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THE EFFECTS OF AGRICULTURAL PRACTICES ON NATIVE BEE COMMUNITY STRUCTURE AND HighbUSH BLUEBERRY CROP PRODUCTION

By

Melanie Joanne Fabian

Accepted in Partial Completion

Of the Requirements for the Degree

Master of Science

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Melanie Fabian

May 5th, 2014
ABSTRACT

Insect pollinators are essential for facilitating cross pollination and reproduction in many crops and wild plants. Both managed honeybees and wild bees provide great monetary value through their role in the production of food crops via cultivated plants. These pollinators are threatened globally, with populations diminishing as natural habitats are destroyed and agricultural intensification increases. Demands for insect pollinated crops continue to rise, and with honeybee colonies continually on the decline due to Colony Collapse Disorder, exploring the factors affecting native bee communities is essential for ensuring sustainable pollination services in the future. Here, I studied the effects of farming practices (conventional vs. organic) on native bee communities and crop yield by collecting native bee and blueberry samples from both conventional and organic ‘Duke’ variety blueberry farms in lowland NW Washington State. I sampled bee communities using pan traps and netting at nine study sites (five conventional, four organic), from early May to mid-June, 2012. During this same period, I collected random clusters of berries at each farm site to compare yields between farm types, and to assess potential correlations between berry production and bee community metrics. I also performed a pollinator exclusion experiment at one of the four organic sites, to determine the importance of pollination services to berry production.

Farming practices had no effect on indices of native bee diversity and richness, but native bee abundance was significantly higher on organic farms compared to conventional farms. Furthermore, farming practices influenced native bee community structure, with a suite of bumblebee species being more common in organic fields. Combining the results of this study with published surveys of bees in various agricultural and natural habitats in the Pacific Northwest, it appears that in general, bee communities on agricultural lands in this region exhibit relatively few native bee individuals and low species richness. Perhaps for this reason, I found that crop yield did not differ between farm types, nor was berry production correlated with measures of bee abundance and diversity, despite the fact that the pollinator exclusion experiments showed that ‘Duke’ variety blueberries are highly pollinator dependent. Specifically, berries exposed to pollinators had significantly larger mass, diameter, and seed counts, and lower abortion rates. Overall, the results of this study indicate that organic farming is favorable for native bee populations in general, and bumblebees in particular, but that neither conventional nor organic farms support many native bees. Future studies should focus on determining if aspects of organic farming that enhance bee populations can be adopted on conventional farms, as well as determining management strategies to improve the condition of native bee communities across agricultural landscapes.
ACKNOWLEDGMENTS

Without the assistance of numerous individuals and organizations, this project would have never been possible. I cannot express in words how thankful I am for my advisor, Merrill Peterson. His advice and time have been invaluable, and I can’t thank him enough for his mentorship, multiple thorough edits of this thesis, for the countless hours he spent helping me identify hundreds of bee specimens, and for being there for me whenever I needed him. I would also like to thank my other committee members, Dietmar Schwarz, Eric DeChaine, David Hooper and Colleen Burrows for their advice and feedback on this project. I am also grateful to Jim Mullen of WWU’s Scientific Technical Services, for construction of the traps used for this project, to the several farmers and Charlie Anderson of Sakuma Brothers Farms for allowing me to conduct research in their blueberry fields, to my fellow graduate students; Jenna Brooks, Kelsey Jesser, Kat Brown, Melissa Habenicht, Leesa Sorber, Mitchell Lee, and Caitlin O’Brien for all of their help with field collections, to the WWU Biology department stockroom supervisor Peter Thut for help with ordering numerous supplies needed for this project, and to Rose Osborne, Mimi Gunderson, Karsten Schick, Amreen Toor and Alisha Foster, my amazing undergrad research assistants to whom I am greatly indebted, as well as Jamie Latham for photographing the bee specimens used for the photographic plate. I would also like to thank Elizabeth Elle for providing access to the SFU collection of native bees, and for providing help with identifications.

The following organizations provided research grants that enabled me to complete this research: the Theodore Roosevelt Memorial Fund of the American Museum of Natural History, the Hodgson family, and WWU’s Office of Research and Sponsored Programs.

