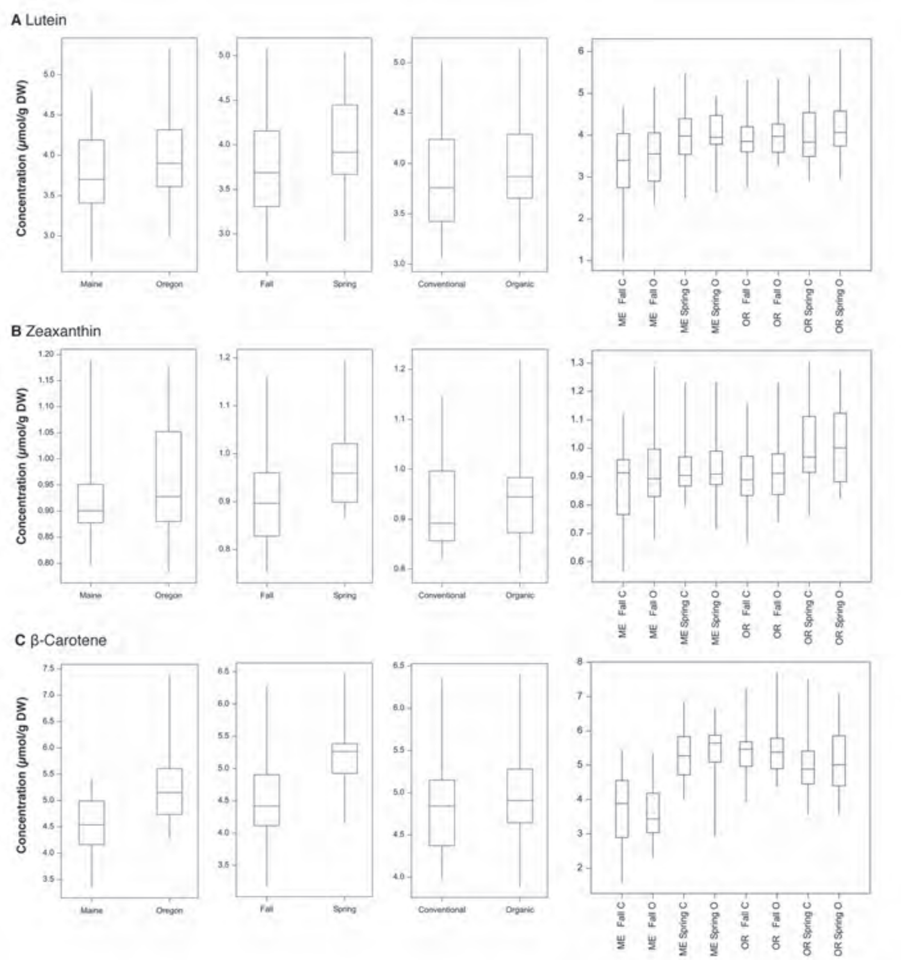
	Maine								Oregon								Overall Cultivar Mean AHW	Overall Cultivar Mean C	Overall Cultivar Mean O
	Fall				Spring				Fall				Spring						
	2006		2007		2007		2008		2006		2007		2007		2008				
	C	O	C	O	C	O	C	O	C	O	C	O	C	O	C	O			
Arcadia	6.12	4.40	13.21	15.60	25.55	31.85	12.12	40.12	29.87	28.17	22.92	28.97	17.41	23.15	20.82	15.37	20.98	18.50	23.45
B1 10	15.90	14.77	17.19	22.07	34.26	44.78	9.87	28.06	28.80	18.29	28.87	33.54	34.00	32.47	26.75	37.30	26.68	24.46	28.91
Batavia			10.09	15.25	29.53	46.89	5.10	30.36			14.73	26.25	27.48	33.77	21.16	34.01	24.55	18.01	31.09
Beaumont				9.32	40.82	22.41	13.99	1.26			25.85	31.63	14.36	12.27	35.77	14.42	20.19	26.16	15.22
Belstar	1.25	2.15	9.25	11.88	17.93	24.37	17.70	17.84	36.24	37.90	26.73	16.10	13.81	15.24	18.57	12.26	17.45	17.68	17.22
Diplomat			30.24	30.96	43.26	38.36	21.01	26.11			26.92	31.53	29.41	25.00	28.68	23.98	29.62	29.92	29.32
Early Green	16.33	20.31	16.46	15.59	32.28	36.62	13.97	15.45	35.74	53.28	43.92	31.91	32.79	32.25	24.24	48.82	29.37	26.97	31.78
Everest	18.09	14.61	16.82	2.16	28.46	55.65			26.52	26.37	21.03	26.01	13.53	9.28	17.21	22.54	21.31	20.24	22.37
Fiesta	2.20	3.05		28.12	32.41	34.56	23.31	37.71	35.64		26.67	19.02	21.30	21.08	44.59	20.32	25.00	26.59	23.41
Green Goliath	25.33	15.65	14.94	23.06	23.12	36.39	22.40	12.98	35.45	38.49	29.97	23.78	18.37	24.57	36.16	36.36	26.06	25.72	26.41
Green Magic	23.60	14.28	17.77	9.13	31.83	13.52	23.28	22.59	51.25	42.92	22.12	20.98	15.91	28.43	32.16	28.17	24.87	27.24	22.50
Gypsy	12.83	11.77	12.39	6.69	43.92	35.55	28.99	43.78	22.45	23.06	13.54	16.64	15.90	23.89	29.42	24.34	22.82	22.43	23.21
Imperial				28.92		49.78	31.48	26.88			23.62	19.08	19.02	17.43	19.48	15.31	25.10	23.40	26.23
Marathon	5.01	2.17	16.76	23.46	28.80	36.01	25.07	25.58	53.44	48.81	13.15	24.44	16.38	25.14	29.05	28.40	25.10	23.46	26.75
Maximo	1.93	2.71	15.11	21.69	16.83	34.36	18.22	29.78	43.98	29.99	20.51	13.72	21.12	20.02	21.63	19.79	20.71	19.92	21.51
Nutribud	18.62	15.30	21.97	9.86	32.59	37.11	26.17	1.42	35.71	36.68	16.68	21.52	30.24	43.28	35.43	38.12	26.29	27.17	25.41
OSU OP	20.00	22.96	25.90	34.72	34.50	45.86	37.77	17.06	68.08	65.97	40.50	50.85	49.13	54.93	62.52	46.68	42.34	42.30	42.38
Packman	18.24	15.14	19.76	9.71	57.57	49.02	30.63	12.66	25.77	36.28	23.40	26.07	34.37	39.51	45.55	29.82	29.59	31.91	27.28
Patriot			15.23	18.26	15.57	58.73	38.21	33.25			16.21	16.67	23.32	22.89	10.94	17.69	23.91	19.91	27.91
Patron	19.09	20.31	15.60	18.19	41.37	31.79	33.11	30.70	34.24	31.97	19.03	14.57	20.22	35.81	21.13	19.23	25.40	25.47	25.32
Premium Crop	18.74	24.92	11.65	10.21	29.53	37.07	26.48	24.01	44.69	30.79	14.35	20.18	24.14	25.32	25.30	32.36	24.98	24.36	25.61
USVL 048	0.98	0.36		23.70	44.16	25.88	28.52	34.06			13.50	14.81	15.43	27.79	20.38	9.68	19.94	20.49	19.47
USVL 093	14.74	14.76	18.65	26.39	93.52	39.10	30.94	27.78			31.01	44.57	47.49	31.00	25.79	34.86	34.33	37.45	31.21
																Mean	25.51	25.21	25.83



Supplemental Figure 5.1 Comparison of broccoli cultivars for glucosinolates (µmol/g DW) grown across all trials in two locations (Maine and Oregon), in two seasons (Fall and Spring), in two management systems (Conventional and Organic), and at the individual trial level, 2006-2008. A. Glucoraphanin, B. Glucobrassicin, C. Neoglucobrassicin



Supplemental Figure 5.2 Comparison of broccoli cultivars for tocopherols (µmol/g DW) grown across all trials in two locations (Maine and Oregon), in two seasons (Fall and Spring), in two management systems (Conventional and Organic), and at the individual trial level, 2006-2008. A. δ-tocopherol, B. γ-tocopherol, C. α-tocopherol.



Supplemental Figure 5.3 Comparison of broccoli cultivars for carotenoids (μmol/g DW) grown across all trials in two locations (Maine and Oregon), in two seasons (Fall and Spring), in two management systems (Conventional and Organic), and at the individual trial level, 2006-2008. A. Lutein, B. Zeaxanthin, and C. β-carotene.

Chapter 6

General Discussion

Chapter 6

General Discussion

6.1 Introduction

The overall objective of the research reported in this thesis was to analyse inter-related regulatory and technical challenges in the organic seed and breeding sector, using broccoli (*Brassica oleracea* var. *italica*) as a model crop and the US as the location. The research aimed to understand and analyse the tensions between farmers' and seed companies' interests that have been created by evolving organic seed regulations, and identify ways to develop a domestic and international organic seed regulation to better support organic agriculture in general and crop improvement in particular. However, in order to be able to translate the diverse crop requirements identified for stakeholders in the broccoli seed chain in the US into a strategy for plant breeders, the horticultural and phytochemical performance of commercially available broccoli cultivars had to be established. The research thus also studied the performance of broccoli cultivars grown under organic and conventional farming conditions in two contrasting broccoli producing areas (Maine and Oregon, US).

This chapter summarizes the main findings of the four component studies that address the objective. Then, by combining the findings of the organic seed regulatory studies and the field trials, a synthesis and discussion is provided based on the following five propositions: (1) Regulatory clarity is the foundation for organic seed sector development, (2) Organic management systems influence horticultural and phytochemical trait performance, (3) A crop ideotype can serve as a communication tool to arrive at an appropriate variety assortment, (4) Genetic variation is a requirement to develop optimized cultivars, and (5) Multiple seed system models contribute to organic sector growth.

6.2 Main findings

The current organic seed regulatory structure in the US does not optimally support organic seed sector development (Chapter 2). In the US case, the regulators are waiting for the non-governmental stakeholders to organize the sector to comply with organic seed regulations. Self-organisation has been only partially achieved, and sector development is evolving too slowly to optimally support organic seed market growth. While other on-farm organic inputs are rigorously regulated (e.g. compost, manure), seed is seemingly not recognized by the regulators as an input (although it could be considered a foundational input). Regulators appear unsympathetic to the dilemma created for certifiers, growers and seed companies by the lack of clear regulatory language and failure to establish a clear process, procedures and timeline for achieving closure on interpretation, implementation and enforcement. At the same time the state of the US regulation has put the organic sector at risk of violating organic integrity. The regulatory ambiguity contributes to potential violations in the use of non-acceptable seed and seed treatment inputs, and perpetuates inconsistency in certifier seed regulatory interpretation and enforcement. It has failed (so far) to establish a level playing field among stakeholders. The organic regulation has perpetuated a concern amongst the diverse stakeholder groups that strict enforcement would limit the varietal assortment (genetic diversity and farmers' choice) available, increase grower costs and require seed companies to invest in a market that they consider relatively small or that they do not have the skills or resources to support (in regards to seed production or breeding). Simultaneously, however, the dynamic relationships that have evolved in the various networks that have emerged in response to the seed regulation, have shaped the unfolding process of regulatory governance. In spite of regulatory ambiguity, the seed sector is developing, and a broader variety assortment and larger quantities available of higher quality have become available. These developments however, are too slow to meet the growth in the organic sector and seed shortages and lack of a broad range of appropriate varieties continue to affect the sector. Conversely, the lack of an appropriate assortment is shown to be one of the root causes of stakeholders' reluctance to push for 100% compliance with the US seed regulation. To enable to regulators to improve the regulatory guidance documents, the seed sector should communicate better the changes in organic seed availability and quality.

In the second study (Chapter 3), when the US organic seed regulatory environment was compared to that of the EU and Mexico, delays in seed sector growth caused by regulatory ambiguity was found with each jurisdiction studied. The analysis identified important risks of non-tariff trade barriers in the organic sector, arising from incompatible regulatory frameworks and the uneven progress in each case toward achieving 100% closure. Specifically, as the EU moves at a more steady rate toward 100% closure, there are both positive and negative implications for the US and Mexico. In the more mature EU regulatory environment, there is increasing investment in the organic seed sector with more cultivars produced and bred for the global organic market.

Each region was shown to demonstrate varying capacity for self-organising governance of their seed sector in relation to the state's regulatory role. In the EU context, the work of the non-profit organisation, ECO-PB, has been instrumental in moving matters forward, combined with clear regulatory language and specification of the interpretive requirements (such as establishment of a database of all approved cultivars and their availability). These measures can be compared to the US, where the initiatives of non-profit organizations have attempted to interpret the regulations in ways that lack official sanction. Mexico is early in the process of outlining their organic seed regulation, and until now has functioned in response to EU and US requirements. The additional complexity of strict phytosanitary requirements that conflict with organic regulation has delayed progress in the organic seed sector in Mexico.

This study demonstrated that progress toward regulatory harmonisation in the organic seed sector among the three cases studied has been slow, uneven, and motivated by varying levels of formal governance, corporate influence and stakeholder engagement. It is suggested that both the US and Mexico would benefit from the policy instruments that the EU member states have put in place to govern its organic seed sector, and from bringing to an end derogations that allow use of conventional seed. The instruments include implementation of national databases to provide an overview of available organic seed, and expert groups to annually assess available variety assortments in each crop group in order to compose categories of crops with sufficient quantity and diversity of seed available. All jurisdictions would benefit from analysing other aspects of their agricultural policy (e.g. phytosanitary regulation in Mexico) and how these measures potentially align or conflict with the evolving organic regulatory environment, in order to avoid impeding further regulatory developments and creating non-tariff barriers to market growth.

In the field trial and phytochemical testing component of this study (Chapters 4 and 5), the aim was to determine if commercially available broccoli cultivars would perform differently (by trait performance, cultivar ranking and trait repeatability) in organic compared to conventional environments in order to identify appropriate cultivars for organic growers and the best selection environment for breeding for organic agriculture. Organic trial locations were intentionally selected on farms under long term organic management as less mature organic farms or those in conversion may more closely resemble conventionally managed farms. Our organic trials produced comparable head weight to the conventional trial locations, and therefore the level of the environmental stress that we hypothesized would affect trait performance and phytochemical content was minimal. For most traits, there was no management effect across environments. Management main effect was only identified at the per trial level, demonstrating that each individual location/season/year combination constituted a unique environment, and that genotype by management system interactions resulted from different factors in each environment. In the partitioning of variance components across all trials location, season and its interactions were often the largest source of variation, followed by genotype main effect. While we did not see the trait performance differentiation between production systems, we did observe some individual varietal rank changes when performance of cultivars were compared between organic and conventional management, including changes in stability of performance (by head weight and by phytochemical concentrations) across trial environments. Larger genotypic variances in organic environments for horticultural but not phytochemical traits were observed, demonstrating the innate heterogeneity in the organic agricultural system and varietal response to such variation. Our results produced comparable or higher repeatabilities under organic and the ratio of correlated response to direct response for all traits was close to 1. The combined analysis of the repeatabilities and ratio of correlated response to direct response would suggest that selection in organic environments is equal or superior to selection in conventional environments.

As with horticultural traits, management main effect did not play a significant role across trials in the phytochemical component of the trials (Chapter 5). At the individual compound level, genotype main effect was most important for glucoraphanin, neoglucbrassicin and the carotenoids, while glucobrassicin and the tocopherols were more influenced by environment and various interactions. We identified distinct positive and negative trait correlations (e.g. glucoraphanin positively correlated with head weight and negatively correlated with carotenoids). For the content of the glucosinolates, glucobrassicin and neoglucobrassicin, the early maturing F_1 hybrids and open pollinated varieties had the highest levels, while for glucoraphanin highest levels were found in the late maturing F_1 hybrids. For traits that were strongly associated with genotype main effect (i.e. glucoraphanin and lutein) the cultivars with the highest concentrations of these compounds were also the most stable across trials. Season effect was greater compared to the location (Maine versus Oregon) effect for the phytochemicals compared to the horticulture traits (glucoraphanin being higher in fall environments; carotenoids higher in spring environments). Unlike the horticultural traits, phytochemical variances were not larger in organic compared to conventional growing conditions, but repeatabilities and the ratio of correlated response to direct response were similar, which would support the benefit of selecting in organic systems to optimize nutrition targeted breeding programmes.

We can summarise our findings as follows. The three hypotheses stated at the start of the research reported in this thesis were: (1) An organic seed regulation is a necessary step toward an optimized organic seed sector, (2) Cultivars bred for high input conventional growing conditions may not be optimal for organic farming systems, and (3) Organic production systems produce crops of higher nutritional value. Hypothesis 1 and 2 were confirmed by our study. Hypothesis 3 was not confirmed. We found that genotypic, location and season main effects were more important and that no major differences were found for nutritional value by management system. These findings are elaborated in section 6.3.

6.3 Discussion of research findings

The five propositions introduced at the beginning of this chapter are now discussed in light of the research findings and relevant literature.

6.3.1 Regulatory clarity is the foundation for organic seed sector development

This study brought to light the dilemma that organic regulation can help to push the sector toward 100% organic seed usage, and support the values of organic agriculture, but also that organic seed regulation can limit the available assortment of cultivars at least in the short term. Seed company representatives argue that, given the current ambiguity in the US in the organic seed regulation, there are economic restrictions to the number of cultivars that can be included in a company's portfolio of certified organic seed. In the US, growers do not want their varietal assortment options limited through strict regulatory enforcement. They claim that biodiversity (both broader genetic background and cultivar diversity) is an important component within management practices to enhance stability and resilience in an organic agricultural system. Organic growers would rather have cultivars suited to their management system than adapt their management to cultivars. Under the IFOAM principles of organic agriculture this is expressed in the Principle of Ecology (Organic Agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them, see Table 1.1 in Chapter 1 (IFOAM, 2012). The interviews in this study also indicated that smaller-scale direct market growers tend to grow a larger range of crop species and are searching for a larger diversity of cultivars within each species to distinguish themselves in the market. Large-scale growers grew a more limited number of crops and wanted access to the same cultivars as their conventional counterparts to adhere to the same strict market product conformities. Overall, the diversity of growers' interests calls for making available a wide diversity of cultivars. A consideration for the evolution of the organic seed regulatory environment is how to attain a balance between stimulating growers to use organic seed without too strictly forcing limitations on the diversity of the crops/varieties they use.

This study demonstrated that the full potential of an optimized organic seed sector cannot be realized without enhanced regulatory stipulations but also that without an established organic seed market, there will be too little stimulus for investment to breed cultivars better adapted to organic agriculture. The long term implications of on-going regulatory ambiguity (resulting in too many options for obtaining derogations for use of conventional seed) is that it frustrates commercial returns on investment in organic seed production and limits improvements in the capacities of seed companies to produce high quality organic seed. The EU has made the most progress (of the three jurisdictions studied) in moving toward 100% use of organic seed. One can still wonder whether the deliberate step by step approach that has occurred in the EU (where, in several member states, derogation options are closing for an increasing number of crops that already have a sufficient diversity of cultivars available in organic seed form), will be sufficient to secure 100% use of organic seed in all member states. Perhaps a more rigorous approach is needed, to ensure compliance across all member states, and this may be proposed in the EU in the near future. The European Commission (EC) recently revisited the overall organic standards and *Der Spiegel*, a leading German newspaper, has reported that the EC considers the number of options for achieving derogations that allow use of conventionally produced inputs to be a violation of the integrity of the organic sector, and is about to propose to drop the derogation option (Anonymous, 2014).

6.3.2 Organic management systems influence horticultural and phytochemical trait performance

An important aspect of developing a full assortment of organically appropriate cultivars is the question of which cultivars to have in the assortment. To answer that question one needs to understand how different organic management systems are compared to conventional systems and how cultivars perform in different systems. We first address whether the trial results in this study were representative for the organic sector.

Fundamentally, organic agricultural systems are premised on the ecological functioning of its soils. Under IFOAM principles of organic agriculture this is expressed in the Principle of Health, referring to the interrelationship of healthy soils, plants and animals (IFOAM, 2012). According to Ugarte and Wander (2012) and as observed in our study, soil factors related to organic matter, microbial activity (abundance and diversity), and potential mineralizable nitrogen are often higher in farming systems with well managed organically fertilised soils compared to mineral fertilised soils with water soluble nitrogen. In this study, the higher total nitrogen and higher potentially mineralizable nitrogen of the organic locations provided higher nitrogen availability compared to the conventionally managed trial sites. Soil levels of P and K in both management systems were adequate for good broccoli production (Greenwood et al., 2005, 2006; Li et al., 2011).

In this study, we found that the broccoli cultivars grown under organic management produced on average comparative yields (head weight) to those grown under conventional management. This is in contrast to much of the literature (de Ponti et al., 2012; Seufert et al., 2012) who after reviewing comparative studies concluded that overall organic yields were on average lower (a reduction of 5-34%) compared to conventional. The farms for the study were chosen intentionally for long-term organic management (>5 years) because of what earlier studies had revealed (Smukler et al., 2008; Knight et al., 2010). The comparable yields between organic and conventional trials were also in contrast to what we anticipated, because such field comparisons had not yet been published in the literature for broccoli.

This study did reveal a broader variance in trait performance under organic compared to conventional conditions, and certain cultivar trait rank changes. In certain trials (specifically in Oregon) some cultivars showed higher yields under organic than under conventional, as often experienced under organic conditions where mineralisation continues under warm fall conditions and favours nitrogen responsive cultivars. Broccoli grown under spring conditions may be at more of a disadvantage due to slower nitrogen mineralization rates under cooler temperatures affecting soil microbial activity resulting in reduced yields compared to conventional production fields. This was observed in trials in Oregon where there were 100 fewer growing degree days (GDD) in Spring in 2008 compared to 2007 and where organic yields were lower than under conventional conditions. This supports the argument of the organic sector that yield stability across various growth conditions is even more important for organic growers than for conventional growers who can support crop growth more easily with water soluble fertilisers. One of the organic plant breeding challenges identified from this study is the need to breed for better nitrogen use efficiency under cool spring conditions.

6.3.3 A crop ideotype can serve as a communication tool to arrive at an appropriate variety assortment

Organic growers need to comply with organic regulations that require the seeds used in organic production systems are: (1) produced organically and, (2) comply with the permitted breeding methods (e.g. refraining from genetic engineering). In addition, seed producers need to ensure that seeds produced for the organic sector perform well under organic management practices, and meet the varietal needs of growers operating in diverse locations and producing for diverse end uses. For breeders to incorporate the right traits into a breeding program for organic agriculture, good communication between breeders and growers is needed. This study highlights the distinctive role of certifiers in the organic seed sector in determining the seed assortment. In the US the certifiers are positioned to play a central role in decisions concerning derogations but they lack expertise on required varietal traits to inform their decisions. In Europe, in an increasing number of countries, Expert Groups annually assess the available assortment, and use this information to guide derogation decisions. Thus, organic growers need also to communicate with certifiers about the cultivars they choose to use and the traits they require to fulfil their regulatory requirements to use certified organic seed. Under the IFOAM principles of organic agriculture this is expressed in the Principle of Fairness and in terms of this study is represented through the shared stewardship that farmers, breeders, certifiers and seed companies have in co-creating the organic seed sector (IFOAM, 2012).