I would especially like to thank my parents, John and Peggy Davis, for their emotional and financial support, and for always encouraging me throughout my academic pursuits. Finally, my husband Jon Fabian, who provided immense help in the field and in the lab, designed and built the auto bee dryer used in this project, and most of all, always supported me throughout this crazy emotional journey.
# TABLE OF CONTENTS

**ABSTRACT** .................................................................................................................. iv

**ACKNOWLEDGMENTS** ............................................................................................... v

**LIST OF FIGURES** .................................................................................................... ix

**LIST OF TABLES** ....................................................................................................... x

**INTRODUCTION** ........................................................................................................ 1

- Threats to honeybee pollination services ................................................................. 2
- Bee diversity .................................................................................................................. 3
- The role of native pollinators in agriculture ............................................................... 4
- Factors influencing bee diversity in agroecosystems .................................................. 5
- Blueberry pollination and production ....................................................................... 7
- Research objectives ................................................................................................... 10

**METHODS** ............................................................................................................... 12

- Study sites .................................................................................................................. 12
  - Assessing land use surrounding farm sites ............................................................ 14
  - Data analyses ........................................................................................................... 15
- Bee community structure .......................................................................................... 15
  - Methods/experimental design ............................................................................... 15
  - Specimen processing and identification ................................................................. 19
  - Data analyses: bee diversity and abundance ......................................................... 20
    - Univariate analyses .............................................................................................. 20
    - Multivariate analyses ......................................................................................... 21
    - Land use and native bee community integrity .................................................. 23

vi
APPENDICES

Appendix A. Bee families and their characteristics ...........................................74

Appendix B. Location, size and elevation of study sites................................. 75

Appendix C. Study site attributes.................................................................. 76

Appendix D. Dates for pan trap collections..................................................... 77

Appendix E. Assembly drawing of Auto Bee Dryer ......................................... 78

Appendix F. Image of Auto Bee Dryer ............................................................... 79

Appendix G. Native bee community statistics for this study and seven additional studies in Oregon and Western Canada......................................................... 80

Appendix H. Photographic plate of bee species collected in this study.......... 81

Appendix I. Site and species-specific counts of bees collected in this study.... 82

Appendix J. Relative abundance of native bee species collected.................... 83

Appendix K. Average capture rates for both native bees and honeybees........ 84

Appendix L. Diversity indices, evenness, species richness and abundance.... 85
LIST OF FIGURES

Figure 1. Map of farm sites used in this study ......................................................... 13
Figure 2. Images of pan traps used for bee collection ........................................... 17
Figure 3. Example of randomly-selected pan trap locations (farm site O3) ............... 18
Figure 4. Bagged flowers and blueberry clusters .................................................... 26
Figure 5. Native bee and honeybee abundance at conventional and organic farms ... 31
Figure 6. Average Shannon Diversity indices (H’), Simpson Diversity indices (D), species richness (S), Margalef richness indices (d), and Pielou’s species evenness (J’) for conventional and organic farms ................................................................. 32
Figure 7. Ordination plot displaying the clustering of farm sites based on similarity in native bee community composition ................................................................. 33
Figure 8. Dendrogram plot displaying the clustering of farm sites based on similarity in native bee community composition ................................................................. 34
Figure 9. Relationship between percentage of surrounding forested area and native bee abundance, honeybee abundance and several metrics of native bee community structure for both conventional and organic farms ................................................................. 38
Figure 10. Relationship between farm size (ha) and native bee abundance, honeybee abundance and several metrics of native bee community structure for both conventional and organic farms ................................................................. 39
Figure 11. Relationship between tillage (yes or no) and native bee abundance, honeybee abundance and several metrics of native bee community structure for both conventional and organic farms ................................................................. 41
Figure 12. Relationship between native bee abundance and native bee species richness (S) for eight studies in Washington, Oregon, and Canada ........................................... 42
Figure 13. Relationship between native bee abundance, native bee species richness (S) and person hours of netting for four studies in Washington, and Canada ................... 43
Figure 14. Relationship between native bee abundance, native bee species richness (S) and total trap days for four studies in Washington, and Oregon ........................................... 44
Figure 15. Average mass, diameter, number of seeds, and berry abortion rates for openly-pollinated and pollinator-excluded berries ................................................................. 46
Figure 16. Average berry mass, diameter, number of seeds per berry, and berry abortion rates for both conventional and organic farms ................................................................. 47
Figure 17. Pearson product-moment correlations between pooled average berry mass (g) and bee community measures ................................................................. 48
Figure 18. Pearson product-moment correlations between pooled average berry diameter (mm) and bee community measures ................................................................. 49
Figure 19. Pearson product-moment correlations between pooled average seed counts and bee community measures ................................................................. 50
LIST OF TABLES

Table 1. Farming practices that affect bees .................................................................6
Table 2. Important differences between organic and conventional agricultural practices……8
Table 3. The three species that contributed most to the average similarity in native bee community composition within each farm type (conventional and organic)………………. 36
Table 4. The three species that contributed most to the average dissimilarity in native bee community composition between farm types (conventional and organic)………………………….. 37
INTRODUCTION

Pollination by bees and other insects is often underappreciated though it is critical for reproduction by many angiosperms; at least 87% of flowering plants depend on animals, primarily bees, for proper pollination and reproduction (Kearns and Inouye 1997, Morandin and Winston 2005, Michener 2007, Power and Stout 2011, Gonzalez-Varo et al. 2013, Winfree 2013). These pollinators provide essential ecosystem services in both natural and managed systems (Vanbergen et al. 2013, Winfree 2013). Furthermore, insect pollination provides great monetary value through the production of food crops (Kearns et al. 1998); an estimated 35% of crops consumed globally by humans depend on insect pollination (Buchmann and Nabhan 1996, Klein et al. 2007, Bates et al. 2011, Russo et al. 2013). The value of such pollination is continually rising, with wild and managed services exceeding $200 billion globally, and $15 billion in the United States alone (Calderone 2012, Vanbergen et al. 2013). Despite these values, there is remarkably little knowledge about the factors influencing pollinator diversity in natural and managed systems and the effects of diminishing bee abundance and diversity on crop production (Klein et al. 2003, Morandin and Winston 2005).

Native bees can fully pollinate a wide variety of crops, but sufficient habitat and resources are required to maintain large enough populations of these bees to be effective (Russo et al. 2013). Historically, native bee populations could adequately pollinate most managed crops, but human activities have severely reduced habitat and resources, diminishing native bee populations and resulting in cases of low crop production or complete crop failure (Allen-Wardell et al. 1998, Morandin and Winston 2005, Michener 2007, Russo et al. 2013). Trends in agricultural practices (increased use of pesticides, herbicides, tilling,
etc.) have destroyed nesting sites and alternate nectar/pollen sources for native bee species, reducing their abundances to the point that growers now must rent honeybee (*Apis mellifera* Linnaeus) colonies to supplement wild bee pollination services (MacKenzie and Eickwort 1996, Michener 2007, Carré et al. 2009, Gonzalez-Varo et al. 2013). Managed colonies are moved into fields during bloom and out of fields during pest management activities, allowing farmers to use chemical pesticides to control pests throughout the growing season without losing a considerable amount of insect pollination (Shuler et al. 2005, Isaacs and Kirk 2010).

**Threats to honeybee pollination services**

Renting managed colonies of honeybees is costly for farmers and these costs continue to rise (Burgett 2007, Sagili and Burgett 2011). Dependence on this single pollinator species is not only expensive, but risky, especially since honeybee colonies have declined due to both parasitic mites (*Varroa destructor*) and Colony Collapse Disorder (Kremen and Chaplin-Kramer 2007, Jacobsen 2008, Klein et al. 2012, Yang et al. 2012, Russo et al. 2013). The rapid spread of *Varroa destructor* has caused severe losses of managed colonies globally, and has decimated feral honeybee colonies in North America since its introduction only 25 years ago (Locke 2012).

Currently, Colony Collapse Disorder (CCD) is the leading cause of honeybee declines, and is characterized by the disappearance of worker bees from hives that are considered healthy (Jones and Sweeney-Lynch 2011, Lu et al. 2012). Foraging bees are unable to navigate back to the hive and eventually die, ultimately leaving the hive devoid of adult bees (Jacobsen 2008, Yang et al. 2012). The cause of CCD is still unclear, but it appears that a combination of factors including stress on colonies during shipping for
pollination services, single source diets, introduced bee viruses, systemic pesticides (neonicotinoids, specifically imidacloprid), and the recent emergence of the debilitating microsporidian pathogen, *Nosema apis*, could be contributing to this mysterious disorder (Jacobsen 2008, Guzmán-Novoa et al. 2010, Jones and Sweeney-Lynch 2011, Gradish et al. 2012).

Through the combined effects of *Varroa* mites and CCD, the number of managed honey bee colonies has declined approximately 45% in the U.S. over the last 60 years (U.S. National Academy of Sciences 2007, Jacobsen 2008, Le-Conte et al. 2010, Jones and Sweeney-Lynch 2011, Yang et al. 2012). As a result, agriculture faces reduced pollination services, increased cost of renting hives, and potential shortages of many crops (Jones and Sweeney-Lynch 2011, Vanbergen et al. 2013). Native bees provide a potential means of reducing our reliance on honeybees, but only if we adopt agricultural methods that promote thriving native bee communities.