An organic crop ideotype outlines the list of crop varietal traits required by organic growers for optimal cultivar performance in an organic production system. Defining an organic crop ideotype provides a useful format for growers and breeders to communicate the required traits. Once an ideotype has been defined, growers can match their needs with the cultivars available, and breeders have a “blueprint” for cultivar development as e.g. described generally by Lammerts van Bueren et al. (2002) and more specifically for wheat by Löschenberger et al. (2008). An organic crop ideotype also can be used as a communication tool between growers and certifiers i.e. to communicate varietal differences that could support derogation requests. There are various methods for developing an organic crop ideotype. Annicchiarico and Filippi (2008a) performed variety trials and assessed the value of an index of a variety’s suitability for organic systems for field pea in Northern Italy. Lammerts van Bueren et al. (2012) created a crop ideotype for onions through farmer field trials and Osman et al. (2008) through interviews with breeders. Wolfe et al. (2008) took the organic crop ideotype concept one step further and included the analysis of the marketplace and divided the ideotype into market segments for wheat by including the requirements of retailers and processors.

Preferred traits identified

During the Oregon broccoli trials in July of 2007 and 2008, organic and conventional growers were invited to attend the variety trial locations and to identify their top five best performing cultivars. Farmers were also surveyed through a questionnaire for their preferred broccoli cultivar traits and their standard broccoli cultivar choice (Renaud et al., 2010). The organic growers tended to focus on fresh market production and thus sought broccoli cultivars that provided a primary harvest and a continued harvest with side-shoot development. While both the conventional and organic growers prioritized 'head size, head weight and overall yield', conventional growers ranked 'uniformity in maturing' and 'capacity to harvest mechanically' higher than their organic counterparts. The grower survey results indicated that the organic growers prioritized 'abiotic stress resistance' and 'disease resistance' higher than their conventional counterparts. Factors more important to organic than to conventional growers included broccoli cultivars with vigorous growth in soils with potentially low or fluctuating mineralization rates of nutrients, and the ability to tolerate weeds. In both the interviews and the field discussions, the organic growers expressed interest in knowing about the cultivars with higher levels of nutritional quality so that they could translate this information to their customer base and incorporate these cultivars into their production systems (Renaud et al., 2010).

In addition to the interviews (Renaud et al. 2010; Chapter 2), the results of the field trials and a literature review were used to develop a broccoli crop ideotype trait list in which the relative importance of traits is compared between organic and conventional production systems. Traits identified can be grouped into three categories, based on the scoring (indicating importance for conventional and organic systems, respectively) shown in the last two columns of Table 6.1.

Category 1: Traits of equal and high importance to both organic and conventional growers.

Traits that fell under this category included high head weight and high percentage harvestable yield, even maturity, and quality characteristics such as head firmness, smoothness and small, uniform bead size. Both sets of growers desired good field holding capacity in order to have some flexibility with their harvest schedules.

Category 2: Traits of which importance varies by production scale, not production type.

Some traits identified depended upon the size of the growers' production system such as large scale, mechanical or small scale production per crop and consider such traits in a diversified crop rotation. As conventional production consists of primarily large-scale growers moving towards mechanised harvest and aiming at both the fresh market and processing industries, traits related for mechanical harvest are more important than for a local, fresh market type. Many organic producers preferred flexibility in maturation and extended harvest from side-shoot development (Myers et al., 2012). Large scale mechanical harvest requires uniform plants, high head placement in the plant and head maturity for a once over harvest. Processors have specific requirements concerning head diameter, dark uniform head- and stem colour and a crown cut type.

Table 6.1 A list of traits identified to define an organic broccoli crop ideotype for Oregon, Pacific Northwest, US derived from farmer surveys, interviews, field day evaluations and field trial results (rated with significance to conventinoal and organic agriculture)[1].

Broccoli Trait	Description and Considerations	Conv	Org
Head Characteristics			
Head Shape	flat or domed: overall preference dome shaped for crown cut and processing; dome shape sheds water and reduces rot	††	†††
Head Surface	smooth; no cat eyeing	††	††
Floret Exertion	floret exertion; appreciated by select organic growers who desire on-going harvest and broccoli raab breeding model	†	††
Head Diameter (Size, cm)	larger heads preferred for processing; larger heads prone to buttoning	†††	††
Head Colour	dark color preferred; processor requirement for color uniformity	†††	††
Bead Size	inflorescence density important in resistence to compression stress; small beads preferred and reduce head rot	††	†††
Head Firmness	curd and head firmness increase post-harvest quality	†††	†††
Head Weight (g)	yield, minimum 300g	†††	†††
Side-Shoot Production	not modern breeding objective; appreciated by select small-market growers for on-going harvest		††
Stem Colour	dark preferred; processor requirement for color uniformity	††	††
Stem Size	bunch market (15-20 cm. length; diametre >5cm.); processing market (7.5-15cm. length; 0.6 cm. diametre)	††	††
Hollow Stem	none preferred; presence of hollow stem can lead to head rot	†††	†††
Plant Architecture			
Head Height	taller heads ease of harvest mechanically and by hand	††	††
Leaf Height	larger leaves contribute to weed suppression by shading the soil; too large impede mechanical cultivation	††	†††
Leaf Attitude	planofile leaves have better weed suppression than erect leaf cultivars	†	†††
Plant Uniformity	ease of mechanical harvesting if plants are uniform	†††	††
Good Root Development	required in organics especially for spring plantings and slow release organic fertilizers	†	†††
Harvestable Product			
Uniformity in Maturation	heads harvestable at one time	†††	††
Days to Maturity	maturation preferrences related to season: early for spring and mid-season for fall (higher yield)	†††	†††
Harvestable Yield	net yield; high percentage harvestable plants	†††	†††
Crown Cut	less stem; larger head; outer spear length important; stem diameter specific	†††	††
Bunch	smaller head size; a lot of stem remaining	†††	††
Processing	larger, dense heads preferred; for floretting, floret specs should fit into 5.7cm. cube when head is cut; branch angle and depth influences size of florets	†††	††
Yield Stability	consistency in yield season to season under less predictable organic conditions	††	†††
Post-Harvest Quality	holding ability for fresh market especially for long distance shipping; types that are slow to become chlorotic preferred	†††	††

Table 6.1 A list of traits identified to define an organic broccoli crop ideotype for Oregon, Pacific Northwest, US derived from farmer surveys, interviews, field day evaluations and field trial results (rated with significance to organic agriculture) (Continued).

Broccoli Trait	Description and Considerations	Conv	Org
Abiotic Stress Resistance/Tolerance			
Adaptation to cold spring conditions	early adaptability to cool spring conditions fundamental for organics	††	†††
Heat Tolerance	cultivars that have head stability under hot conditions	††	†††
Drought Tolerance	cultivars that reduce irrigation dependency	†	†††
Nutrient efficiency/rapid nutrient uptake	cultivars required that take up and use nutrients efficiently	†	†††
Biotic Stress Resistance/Tolerance			
Disease Resistance			
Black rot (Xanthomonas campestris)	organic seed treatment available (hot water treatment); Potassium bicarbonate application	†	††
Club root (Plasmodiophora brassicae)	genetic resistance available; grow on high pH soils	†	††
Downy mildew (Peronospora destructor)	no synthetic fungicide use in organic; some cultivars with resistance; crop rotation; avoidance of overhead irrigation; proper plant spacing	†	††
Alternaria leaf spot (Alternaria spp.)	fungal disease, seed borne (hot water treatment effective) and crop debris; plant waxy leaved cultivars	†	††
Black leg (Leptosphaeria maculans)	fungal disease, seed borne (hot water treatment effective)	†	††
Bacterial Complex (Erwinia / Pseudomonas spp.)	bacterial disease(s), limited organic control	†	††
Insect Resistance			
Cabbage looper (Autographa californica and Trichoplusia ni)	no organic control	†	†
Cabbage moth (Pieris rapae)	floating row cover; biological controls (Bacillus thuringiensis and Saccharopolyspora spinosa)	†	†
Diamondback moth (Plutella xylostella)	floating row cover; biological controls (Bacillus thuringiensis and Saccharopolyspora spinosa)	†	†
Cutworm (Agostis ipsilon and Peridroma saucia)	no organic control	†	†
Armyworm (Spodoptera exigua, Mamestra configurata and Spodoptera praefica)	no organic control	†	†
Cabbage maggot (Delia brassicae)	floating row cover	†	†††

Broccoli Trait	Description and Considerations	Conv	Org
Symphylans (Scutigerella immaculata)	cause stunting; like high organic matter so more common in organic; few organic tools	††	†††
Flea beetle (Phyllotreta cruciferae)	glossy leaf types increase susceptibility; waxy types more resistant (plant in spring); floating row cover; short term insecticides	†	†††
Cabbage aphid (Brevicore brassicae)	problem in fall; glossy leaf types can increase resistance (plant in fall)	†	††
Nutritional Quality			
Vitamin, mineral and phytochemical content	contribution to human health important issue but exploration limited to glucoraphanin and lutein	†	††
Cultivar Type			
F1 versus OP cultivar	large-scale grower preference for hybrid cultivars versus select small-scale growers who prefer OPs	na	††
F1 Hybrid Breeding			
Self-Incompatibility (SI)	compliant with organic values	†	†††
Cytoplasmic Male Sterility (CMS)	compliance with organics under review; considered genetic modification technique	†††	†

[1] († low importance to ††† high importance; na = not applicable).

Category 3: Traits of greater importance for organic growers.

There is also category of traits that are not necessary different from traits of importance for conventional growers, but have a higher priority for organic growers compared to conventional growers such as resistance to biotic and abiotic stress. This is because organic growers refrain from chemical crop protectants and therefore need more emphasis on varietal characteristics related to abiotic and biotic stress tolerance. For some diseases, resistance is available such as for club root (Piao et al., 2009), downy mildew (Farnham et al., 2002; Vicente et al., 2012), and black rot (Tonguc and Griffiths, 2004). However, in the case where breeding has not yet been conducted for the release of resistant cultivars other options can be applied. For example, hot water treatments are used for control of the seed borne diseases black leg and black rot in cultivars that are not resistant (Lammerts van Bueren et al., 2003). Where disease resistant cultivars are not available, certain morphological traits can reduce disease or pest incidence and compensate for use of chemical crop protectants. Examples are small beads and domed head shape that shed water more easily to prevent head rot (Myers et al., 2012). Osman et al. (2008) reported that for onions more erect leaves can shed water more easily reducing incidence of disease development. Another example of a morphological trait reducing ear disease incidence in cereals is in the length of the peduncle of wheat by selecting for cultivars that the ear rise above the leaf canopy and dries more rapidly after rain or morning dew (Löschenberger et al., 2008). Specific to Brassicas, epicuticular wax is another trait that can be manipulated to affect pest resistance where glossy leaves have shown less damage from lepidopteran pests, reduced tissue damage from thrips and but may contribute to more potential damage by flea beetles (Lammerts van Bueren et al., 2011). Also with respect to weed suppression certain morphological traits can replace the use of herbicides by choosing for more planophile and large leaf types that provide more shade to the soil and therefore better suppress weeds.

With respect to abiotic stress tolerance, traits are related to adaptation to low-inputs of water and nutrients are of importance for organic growers. These traits relate to a reduced dependence on irrigation and an extensive root system to explore large soil volumes and improve capacity of nutrient uptake and use under cold spring conditions (see e.g. Messmer et al., 2012). As organic growers often incorporated broccoli in their product assortment but are not located in optimal regions where broccoli is mainly bred for, growers were concerned with broccoli head development during hot summer periods (lack of vernalization, leafy heads). Because broccoli develops uneven-sized flower buds on its inflorescence when temperatures are above 24ºC to 30ºC (Heather et al., 1992), therefore this should be a breeding priority for non-temperate environments (Farnham and Björkman, 2011a and b).

Not all of the priority traits identified were evaluated in the field trial component of this study e.g. leaf attitude, floret extension, field holding capacity and post-harvest quality were not studied. These traits should be prioritized in future breeding, with specific attention to their role in an organic production system compared to conventional. What we did learn from our study through analysing genetic correlations and GGE PCA Biplots (Chapter 4 and Chapter 5), was that broccoli head yield trials were not positively genetically correlated to head quality characteristics (head shape, bead uniformity). Therefore, if the goal is to breed for head firmness or bead uniformity, this can be achieved without relinquishing yield. As organic growers not only search for cultivars that fit in their management system but that also contribute to the resilience of the organic system, root system research for nutrient efficiency in broccoli should be explored.

Yield stability: the example of 'Arcadia'

The results of the farmer surveys indicated that 'Arcadia' was the most commonly used cultivar by both organic and conventional growers. In the Oregon field evaluations, the both sets of growers also selected this cultivar as their preferred variety. When comparing these results to our own field trial results, we analysed trait performance and stability across trials to see why this cultivar performed successfully in this specific environment. Our results indicated that Arcadia was not a top yielder (a mid-ranking cultivar of the 23 cultivars evaluated across trials, see Chapter 4), but in the top cluster for stability and demonstrated a consistent yield performance across seasons, years and management systems. The same trend was observed for the plant growth traits head diameter, head thickness, uniformity, head height, and leaf height. To dig deeper into why 'Arcadia' was a grower standard and to compare it to the more recently grower selected cultivars, 'Green Magic', and 'Gypsy', we cross-examined trait performance and sought explanations for cultivar trait performance differences. The more recently released cultivars were higher yielding, earlier maturing, more uniform, had shorter plant/head placement architecture and had darker, and higher domed heads compared to 'Arcadia'. These cultivars appeared to be more responsive to nitrogen availability, and produced larger heads and taller plants in organic compared to conventional trials, but developed very quickly and were prone to hollow stem. 'Arcadia' comparatively had a very high head placement in the plant facilitating ease of harvest and a flatter head shape (not preferred) and no incidences of hollow stem. For the trait overall quality, 'Arcadia' was a top performer in the Fall trials, but not in Spring trials. Overall quality appears to represent a group of characteristics including plant/head uniformity, vigor, and head quality as determined from our genetic correlations. 'Green Magic' had strong overall quality ratings in both seasons indicating the cultivar's adaptation to cold conditions and early vigor under lower nitrogen conditions. In this study, there were five cultivars in the quadrant of greatest stability and highest head weight per production system (Chapter 4). Between production systems in the ranking by growers, of the five top performing hybrids, three overlapped and two were different. The example of 'Arcadia' brings to light the importance of yield stability over yield *per se* for the growers that attended our field day. 'Arcadia' demonstrated a capacity to produce sufficiently high yielding heads across years of adequate head quality for their markets. It also brings to light the importance of the stage in which non-target location growers are exposed to new cultivars along the commercialization chain. The growers at our field day had never heard of 'Green Magic', yet it had been on the market for several years already.

Genotype class and breeding techniques

In the context of this study, the analysis aimed at identifying commercial broccoli cultivars that might be suitable for organic agriculture, and in so doing, identify traits for crop improvement that would be translated into a breeding program to optimize broccoli for organic agriculture. Some organic farmers in our study indicated that they preferred cultivars that were open pollinated (OP) and provided harvestable side shoots after the primary inflorescence was harvested to service their market type. The majority of cultivars in our trials were single-harvest heading hybrids. Of the top cultivars identified for head weight, across locations, seasons and management system 'Green Magic' as indicated was a top performer (see Chapter 4). 'Green Magic' is a hybrid cultivar for which seed is generated using a cytoplasmic male sterility, therefore it cannot be reproduced unless one has the maintenance inbred for the maternal parent nor is the genotype accessible to plant breeders. Comparatively, the OP cultivars in our trial were poorer performers than the hybrids studied in terms of horticulture trait performance (yield, stability and quality traits), but demonstrated value for select phytochemicals (e.g. carotenoids, glucobrassicin, neoglucobrassicin). OP cultivars are reproducible and can be used as crossing parental material in breeding programs. There is a desire within the organic sector to have access to reproducible seed. It was apparent from our study that attention to the improvement of OPs for horticulture traits has not been a priority for many years, but that they are of use as base for the development of nutritionally enhanced cultivars. An opportunity for future breeding could focus on improved OPs for horticultural traits and health promotion.

6.3.4 Genetic variation is a requirement to develop optimized cultivars

Genetic variation

Genetic variation is a requirement for effective plant breeding. Most of the cultivars included in this project were those used by growers at the onset of this research project. They were known to be predominantly cultivars selected for broad adaptability in conventional production systems and not purposely bred for high phytochemical content nor for adaptation to organic agriculture. Horticultural and phytochemical trait performance differences of the early maturing versus late maturing cultivars and between open pollinated and F_1 hybrids demonstrated some clear patterns. When these analyses were restricted to the F_1 hybrids only, the patterns were not as distinct in the phytochemical analysis. This leads to the conclusion that there has been little change in the concentrations of phytochemicals over three decades of breeding (the time span of cultivar release for the set of cultivars studied) suggesting that genetic variation for phytochemical content is limited in elite germplasm, or likely the result of a lack of selection for these traits. This may be changing with recent efforts to introgress high glucoraphanin content from the wild brassica species *B. villosa* to produce the high-glucoraphanin F_1 cultivar 'Beneforté' (Traka et al. 2013). However, the genetic diversity introduced into 'Beneforté' is not generally available to any breeders apart from the company that holds the exclusive license for the cultivar. Diversity in a breeding program could be enhanced if sources of variation in the genus *Brassica* were exploited to enhance levels of health-promoting phytochemicals and to broaden the genetic diversity of commercial broccoli germplasm. A molecular marker survey of *Brassica species* could be useful to determine where high levels of genetic variation may exist that could be used to broaden the genetic base of existing *Brassica* crops. Enhancing both the genetic diversity of parental lines *in conjunction with* breeding for performance in various environments is needed by the broccoli industry.

The value of genetic diversity in a breeding program could be taken a step further by considering breeding not for one cultivar at a time, but by considering the cultivar needs for an entire growing season in order to develop a broccoli assortment for each slot in a production cycle per region (a spring, summer, fall 'seasonally slotted broccoli program'). Crisp and Gray (1984) reported that to develop broccoli cultivars for a specific season, populations from different maturity groups should be used to take advantage of high heritability in heading characteristics, head colour and time of maturity. Direct selection in organically managed field conditions for genotypes targeted for organic agriculture offers advantages over indirect selection in conventionally managed field conditions because breeding populations selected in organic environments have higher yields when grown organically, compared to conventionally selected populations that did not perform comparatively well (Kirk et al., 2011). In further studies, early generation broccoli breeding lines and/or populations should be compared to attain a better prediction of genetic correlations for organic, and to explore potential changes that may occur when broccoli breeding lines are bred in the target environment (location and season) from the initiation of the program.

Effective utilization of genetic correlations in breeding for health promotion

When considering breeding targeted for consumers concerned with the health consequences of what they eat, genetic correlations integrating horticultural and phytochemical traits for crop improvement need to be considered. We found some positive correlations and some trade-offs that would apply to setting priorities in strategizing for breeding initiatives that target health promotion against cancer (glucoraphanin) and degenerative eye diseases (the carotenoids). Specifically, the genetic correlations from this study demonstrated that head weight and diameter and late maturing cultivars were positively correlated with glucoraphanin. Head colour was positively correlated with the carotenoids, and positively correlated with early head maturation (particularly in the Spring). Because head and stem colour are important traits to processors, a cultivar could be bred for segmented heads (where the inflorescence divides into individual florets, e.g. broccolini) for early maturation and darker colour. Positive correlation between darker head colour and carotenoids may be a function of chloroplast density while a correlation between early maturity and darker heads may be related to N uptake and use efficiency. A breeding strategy for carotenoids would need to take into account the implications of known genetic correlations, contribution of seasonal influence and nitrogen use efficiency.

Selection environments

As stated in the introduction of this thesis, most studies that have investigated traits needed for organic farming systems have focussed on field crops such as cereals (e.g. Murphy et al., 2007; Löschenberger et al., 2008; Przystalski, 2008; Wolfe et al., 2008; Annicchiarico et al., 2010; Reid et al., 2009, 2011; Kirk et al., 2012; Koutis et al., 2012). Only a few studies had been conducted on vegetable crops, for instance for onion (Osman et al., 2008; Lammerts van Bueren et al., 2012), and that remains the case to date. From the trials performed in this study, the main effects of location and season described the largest source of variation in broccoli trait performance. For example, Oregon trials produced higher average head weights than Maine in both seasons, and the Fall trials produced higher head weights than Spring in both locations (highest overall head weights in Oregon Fall trials). Greater heterogeneity in the organic management systems and genotype by management crossover interactions were observed on a local per trial scale. This supports the idea that direct selection (under organic management) would potentially be beneficial for the development of cultivars for organic agriculture, particularly if the intent of the breeder is to develop cultivars for local adaptation. Burger et al. (2008) concluded that direct selection under organic conditions for complex traits such as yield is preferred, whereas indirect selection can be very efficient for highly heritable traits. Burger et al. discovered that although heritabilities in their trials with genetically broad populations of maize were assumed to be lower under organic farming due to higher experimental error rate, these were compensated by greater genotypic variance evoked under organic conditions. This was also the case in the broccoli trials reported in this thesis.

6.3.5 Multiple seed system models contribute to organic sector growth

Organic production in the US is comprised of numerous small- and large-scattered acreages across the country producing under a broad range of environments and servicing multiple market types. Therefore, the assortment of broccoli cultivars required to meet the demands of the organic market place is diverse. As has been described, organic producers are presently dependent on the commercial cultivar assortment available that were developed predominantly for large-scale industrialized growers in California and Arizona. The breeding, selection and testing of these cultivars are performed in the target region, therefore organic growers (outside the target region) are not exposed to newly released cultivars until the release, distribution and commercialization stage of a breeding process (as seen in our study with grower awareness of 'Green Magic'). In the context of what Ceccarelli et al. (2009) describe as the three major phases of a breeding process: (1) generating genetic variability, (2) selection and testing to identify superior recombinants within the genetic variability created in the first phase, and (3) release, distribution, and commercialization of new cultivars, the contribution of the present seed production and breeding models employed in the sector are now discussed. We further consider the implications in the event of regulatory closure. The four model scenarios presented are (Figure 6.1): (1) 100% conventional seed breeding and production companies (Model 1), (2) conventional seed breeding and production companies with an organic division (Model 2), (3) 100% organic seed breeding and production company (Model 3), and (4) farmer-led or non-profit organic breeding and production initiatives (Model 4). Finally, measures for enhancing each of the models presented are considered.

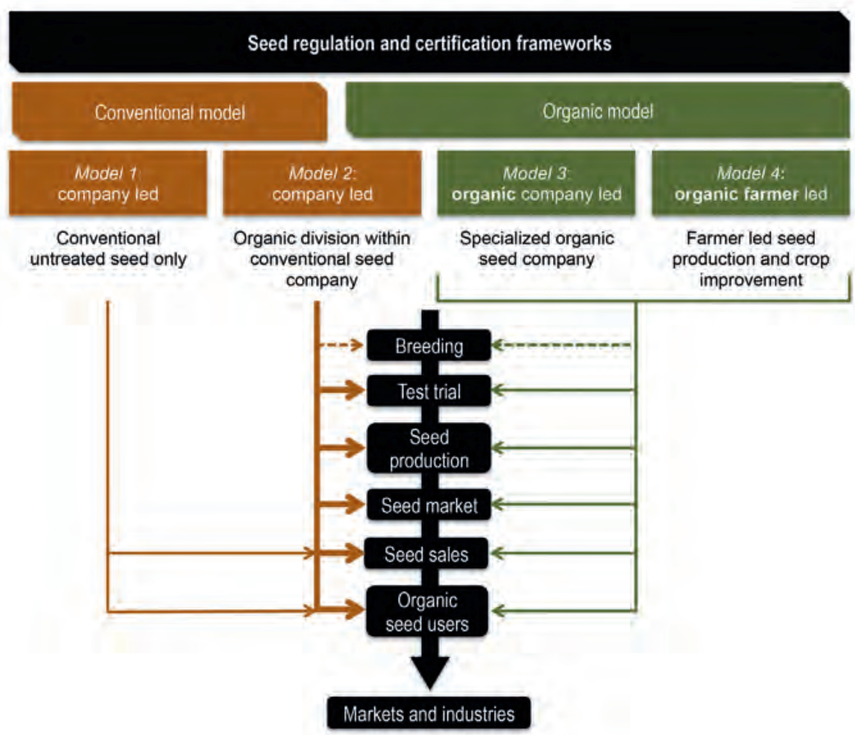


Figure 6.1 Schematic of organic seed system models

The 100% conventional seed company indicated as Model 1 in Figure 6.1, services the organic market with conventional post-harvest untreated seed of a select group of specialized crops. Such companies are not motivated to breed or produce cultivars for the organic market for the most part because they have determined that the market size is too small and fragmented, and does not fit in their business philosophy (often being associated with chemical pest control or GMO testing and development). The service they presently provide the organic sector is to select high quality cultivars of typically a limited group of crops, in conventional post-harvest chemically untreated form. As their cultivars are not available as organic seed, they predominantly but not exclusively service the large-scale organic growers who can obtain derogations and who desire the specific varieties and traits available exclusively from such seed. If seed regulatory closure is to occur, these companies will need to determine if the market they service would be sufficiently large to deem investment in producing seed for that market. As they have no experience in producing organic seed, lack knowledge of the certification process or background in defining organic crop ideotypes, they may not be inclined to participate and become full players in the organic seed market.