**Bee diversity**

The seven families of bees contain about 25,000 known bee species worldwide, almost 4,000 of which live in the United States (Moisset and Buchmann 2011). Bees display a wide variety of size (body lengths from 1.5 to 40 mm) and color (black, orange, yellow, or even metallic blue/green). They also have varying levels of social behavior, including solitary, parasitic and eusocial species (Appendix A). Furthermore, bee species vary substantially in nest site location, with each species using a characteristic nesting substrate (Moisset and Buchmann 2011). Hole-nesters nest in existing holes in trees and other wood structures, while carpenters create their own holes in wood. In contrast, miners (or ground-
nesters) build underground nests, usually in the form of a series of tunnels. Foraging distance also tends to vary among bee species, ranging from 15 m to 800 m, and tends to be positively correlated with body size (Greenleaf and Williams 2007, Vaughan et al. 2007).

**The role of native pollinators in agriculture**

Collectively, the tremendous diversity of native bees likely explains why they are so important in many agroecosystems. Native pollinators provide an estimated $3 billion in crop pollination services each year worldwide (Losey and Vaughan 2006, Mader et al. 2007, Calderone 2012), and without native bees, nearly 75% of the food crops we consume would no longer be available (Moisset and Buchmann 2011). In a variety of crops (various vegetables, apples, blueberries, and cucurbits), over half of the pollinator visits to vegetable, may be from wild bee species (Winfree et al. 2008, Adamson et al. 2012). Native bees can also be more effective and efficient pollinators than honeybees (Russo et al. 2013) by visiting more flowers per minute and depositing more pollen per flower than honeybees, and by performing buzz pollination (Tuell et al. 2009). Buzz pollination occurs when a bee lands on a flower and vibrates its flight muscles at a high frequency, causing pollen to fall from the anthers (Proenca 1992, Rosenthal 2008). Buzz pollination releases pollen from many types of flowers, including those of blueberries, with tubular anthers that do not easily release pollen (Rosenthal 2008). As a result, in plants of this type, buzz pollination can substantially increase fruit set and weight (Greenleaf and Kremen 2006, Rosenthal 2008). Due to such benefits, high native bee diversity and abundance can enhance pollination success in agricultural settings (Klein et al. 2003).
Factors influencing bee diversity in agroecosystems

Because optimal pollination may only occur under high native bee diversity and abundance (Kevan et al. 1997, Kremen et al. 2002, Morandin and Winston 2005), sustaining consistently high crop yields depends on understanding the factors that influence wild bee communities. The effect of agricultural practices on native bee diversity also has important conservation implications (Kremen et al. 2002, Klein et al. 2003), given that agriculture is a dominant landscape feature (Gabriel et al. 2010), and that many native plants in and near agricultural areas rely on native bees for pollination.

In general, the conversion of complex natural ecosystems to simple managed ecosystems, often in the form of large-scale industrialized agriculture, a phenomenon referred to as agricultural intensification, can change the distribution of resources by altering the natural landscape and native plant communities on which wild bees depend for survival (Tscharntke et al. 2005, Kremen and Chaplin-Kramer 2007). Such intensification often results in decreased pollinator species richness, diversity, abundance, and floral visitation rates (Kremen and Chaplin-Kramer 2007, Holzschuh et al. 2010, Power and Stout 2011, Ferreira et al. 2013, Gonzalez-Varo et al. 2013).

In part, the impacts of agricultural intensification on bee communities result from reductions in overall landscape quality and heterogeneity (Carré et al. 2009, Andersson et al. 2013, Kennedy et al. 2013, Smith et al. 2013). However, a variety of in-field methods used in farming, ranging from weed control practices to pest management, may also impact native bee communities (Table 1). For example, herbicides impact bees by destroying weeds and
Table 1. Farming practices and their effects on bee communities (Mader et al. 2007).