The conventional seed company with an organic division indicated as Model 2 in Figure 6.1, services the organic market with both conventional post-harvest untreated and organic seed of a select subset of specialized crops. The strength of a conventional seed company with an organic division is that it has committed to the value of the organic market through its investments. As these companies have a breadth of genetic resources, modern breeding techniques, extensive trial grounds, seed reproduction capacity and strong marketing and sales departments to promote the commercialization of new cultivars, they are in turn able to provide quality cultivars to the marketplace with thorough technical support information. By screening of their breeding and commercial material on grown on organically managed land, they have the capacity to see trait differentiation in their material and define organic crop ideotypes for their crops. Their contribution to breeding for the organic market is indicated with a dotted line in Figure 6.1 because they predominantly screen their conventional material on organic land. At this time, they have a small amount of breeding initiatives directed at the organic market. In the US example, some of the breeder companies do not do direct sales of organic seed to the end user. Their varieties are distributed and marketed through seed dealers. The efforts that the seed companies in Model 2 invest in breeding and producing organic seed are often unknown to the organic sector because the dealer brands the seed. The biggest contribution that these companies make to the organic seed sector is the availability of good performing cultivars with high yield potential and disease resistance in organic form. As a result of their investment in cultivar development (predominantly hybrid), they tend to be higher priced and service the mid-to-large scale grower. The advantage of this model to the end user is the availability of a wider cultivar choice for both organic and conventional production. The limitation of this model is that because the organic sector is a smaller portion of their overall business, it is therefore of lesser market priority. If a comprehensive regulatory policy was to go into effect, these companies would be prepared to expand their organic varietal assortment, invest in more production capacity and increase the inclusion of high priority traits (see 6.3.3) in their overall breeding programs.

The 100% organic seed companies indicated as Model 3 in Figure 6.1 are fully dedicated organic seed companies servicing only the organic market. They are not as large as the average conventional companies. They fulfil all steps in the seed production process (from basic seed to commercial seed) under organic conditions. In this model, the companies breed, produce and distribute organic seed with a value-based message compliant with organic principles. Often, they are performing all functions along the seed development chain, but with limited resources compared to a conventional breeding company. Their strength lies in their knowledge of the organic production system and market, and that they can provide a clear message to their customer. Their values resonate with those of their customer base, and their customer can comprehend the scale of their business model. The relationship is more personal in that the owner/founder is typically highly profiled in advertising and promotion (instead of seed technology). They are driven also by a concern for genetic diversity and farmer diversity and therefore they aim to offer a broad assortment of all crops to a range of grower types (but predominantly small). They supply the marketplace typically, but not exclusively, with improved and older open pollinated varieties cultivars or hybrids typically that are often developed in collaboration with university public breeding programs or purchased from company Model 2 (indicated with dotted line to breeding). Their weakness can lie in the overall seed quality of their varieties due to limited genetic and financial resources for breeding and reproducing seed. If the seed regulation was enforced, these companies would continue to grow in their contribution to the sector.

The Farmer-led organic seed breeder and producer, indicated as Model 4 in Figure 6.1 is representative of a more grassroots approach to organic seed sector development where independent grower or non-profit organizations dedicate themselves to breeding and producing organic seed independent of corporate affiliation. As described in Chapter 2, individual growers are producing their own seed and performing on-farm selection to develop cultivars selected for their specific environment. The seed they produce is either for individual use or for sale to growers typically within their own bioregion. These initiatives are typically motivated by a desire by these growers and organizations to develop a seed sector independent of corporate control, sustain biodiversity (genetic and cultivar), and that function outside the realm of patents that confer exclusive controls and proprietary rights.

The origins of Model 4 have already evolved into more complex and expanding breeding models where the individual seed producer/breeders described in this model have evolved into commercial entities and/or partnered with public breeding institutions to develop regional varieties. The Biodynamic sector in Switzerland and Germany, for example, has created models for self-organization of organic seed breeding and production companies (e.g. Sativa and Bingenheimer Saatgut AG). In the US, participatory plant breeding models, such as NOVIC (which is also described in Chapter 2) where public breeders partner with farmers to develop public cultivars that are selected for site specificity and are open source. Comparable examples exist in Europe, e.g. the collaboration between breeding researchers of the French national agriculture research institute (INRA) in developing participatory approaches in regional cauliflower and broccoli breeding (Chable et al., 2008). The organic sector in the US could also look at adapting models that have been described for several crops in marginal agricultural regions in non-industrialized countries where breeders and farmers work more collaboratively in trait identification, selection and adoption to enhance the efficiency and relevancy of seed improvement (e.g. Manu-Aduening et al., 2006; Li et al., 2012; Reguieg et al., 2013). Potentially other models could exist, for example exchange of genetic material from company Model 2 with either Model 3 or 4 to conduct more regional screening and adaptation determination as well as more targeted commercialization of regionally selected varieties with organic growers in minor regions.

6.3.6 Outlook

The sustainability of current seed production for the major food crops on which global food security currently depends, is increasingly a matter of practical, professional and policy discussion. The work reported in this thesis indicates that the experience of the organic seed sector is relevant to these debates in important ways. In particular, conventional seed companies in the future may see advantage of having an organic division that might prove mutually inspiring and profitable, and traits of high priority for organic agriculture on the short-term might be of benefit to conventional agriculture in the long run as they strive to develop cultivars with characteristics that contribute to sustainable production systems.

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Summary

The overall objective of the research reported in this thesis was to analyse inter-related regulatory and technical challenges in the organic seed and breeding sector, using broccoli (*Brassica oleracea* var. *italica*) as a model crop and the US as the location. Organic farm practices often differ substantially from conventional practices in refraining from chemical-synthetic inputs of fungicides, pesticides and mineral fertilisers, but also in the diversity of crop rotations, number of crops, production area, and market outlets. Organic farming systems are based on organically-derived inputs such as compost and animal manure and focus their management on stimulating long-term biological self-regulatory processes to achieve resilience for stable productivity. However, organic farmers have fewer options to intervene in the short-term when weather or soil conditions are not favourable for optimal crop growth. Therefore organic growers require cultivars with stable performance across variable growing conditions over years. Currently, organic farmers depend largely on cultivars bred for high external input conventional farming systems. Use of organic seed as a required farm input is a component in the overall organic certification process. Recent developments in the interpretation of organic seed regulation have created tensions between farmers and seed companies as to how to provide a sufficiently diverse assortment of cultivars suited for organic agriculture while meeting the requirements.

This research aimed to understand and analyse the tensions between farmers' and seed companies' interests that have been created by evolving organic seed regulations, and identify ways to develop a domestic and international organic seed regulation to better support organic agriculture in general and crop improvement in particular. However, in order to be able to translate the diverse crop requirements identified for stakeholders in the broccoli seed chain in the US into a strategy for plant breeders, the horticultural and phytochemical performance of commercially available broccoli cultivars had to be established. The research thus also studied the performance of broccoli cultivars grown under organic and conventional farming conditions in two contrasting broccoli producing areas (Maine and Oregon, US).The requirements of organic growers were investigated for cultivars that allowed optimization of their production system, and fulfilled consumer expectations for high nutritional value. The

results of the horticultural and phytochemical trait performance studies were translated into a crop improvement strategy for broccoli cultivars adapted to organic agriculture with enhanced phytochemicals by identifying the parameters of an organic broccoli crop ideotype.

Chapter 2 reviews and analyses the evolution of organic seed regulation in the US, as a model case of how challenges in a new regulatory area are being addressed. The study draws on formal interviews of key stakeholders, participant observation, and documents generated over a six-year period between 2007 and 2013. The chapter addresses three main issues: (1) how proposals for the wording and implementation of the regulation constrain seed choices and give rise to unintended consequences, (2) how emergent organizations and procedures have responded to the tension between sustaining seed differentiation to match the characteristics of local markets, organic production and agro-ecologies, and the narrowing of varietal choice in catalogued seed so as to expand commercial organic seed markets and encourage organic plant breeding, (3) why consensus on the content of formal seed policy has failed to develop despite a high level of stakeholder engagement. The study revealed that the official guidance on the interpretation of the regulation has not been sufficiently decisive to prevent divergent interpretation and practices, and therefore the needs of a rapidly growing economic sector are not being met. The chapter concludes by drawing lessons for key areas of regulatory interpretation and practice, and by identifying possible ways to make organic seed governance more effective.

In the US case, the regulators are waiting for the non-governmental stakeholders to organize the sector to comply with organic seed regulations. Self-organisation has been only partially achieved, and sector development is evolving too slowly to optimally support organic seed market growth. While other on-farm organic inputs are rigorously regulated (e.g. compost, manure), seed is seemingly not recognized by the regulators as a significant input. At the same time the state of the US regulation has put the organic sector at risk of violating organic integrity. The regulatory ambiguity contributes to potential violations in the use of non-acceptable seed and seed treatment inputs, and perpetuates inconsistency in certifier seed regulatory interpretation and enforcement. It has failed (so far) to establish a level playing field among stakeholders. The organic regulation has perpetuated a concern amongst the diverse stakeholder groups that strict enforcement would limit the varietal assortment (genetic diversity and farmers' choice) available, increase grower costs and require seed companies to invest in a market that they consider relatively small or that they do not have the skills or resources to support (in regards to seed production or breeding). Simultaneously, however, the dynamic relationships that have evolved in the various networks that have emerged in response to the seed regulation have shaped the unfolding process of regulatory governance. In spite of regulatory ambiguity, the seed sector is developing, and a broader cultivar assortment and larger quantities of higher quality seed have become available.

Chapter 3 analyses the evolution of organic seed regulation in the United States, the European Union and Mexico as model cases of how challenges in global agricultural trade are being addressed. This study wasalso conducted between 2007 and 2013. It highlights how growth of the organic sector is hindered by regulatory imbalances and trade incompatibilities arising from divergent stakeholder interests along the organic seed value chain, and the varying capacity for self-organising governance of the seed sector in relation to the state's regulatory role. The main findings of the regulatory component were: (1) New organizations, procedural arrangements and activities have emerged in the US, EU and Mexico to support organic seed regulatory development, with both positive and negative results; (2) Official guidance on the interpretation of the regulation in the US has not been sufficiently decisive to prevent divergent interpretation and practice, and in consequence the needs of a rapidly growing economic sector are not being met; and (3) Growth of the organic seed sector is hindered by regulatory imbalances and trade incompatibilities within and between global markets. Progress toward regulatory harmonisation in the organic seed sector among the three cases has been slow. The chapter concludes with an assessment of the regulatory processes described including what the regions may learn from each other and lessons for key areas of regulatory policy and practice.

In the second study, when the US organic seed regulatory environment was compared to that of the EU and Mexico, delays in seed sector growth caused by regulatory ambiguity was found with each jurisdiction studied. The analysis identified important risks of non-tariff trade barriers in the organic sector, arising from incompatible regulatory frameworks and the uneven progress in each case toward achieving 100% closure. Specifically, as the EU moves at a more steady rate toward 100% closure, there are both positive and negative implications for the US and Mexico. In the more mature EU regulatory environment, there is increasing investment in the organic seed sector with more cultivars produced and bred for the global organic market. Each region was shown to demonstrate varying capacity for self-organising governance of their seed sector in relation to the state's regulatory role. In the EU context, the work of the non-profit organisation, ECO-PB, has been instrumental in moving matters forward, combined with clear regulatory language and specification of the interpretive requirements (such as establishment of a database of all approved cultivars and their availability). These measures can be compared to the US, where the initiatives of non-profit organizations have attempted to interpret the regulations in ways that lack official sanction. Mexico is early in the process of outlining their organic seed regulation, and until now has functioned in response to EU and US requirements. The additional complexity of strict phytosanitary requirements that conflict with organic regulation has delayed progress in the organic seed sector in Mexico. It is suggested that both the US and Mexico would benefit from the policy instruments that the EU member states have put in place to govern its organic seed sector, and from bringing to an end derogations that allow use of conventional seed. The instruments include implementation of national databases to provide an overview of available organic seed, and expert groups to annually assess available cultivar assortments in each crop group in order to compose categories of crops with sufficient quantity and diversity of seed available.

Chapter 4 sought to determine if present commercial broccoli cultivars met the diverse needs of organic management systems such as adaptation to low nitrogen input, mechanical weed management and no chemical pesticide use, and to propose the selection environments for crop improvement for cultivars best adapted to organic production. To achieve this, we compared horticultural trait performance of 23 broccoli (*Brassica oleracea*L. ssp. *italica*) cultivars (G) under two management (M) systems (organic and conventional) in two regions of the USA (Oregon and Maine), including spring and fall trials. In our trials, location and season had the largest effect on broccoli head weight with Oregon outperforming Maine and fall trials outperforming spring trials. M main effects and G × M interactions were often small but G × M × E (location and season) were large. Cultivars with both greater head weight and stability under conventional conditions generally had high head weight and stability under organic growing conditions, although there were exceptions in cultivar rank between management systems. Larger genotypic variances and somewhat increased error variances observed in organic compared to conventional management systems led to repeatability for head weight and other horticultural traits that were similar or even higher in organic compared to conventional conditions. The ratio of correlated response (predicting performance under organic conditions when evaluated in conventional conditions) to direct response (predicted performance in organic when evaluated under organic conditions) for all traits was close to but less than 1.0 with the exception of bead uniformity. This would imply that in most cases, direct selection in an organic environment could result in a more rapid genetic gain than indirect selection in a conventional environment. The combined analysis of the repeatabilities and ratio of correlated response to direct response would suggest that selection in organic environments is equal or superior to selection in conventional environments.

In Chapter 5 the topic of organic agriculture requiring cultivars that can adapt to organic crop management systems without the use of synthetic pesticides was built on from Chapter 4 by further exploring genotypes with improved nutritional value. The aim of this was to compare the 23 broccoli cultivars for the content of phytochemicals associated with health promotion grown under organic and conventional management in spring and fall plantings in two broccoli growing regions in the US. The phytochemicals quantified included: glucosinolates (glucoraphanin, glucobrassicin, neoglucobrassin), tocopherols (δ-, γ-, α-tocopherol) and carotenoids (lutein, zeaxanthin, β-carotene). For glucoraphanin (17.5%) and lutein (13%), genotype was the major source of total variation (numbers in parentheses are the percent of total variation accounted for by a main effect or interaction); for glucobrassicin, region (36%) and the interaction of location and season (27.5%); and for neoglucobrassicin, both genotype (36.8%) and its interactions (34.4%) with season were important. For δ- and γ- tocopherols, season played the largest role in the total variation followed by location and genotype; for total carotenoids, genotype (8.41-13.03%) was the largest source of variation and its interactions with location and season. Overall, phytochemicals were not significantly influenced by management system. The cultivars with the highest concentrations of glucoraphanin had the lowest for glucobrassicin and neoglucobrassicin. The genotypes with high concentrations of glucobrassicin and neoglucobrassicin were the same cultivars and were early maturing F_1 hybrids. Cultivars highest in tocopherols and carotenoids were open pollinated or early maturing F_1 hybrids. Distinct locations and seasons where phytochemical performance was higher for each compound were identified. Correlations among phytochemicals demonstrated that glucoraphanin was negatively correlated with the carotenoids and the carotenoids were correlated with one another. Little or no association between phytochemical concentration and date of cultivar release was observed, suggesting that modern breeding has not negatively influenced the level of tested compounds. We found no significant differences among cultivars from different seed companies.

In the field trial component of these studies, the organic trial locations were intentionally selected to be farms under long term organic management as less mature organic farms or those in conversion may more closely resemble conventionally managed farms. Our organic trials produced comparable head weight to the conventional trial locations, and therefore the level of the environmental stress that we hypothesized would affect trait performance and phytochemical content was minimal. For most traits, there was no management effect across environments. Management main effect was only identified at the per trial level, demonstrating that each individual location/season/year combination constituted a unique environment, and that genotype by management system interactions resulted from different factors in each environment. Larger genotypic variances in organic environments for horticultural but not phytochemical traits were observed, demonstrating the innate heterogeneity in the organic agricultural system and varietal response to such variation.

As with horticultural traits, management main effect did not play a significant role across trials in the phytochemical component of the trials. At the individual compound level, genotype main effect was most important for glucoraphanin, neoglucbrassicin and the carotenoids, while glucobrassicin and the tocopherols were more influenced by environment and various interactions. We identified distinct positive and negative trait correlations (e.g. glucoraphanin positively correlated with head weight and negatively correlated with carotenoids). For traits that were strongly associated with genotype main effect (i.e. glucoraphanin and lutein) the cultivars with the highest concentrations of these compounds were also the most stable across trials. Season effect was greater compared to the location (Maine versus Oregon) effect for the phytochemicals compared to the horticulture traits (glucoraphanin being higher in fall environments; carotenoids higher in spring environments). Unlike the horticultural traits, phytochemical variances were not larger in organic compared to conventional growing conditions, but repeatabilities and the ratio of correlated response to direct response were similar, which would support the benefit of selecting in organic systems to optimize nutrition targeted breeding programmes.

Chapter 6 assesses the main findings of Chapters 1-5 in the light of the objectives, hypotheses and research questions of this study. Through the combined analyses of the organic seed regulatory studies and the field trials that determined the horticultural and phytochemical trait performance of broccoli cultivars grown under organic and conventional management systems, the results are synthesised and discussed in terms of the following five propositions: (1) Regulatory clarity is the foundation for organic seed sector development, (2) Organic management systems influence horticultural and phytochemical trait performance, (3) A crop ideotype can serve as a communication tool to arrive at an appropriate cultivar assortment, (4) Genetic variation is a requirement to develop optimized cultivars, and (5) Multiple seed system models contribute to organic sector growth.Specifically, the role of an organic crop ideotype(a list of crop varietal traits required by organic growers for optimal cultivar performance in an organic production system) is explored. The defining an organic crop ideotype provides a useful format for growers and breeders to communicate the required traits. Once an ideotype has been defined, growers can match their needs with the cultivars available, and breeders have a "blueprint" for cultivar development. An organic crop ideotype also can be used as a communication tool between growers and certifiers i.e. to communicate cultivardifferences that could support derogation requests. Through this study, we sought to define an organic crop ideotype for broccoli through grower and breeder interviews, field trials and phytochemical analysis. The results of these combined studies are translated into an outline of a broccoli crop ideotype to be used as a foundation for developing a broccoli breeding strategy for organic agriculture. An organic broccoli breeding strategy must consider both the priority traits defined in a crop ideotype and the allowed breeding techniques in organic agriculture. A multi-prong market and breeding capacity approach must be considered to support a growing organic seed sector.

The sustainability of current seed production for the major food crops on which global food security currently depends, is increasingly a matter of practical, professional and policy discussion. The work reported in this thesis indicates that the experience of the organic seed sector is relevant to these debates in important ways. In particular, conventional seed companies in the future may see advantage of having an organic division that might prove mutually inspiring and profitable, and traits of high priority for organic agriculture on the short-term might be of benefit to conventional agriculture in the long run as they strive to develop cultivars with characteristics that contribute to sustainable production systems and improved nutritional quality.

Samenvatting

De algemene doelstelling van het onderzoek beschreven in dit proefschrift was om onderling samenhangende regelgeving en technische uitdagingen in de biologisch zaaizaad- en veredelingssector te analyseren, aan de hand van broccoli (*Brassica oleracea* var. *italica*) als modelgewas en de Verenigde Staten (VS) als de locatie. Biologische landbouwmethoden verschillen vaak aanzienlijk van gangbare praktijken door geen gebruik te maken van chemisch-synthetische gewasbeschermingsmiddelen en kunstmest, maar ook in de diversiteit van de vruchtwisseling, aantal gewassen, productie areaal, en afzetkanalen. Biologische landbouwsystemen zijn gebaseerd op hulpbronnen van biologische oorsprong zoals compost en dierlijke mest, en richten hun beheer op het stimuleren van lange termijn biologische, zelfregulerende processen ten behoeve van veerkracht voor stabiele productiviteit. Echter, biologische boeren hebben minder mogelijkheden om op de korte termijn in te grijpen als het weer of de bodemomstandigheden niet gunstig zijn voor een optimale gewasgroei. Daarom hebben biologische telers rassen nodig die onder variabele groeiomstandigheden en over verschillende jaren toch goed presteren. Momenteel zijn biologische telers grotendeels afhankelijk van rassen die veredeld zijn voor gangbare systemen met hoge inzet van externe hulpbronnen. Gebruik van biologisch zaad maakt een onderdeel uit van de vereisten van het totale biologische certificeringsproces. Huidige ontwikkelingen in de interpretatie van biologisch zaadregelgeving hebben tot spanningen geleid tussen telers en zaadbedrijven over de vraag hoe tot een voldoende gevarieerd assortiment van rassen te komen die passen bij de vereisten van de biologische landbouw.

Dit onderzoek was gericht op het begrijpen en analyseren van de spanningen tussen de belangen van telers en zaadbedrijven die ontstaan zijn in het ontwikkelingsproces rond de regelgeving voor biologisch zaaizaad, en op het identificeren van manieren om een nationale en internationale biologische zaadregelgeving te ontwikkelen die de biologische landbouw in het algemeen en de veredeling in het bijzonder beter ondersteunt. Echter, om de verschillende productvereisten zoals voor diverse actoren in de broccoliketen in de VS vastgesteld, te kunnen vertalen naar een veredelingsstrategie, moesten eerst de landbouwkundige prestaties en inhoudstoffen van commercieel beschikbare broccolirassen worden beoordeeld. Het onderzoek richtte zich dus ook op het vergelijken van de rassen onder biologische en gangbare teeltomstandigheden in twee contrasterende broccoliteeltgebieden in de VS (Maine en Oregon). Raskenmerken zijn onderzocht die biologische telers belangrijk vinden om hun productiesysteem te optimaliseren en om aan de verwachtingen van consumenten voor hoge voedingswaarde te voldoen. De resultaten van het onderzoek naar de rasprestaties wat betreft de landbouwkundige eigenschappen en inhoudstoffen is vervolgens vertaald naar een veredelingsstrategie voor broccolirassen die beter aangepast zijn aan de biologische landbouw met verhoogde voedingswaarde door aan te geven welke parameters van belang zijn voor zo'n een biologisch gewasprofiel.

Hoofdstuk 2 bespreekt en analyseert de ontwikkeling van de biologische zaadregelgeving in de VS, als een voorbeeldcasus hoe de uitdagingen van een nieuw terrein voor de regelgeving worden aangepakt. De studie is gebaseerd op formele interviews met belangrijke stakeholders, participatieve observaties, en documenten die over een periode van zes jaar tussen 2007 en 2013 zijn verschenen. Het hoofdstuk bespreekt drie punten: (1) hoe voorstellen voor de formulering en uitvoering van de zaadregelgeving keuzes inperken en aanleiding geven tot onbedoelde gevolgen, (2) hoe nieuw opkomende organisaties en procedures hebben gereageerd op de spanning tussen enerzijds het behouden van verscheidenheid aan zaden die passen bij de lokale markten, bij de biologische productie en de regionale agro-ecologische verschillen, en anderzijds de mate waarin van het aangeboden rassenpakket wordt versmald opdat uitbreiding van de commerciële zaadindustrie mogelijk wordt en biologische plantenveredeling wordt aangemoedigd, (3) waarom het maar lukte consensus te creëren over de inhoud van het formele zaadbeleid, ondanks een hoge mate van betrokkenheid van belanghebbenden. De studie toonde aan dat de officiële richtlijnen voor interpretatie van de regelgeving niet voldoende duidelijk zijn geweest om uiteenlopende interpretaties en uitvoeringspraktijken te voorkomen, en er dus aan de behoeften van een snel groeiende economische sector niet werd voldaan. Het hoofdstuk sluit af met het trekken van lessen voor de belangrijkste thema's rond de interpretatie en uitvoering van de regelgeving, en met het aangeven van mogelijke routes waarlangs sturing van biologisch zaaizaadontwikkeling effectiever kan worden.

In het geval de VS, verwachten de beleidsambtenaren dat de niet-gouvernementele actoren zelf de sector zullen organiseren om te voldoen aan biologische zaadregelgeving. Zelforganisatie is slechts gedeeltelijk bereikt, en de ontwikkeling van de sector verloopt te traag om optimale groei van een biologische zaadmarkt te ondersteunen. Terwijl andere biologische externe hulpbronnen strikt worden gereguleerd (bijvoorbeeld compost, mest), wordt zaad schijnbaar niet door de regelgevende instanties erkend als een belangrijke input. Tegelijkertijd leidt de huidige situatie rond de Amerikaanse regelgeving tot risico's van schenden van de integriteit van de biologische sector. De onduidelijkheid rond interpretatie van de regelgeving draagt bij aan mogelijke overtredingen op het gebruik van niet-aanvaardbare zaden en zaadbehandelingen, en bestendigt inconsistentie bij de interpretatie en handhaving van de zaadregelgeving. Het is (tot nu toe) niet gelukt om een gelijk speelveld tussen belanghebbenden te creëren. De biologische zaadregelgeving heeft onder de diverse belanghebbende groepen niet de bezorgdheid kunnen wegnemen dat strikte handhaving zal leiden tot een beperking van het rassenassortiment (genetische diversiteit en keuzevrijheid van boeren), tot verhoging van telerskosten en tot het vragen van zaadbedrijven te investeren in een markt die zij beschouwen als relatief klein of waarvoor zij niet de kennis of middelen hebben om die te ondersteunen (met betrekking tot de zaadproductie of veredeling). Desalniettemin, hebben de dynamische relaties die zich ontwikkeld hebben in de verschillende ontstane netwerken in reactie op de zaadvoorschriften bijgedragen aan het uitrolproces rond beleid van de regelgeving. Ondanks de onduidelijkheid in de regelgeving ontwikkelt de zaadsector zich, en is een breder rassenassortiment en groter aanbod van kwalitatief beter zaad beschikbaar gekomen.

Hoofdstuk 3 vergelijkt de ontwikkeling van de biologische zaadregelgeving in de VS, de Europese Unie (EU) en Mexico als voorbeelden hoe de uitdagingen in de wereldwijde handel in landbouwproducten worden aangepakt. Ook deze studie werd uitgevoerd tussen 2007 en 2013. Het belicht hoe de groei van de biologische sector wordt belemmerd door onevenwichtigheden in de regelgeving en onverenigbare situaties in het handelsverkeer die voortvloeien uit uiteenlopende belangen van partijen door de hele waardeketen van biologische zaaizaad heen, en het variërende vermogen voor zelf-organiserende bestuur van de zaadsector in relatie tot de regulerende rol van de overheid.

De belangrijkste bevindingen rond de regelgevingsaspecten waren: (1) Nieuwe organisaties, procedurele regelingen en activiteiten zijn ontstaan in de VS, EU en Mexico ter ondersteuning van de verdere ontwikkeling van de regelgeving voor biologisch zaad, met zowel positieve als negatieve resultaten; (2) De officiële richtlijnen voor interpretatie van de regelgeving in de VS hebben niet voldoende handvaten geboden om uiteenlopende interpretaties en uitvoeringen te voorkomen, en als gevolg wordt niet voldaan aan de behoeften van een snelgroeiende economische sector; en (3) De groei van de biologische zaadsector wordt belemmerd door onbalans in de regelgeving en onverenigbare situaties in het handelsverkeer binnen en tussen wereldwijde markten. Vooruitgang in de richting van harmonisatie van de regelgeving in de biologische zaadsector tussen de drie voorbeeldlanden is traag. Het hoofdstuk wordt afgesloten met een beoordeling van de regelgevende processen met inbegrip van wat de landen van elkaar kunnen leren en welke lering getrokken kan worden voor de belangrijkste aspecten van het beleid rond de regelgeving en de uitvoering.

In deze studie waarbij de Amerikaanse biologische zaadregelgeving is vergeleken met die van de EU en Mexico, zijn vertragingen in de zaadsectorontwikkeling, veroorzaakt door onduidelijkheden in de regelgeving, in elk rechtsgebied gevonden. De analyse identificeerde de belangrijke risico's van handelsbelemmeringen in de biologische sector door importheffingen, als gevolg van onverenigbare regelgeving en de ongelijke ontwikkelingen om tot 100% gebruik van biologisch zaaizaad te komen. Temeer daar de EU gestaag toewerkt naar 100% gebruik van biologisch uitgangsmateriaal, zijn er zowel positieve als negatieve gevolgen voor de VS en Mexico. Door de meer volwassen EU-regelgeving, wordt er meer geïnvesteerd in de biologische zaadsector met een toenemend aantal rassen dat geproduceerd wordt of veredeld voor een wereldwijde biologische markt. Elke van de drie voorbeeldlanden vertoonde een verschillend vermogen van zelf-organiserende bestuur van hun zaadsector in relatie tot de regulerende rol van de overheid. In EU-verband, is het werk van de non-profit organisatie European Consortium for Organic Plant Breeding (ECO–PB) instrumentaal geweest om de zaak vooruit te helpen, in combinatie met duidelijke taal in de regelgeving en specificatie van de interpretatieve eisen (zoals invoering van een database van alle goedgekeurde rassen en hun beschikbaarheid). Als men deze maatregelen vergelijkt met die in de VS, ziet men dat daar initiatieven van non-profit organisaties hebben geprobeerd om de regelgeving op een bepaalde manier te interpreteren maar zonder officiële goedkeuring. Mexico staat aan het begin van het proces van vormgeven van hun biologische zaadregelgeving door steeds te reageren op de vereisten vanuit de EU en de VS. Bovendien hebben de gecompliceerde, strenge fytosanitaire eisen in Mexico, die strijdig zijn met de biologische regelgeving, de voortgang in de biologische zaadsector aldaar vertraagd. De suggestie wordt gedaan dat zowel de VS als Mexico zouden kunnen profiteren van de beleidsinstrumenten die de EU-lidstaten hebben ingevoerd om de biologische zaadsector te reguleren, en die toewerken naar het beëindigen van de mogelijkheid om ontheffing te verkrijgen voor gebruik van gangbaar zaad. De instrumenten bestaan uit implementatie van nationale databases om een overzicht van beschikbaar biologisch zaad te bieden, en instellen van expertgroepen die jaarlijks het beschikbare rassenassortiment voor elke gewasgroep beoordelen om tot categorieën van gewassen te komen met voldoende hoeveelheid en diversiteit van beschikbare zaden.

Hoofdstuk 4 richt zich op de vraag of huidige commercieel beschikbare broccoli rassen voldoen aan de uiteenlopende behoeften van biologische productiesystemen, zoals aanpassing aan lage stikstofgift, mechanische onkruidbestrijding en geen gebruik van chemische bestrijdingsmiddelen, en om tot aanbeveling van selectiemilieu's te komen voor veredeling van rassen die optimaal aangepast zijn aan biologische productie. Om dit te bereiken, hebben we de landbouwkundige prestaties van 23 broccoli (*Brassica oleracea* L. ssp. *italica*) genotypen (G) onder twee management (M) systemen (biologisch en gangbaar) in twee teeltgebieden van de VS (Oregon en Maine) vergeleken, inclusief voor- en najaarsproeven. In onze proeven, hadden locatie en seizoen het grootste effect op de broccoli schermgewichten, die in Oregon hoger waren dan in Maine, en in het najaar hoger dan in de voorjaarsproeven. De effecten van managementsystemen en G × M interacties waren vaak klein, maar G × M × E (locatie en het seizoen) waren groot. Gemiddeld genomen hadden rassen met zowel een hoog schermgewicht als stabiliteit onder gangbare landbouwomstandigheden dat ook onder biologische teeltomstandigheden, hoewel er verschillen in rasvolgorde tussen beide productiesystemen voor kwamen. Grotere genetische variatie en enigszins verhoogde varianties van proefveldfouten die zijn waargenomen in de biologische productiesystemen in vergelijking met gangbare systemen, leidden tot een herhaalbaarheid voor schermgewicht en andere landbouwkundige eigenschappen die vergelijkbaar of zelfs hoger waren in de biologische teelt dan in de gangbare teeltomstandigheden. De verhouding van gecorreleerde respons (voorspellen van prestaties onder biologische omstandigheden indien beoordeeld onder gangbare omstandigheden) tot directe respons (voorspelde prestaties voor biologische teelt indien beoordeeld onder biologische omstandigheden) voor alle eigenschappen was bijna, maar minder dan 1,0 met uitzondering van de uniformiteit van de bloemknoppen. Dit zou betekenen dat in de meeste gevallen directe selectie in een biologisch milieu kan leiden tot een snellere genetische vooruitgang dan indirecte selectie onder gangbare teelt. De gecombineerde analyse van de herhaalbaarheid en de verhouding van gecorreleerde respons tot directe respons suggereert dat de selectie onder biologische omstandigheden gelijk of beter kan zijn dan de selectie onder gangbare omstandigheden.

In hoofdstuk 5 is voortgebouwd op de vraag van de biologische landbouw naar rassen die aanpast zijn aan biologische teeltsystemen zonder het gebruik van chemisch-synthetische bestrijdingsmiddelen (zie hoofdstuk 4) door de aandacht te richten op selectie van genotypen met verhoogde voedingswaarde. Het doel hiervan was om de 23 broccoli rassen te vergelijken voor inhoudstoffen met gezondheidbevorderende werking onder biologische en gangbare teelt in voorjaars- en herfst beplantingen in twee broccoli teeltgebieden in de VS. De gekwantificeerde inhoudstoffen omvatten: glucosinolaten (glucorafanine, glucobrassicine, neoglucobrassine), tocoferolen (δ-, γ-, α-tocoferol) en carotenoïden (luteïne, zeaxanthine, β-caroteen). Voor glucorafanine (17.5 %) en luteïne (13 %), was genotype de belangrijkste bron van de totale variatie (tussen haakjes zijn het percentage van de totale variatie verklaard door een hoofdeffect of interactie); voor glucobrassicine was teeltgebied (36 %) en de interactie van de locatie en het seizoen (27,5%) belangrijk; en voor neoglucobrassicine waren zowel genotype (6,8 %) als de interacties met het seizoen belangrijk. Voor δ- en γ-tocoferol speelde seizoen de grootste rol in de totale variatie, gevolgd door de locatie en genotype; voor het totaal aan carotenoïden was genotype (8,41-13,03 %) was de grootste bron van variatie en de interacties met de locatie en het seizoen. Over het algemeen werden deze inhoudstoffen niet significant beïnvloed door het managementsysteem. De rassen met de hoogste concentraties glucorafanine hadden de laagste concentraties aan glucobrassicine en neoglucobrassicine. De genotypen met hoge concentraties glucobrassicine en neoglucobrassicine waren dezelfde vroegrijpende F[1]-hybriden. Rassen met de hoogste concentraties van tocoferolen en carotenoïden waren zaadvaste rassen of vroegrijpende F[1]-hybriden. Specifieke locaties en seizoenen waar afzonderlijke inhoudstoffen het hoogst waren, zijn geïdentificeerd. Correlaties tussen inhoudstoffen toonden aan dat glucorafanine negatief was gecorreleerd met carotenoïden en carotenoïden onderling correleerden. Weinig of geen verband werd waargenomen tussen de concentratie van inhoudstoffen en de datum van marktintroductie van rassen, wat suggereert dat de moderne veredeling geen negatieve invloed heeft gehad op het niveau van de onderzochte inhoudstoffen. We vonden ook geen significante verschillen tussen de rassen van verschillende zaadbedrijven.

Voor de veldproeven van deze studies is opzettelijk gekozen voor biologische bedrijven die al lang onder biologisch beheer zijn omdat minder volwassen biologische bedrijven of die nog in omschakeling zijn meer op gangbare bedrijven lijken. Onze biologische proeven produceerden vergelijkbare schermgewichten als de gangbare proeflocaties, waardoor het niveau van abiotische stress, waarvan we hypothetisch stelden dat die van invloed zou zijn op de mate van expressie van de landbouwkundige eigenschappen en inhoudstoffen, minimaal was. Productiesysteem was alleen van invloed op individueel proefniveau, hetgeen laat zien dat elke individuele locatie/seizoen/jaar combinatie een unieke milieu vormde, en dat genotype × productiesysteem interacties het gevolg waren van verschillende factoren in elke omgeving. Grotere genotypische verschillen in biologische productiesystemen werden voor landbouwkundige eigenschappen, maar niet voor inhoudstoffen waargenomen, hetgeen de intrinsieke heterogeniteit in de biologische landbouwsystemen en de respons van rassen op deze variatie liet zien.

Zoals wel met betrekking tot de landbouwkundige eigenschappen het geval was, speelde productiesysteem geen significante rol met betrekking tot het niveau van de inhoudstoffen. Op individueel niveau van de inhoudstoffen, was het genotype het meest bepalend voor glucorafanine, neoglucbrassicine en de carotenoïden, terwijl glucobrassicine en de tocoferolen meer beïnvloed werden door de milieuomstandigheden en diverse interacties. We identificeerden verschillende positieve en negatieve correlaties tussen eigenschappen (bijv.

glucorafanine was positief gecorreleerd met het schermgewicht en negatief gecorreleerd met carotenoïden). Voor eigenschappen die sterk geassocieerd waren met genotype (d.w.z. glucorafanine en luteïne) waren rassen met de hoogste concentraties van deze verbindingen ook de meest stabiele rassen over alle proeven. Seizoenseffecten waren groter dan de locatie-effecten (Maine versus Oregon) voor de inhoudstoffen in vergelijking met de landbouwkundige eigenschappen (glucorafanine was hoger in de herfst; carotenoïden hoger in het voorjaar). Anders dan bij de landbouwkundige eigenschappen, was de variatie in concentraties van inhoudstoffen niet groter onder biologische dan onder gangbare teeltomstandigheden, maar herhaalbaarheid en de verhouding van gecorreleerde respons en directe respons was vergelijkbaar, hetgeen veronderstelt dat het selecteren onder biologische omstandigheden effectief kan zijn voor het optimaliseren van veredelingsprogramma's gericht op voedingstoffen.

Hoofdstuk 6 evalueert de belangrijkste bevindingen van de hoofdstukken 1-5 in het licht van de doelstellingen, hypotheses en onderzoeksvragen van dit onderzoek. Door de gecombineerde analyses rond de biologische zaadregelgeving en de veldproeven die de landbouwkundige eigenschappen en niveau van inhoudstoffen van broccoli rassen onder biologische en gangbare teeltsystemen bepaalden, worden de resultaten samengevat en besproken aan de hand van de volgende vijf stellingen: (1) heldere regelgeving is de basis voor de ontwikkeling van de biologische zaadsector, (2) biologisch productiesystemen beïnvloeden landbouwkundige eigenschappen en niveau van inhoudstoffen van rassen, (3) een gewasideotype kan dienen als communicatie-instrument om te komen tot een geschikt rassenassortiment, (4) genetische variatie is een vereiste om optimale rassen te ontwikkelen, en (5) meerdere modellen voor zaaizaadsysteem dragen bij aan de groei van de biologische sector. In het bijzonder is de rol van een biologisch gewasideotype (een lijst van door biologische telers gewenste raskenmerken voor optimale rasprestaties in een biologisch productiesysteem) verkend. Het definiëren van een biologische gewasideotype levert een bruikbaar instrument voor telers en veredelaars om over de vereiste eigenschappen te communiceren. Zodra een ideotype is gedefinieerd, kunnen telers zorgen dat hun behoeften aansluiten bij beschikbare rassen, en hebben veredelaars een 'blauwdruk' voor de rasontwikkeling. Een biologisch gewasideotype kan ook worden gebruikt als communicatiemiddel tussen telers en certificeerders, d.w.z. om rasverschillen te communiceren die een derogatieaanvraag kunnen ondersteunen. Door deze studie hebben we getracht een biologische gewasideotype te definiëren voor broccoli aan de hand van de beschikbare interviews met veredelaars en telers, de veldproeven en de analyses op inhoudstoffen. De resultaten van deze gecombineerde studies zijn vertaald naar een beschrijving van een broccoli gewasideotype om te worden gebruikt als basis voor het ontwikkelen van een broccoli veredelingsstrategie voor de biologische landbouw. Een biologische broccoli veredelingsstrategie moet rekening houden met zowel de geprioriteerde eigenschappen gedefinieerd in een gewasideotype en de toegestane veredelingstechnieken in de biologische landbouw. Zowel een veelzijdige markt als de veredelingsmogelijkheden moeten in beschouwing genomen worden om een groeiende biologische zaadsector te ondersteunen.

De duurzaamheid van de huidige zaadproductie voor de belangrijkste voedselgewassen waarvan de mondiale voedselzekerheid momenteel afhankelijk is, is in toenemende mate een kwestie van praktische, professionele en politieke discussie. Het werk beschreven in dit proefschrift geeft aan dat de ervaring van de biologische zaadsector relevant is voor deze discussies in vele opzichten. In het bijzonder, kunnen gangbare zaadbedrijven in de toekomst voordeel zien in het hebben van een biologische afdeling die wederzijds inspirerend en winstgevend zou kunnen blijken; en eigenschappen met op de korte termijn een hoge prioriteit voor de biologische landbouw zouden ook op lange termijn de gangbare landbouw kunnen dienen als ze streven naar rassen met eigenschappen die bijdragen aan duurzame productiesystemen en verbeterde voedingskwaliteit.

About the Author

Erica Natalie Claire Renaud was born in Kitchener, Ontario Canada, 24th of December 1970. She grew up in Kitchener where she attended St. Mary's Highschool and graduated in 1988. Subsequently, Erica pursued a Bachelors of Arts in Comparative Development and Environmental and Resource Management Studies from Trent University in Peterborough, Ontario, Canada, graduating in 1993. During her studies she spent one year abroad working and researching in Ecuador where her appreciation for sustainable agriculture developed. After practicing organic farming, she began a Master of Science programme in Sustainable Systems with a focus on Agroecology at Slippery Rock University in Slippery Rock, Pennsylvania, graduating in 1997. Upon completion of her MSc work, Erica worked for Frontier Natural Products Co-op, in Norway, Iowa, conducting research on herb cultivar performance under organic conditions and translating the results to farmer-producers supplying the company. Following this work, she managed quality control processes and organic certification of medicinal and aromatic plant production and wild harvesting with farmers in sub Saharan, Africa through the USAID-funded project, Agribusiness in Sustainable Natural African Plant Products (ASNAPP), at Rutgers University in New Jersey. Later, she managed organic seed research and the trials farm for Seeds of Change, in El Guique, New Mexico. Presently, Erica is the Business Development Manager for Vitalis Organic Seeds, North America, the organic division of the Netherlands based breeding and seed production company Enza Zaden. Erica was responsible for launching the brand in Canada, the US and Mexico in 2007. With responsibility for establishing a vibrant organic seed business in each country, and for supporting the growth of that business through the distribution of certified organic vegetable and herb seed, Erica spends considerable time working with policymakers, growers and breeders to help communicate programs and policy, and to address obstacles and opportunities for organic seed sector growth. She is an active member and past-chair of the organic seed committee of the American Seed Trade Association (ASTA). She is presently engaged in multiple project initiatives with the Organic Seed Alliance (OSA), aiming to improve the functionality of the US national organic seed finder database and to determine methods of collecting market data on organic seed sector growth.

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 (6 ECTS)

- Approaches to stimulate the development of new varieties for organic agriculture (2007)

Writing of project proposal (4.5 ECTS)

- Designing breeding strategies for organic broccoli (*brassica oleracea* L. var. *italica*) in the USA: genotype-environment-management interactions for agronomical and nutritional aspects, and stakeholder involvement

Post-graduate courses (6 ECTS)

- Basic statistics; PE&RC (2008)
- Advanced statistics; PE&RC (2008)
- Biodiversity and ecosystem services in a sustainable world; PE&RC (2008)

Laboratory training and working visits (3 ECTS)

- Broccoli breeding and germplasm conservation; Department of Horticulture, Oregon State University (2008)
- Broccoli phytochemical analysis training; University of Illinois (2008)

Deficiency, refresh, brush-up courses (3 ECTS)

- Organic plant breeding (2007)
- Plant breeding (2008)
- Breeding for resistance & quality (2009)

Competence strengthening / skills courses (4.5 ECTS)

- -Academic writing; WUR (2010)
- -INSEAD Professional development training for senior managers; Enza Zaden / INSEAD (2011-2012)

- Enza Zaden internal training on advancements in plants breeding; Enza Zaden (2012)
- Enza Zaden internal training on advancements in plants breeding; Enza Zaden (2013)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)
- PE&RC Weekend (2008)
- PE&RC Day (2009)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)
- Stakeholder participation in research, at WUR (2008)
- Organic Seed Alliance- Organic Seed Conference (2008, 2010, 2012)
- Product Advancement Team Meetings (2010-2014)

International symposia, workshops and conferences (9 ECTS)
- EUCARPIA Symposium-Plant breeding for organic and sustainable, low-input agriculture; dealing with genotype-environment interactions (2007)
- EUCARPIA Symposium-2nd Conference of the Organic and Low-Input Agriculture section; oral presentation (2010)
- Mexico Organic Seed Importation Meeting; oral presentation; Celaya, MX (2010)
- Organicology Conference; oral presentation (2011)
- North America Plant Protection organization (NAPPO); oral presentation (2012)
- Florida Small Farmers Conference; oral presentation; University of Florida (2013)
- Organic Seed Alliance-Organic Seed Conference; oral presentation (2014)
- American Seed Trade Association (ASTA); oral presentation (2009-2013)

Lecturing / supervision of practical's / tutorials (1.8 ECTS)
- Organic plant breeding; WUR (2007/2008)
- Student Organic Seed Symposium; oral presentation; Vermont (2012)
- Student Organic Seed Symposium; oral presentation; Washington State University (2013)

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