<table>
<thead>
<tr>
<th>WEED CONTROL PRACTICES</th>
<th>Effect on Bees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Tillage¹</td>
<td>Detrimental</td>
</tr>
<tr>
<td>Secondary Tillage²</td>
<td>Neutral</td>
</tr>
<tr>
<td>Flame Weeding</td>
<td>Detrimental</td>
</tr>
<tr>
<td>Hand Weeding</td>
<td>Neutral</td>
</tr>
<tr>
<td>Plastic Mulch</td>
<td>Detrimental</td>
</tr>
<tr>
<td>Straw/Wood Mulch</td>
<td>Neutral</td>
</tr>
<tr>
<td>Chemical Herbicides</td>
<td>Detrimental</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PEST MANAGEMENT</th>
<th>Effect on Bees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fruit Bagging</td>
<td>Neutral</td>
</tr>
<tr>
<td>Chemical Pesticide Application</td>
<td>Detrimental</td>
</tr>
<tr>
<td>Conservation Biological Control³</td>
<td>Beneficial</td>
</tr>
<tr>
<td>Crop Rotation</td>
<td>Neutral</td>
</tr>
<tr>
<td>Crop Diversity</td>
<td>Beneficial</td>
</tr>
<tr>
<td>Resistant Varieties</td>
<td>Neutral</td>
</tr>
<tr>
<td>Sticky Traps⁴</td>
<td>Neutral</td>
</tr>
<tr>
<td>Pheromone Traps⁴</td>
<td>Neutral</td>
</tr>
<tr>
<td>Trap Crops⁵</td>
<td>Neutral</td>
</tr>
</tbody>
</table>

¹ Initial major soil manipulation that loosens soil and helps to anchor or bury plant materials (Soil Science Society of America 2013).
² Any tillage performed after primary tillage (Soil Science Society of America 2013).
³ A safe and effective method of controlling pest species by enhancing natural enemy efficiency through modification of the environment (Jonsson et al. 2008).
⁴ Traps that lure pest insects into the trap by either using shape/color or synthesized scents that mimic pheromones of the target insect (Majumdar 2013).
⁵ Plants that are grown to attract pest insects in order to protect target crops from attack (Shelton and Badenes-Perez 2006).
native plants that provide refuge and food sources for bees when crops are not in bloom (USDA 2007, Gonzalez-Varo et al. 2013), tilling ruins nests and kills the subterranean brood of some wild bees (Shuler et al. 2005).

Furthermore, pesticides can cause harm bees on contact at the time of application or, in the case of systemic pesticides, via pesticide-laden nectar and pollen of crop flowers (Whitehorn et al. 2012). The intensity of these factors can vary with farming methods, such as the use of conventional vs. organic practices. Compared to conventional farms, organic farms generally use less intensive in-field practices (Table 2), perhaps explaining why organic farms sometimes support more diverse native bee communities (Klein et al. 2007, Kremen and Chaplin-Kramer 2007, but see Brittain et al. 2010). Results across a variety of crops have been mixed; with organic farms having positive, negative, and neutral effects on native bee populations (Klein et al. 2007, Kremen and Chaplin-Kramer 2007, Holzschuh et al. 2008, Brittain et al. 2010). These mixed results may be due to varying differences in taxon resource dependency and surrounding land use (Brittain et al. 2010).

**Blueberry pollination and production**

Highbush blueberries (*Vaccinium corymbosum* Linnaeus) are an economically important crop that is planted and grown throughout various parts of the world, with most of the acreage occurring in North America (Free 1970, USDA 2012). The demand for blueberries continues to increase and production has doubled over the last 40 years, and to meet consumer demands (both locally and via exports) highbush blueberry acreage in the United States has increased more than 80% since 1990 (Vicente et al. 2007, USDA 2012). In 2011, the United States produced nearly $860 million worth of blueberries, with Washington
Table 2. Principal differences between organic and conventional crop farming practices (USDA-FDA 2012)

<table>
<thead>
<tr>
<th>Management Goal</th>
<th>Organic</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilization</td>
<td>Application of natural fertilizers, such as compost or manure.</td>
<td>Application of synthetic chemical fertilizers.</td>
</tr>
<tr>
<td>Weed Control</td>
<td>Hand weeding, tillage and application of mulch.</td>
<td>Tillage and application of chemical herbicides.</td>
</tr>
<tr>
<td>Pest Control</td>
<td>Crop rotation, use of beneficial predators and parasites of pests, mating disruption, and physical traps, and natural pesticides.</td>
<td>Synthetic chemical insecticides.</td>
</tr>
</tbody>
</table>
State being the highest contributor. Indeed, the 7,000 acres of blueberries in Washington produced a total blueberry crop worth $122 million (USDA 2012). Skagit County is one of the leading producers in the state, boasting about 18% of the statewide acreage of blueberries (McMoran 2011).

Highbush blueberries vary widely in pollination requirements, with partial to complete self-incompatibility being normal in most cultivars (Ackermann et al. 2009, Chavez and Lyrene 2009). Although successful self-pollination can occur in highbush blueberries, the anatomy of blueberry flowers often makes it difficult for self-pollination to occur without facilitation by insects (Free 1970, McGregor 1976); the bell-shaped flowers have a long, stigma-bearing style that is receptive only at the tip, surrounded by ten very short pollen-producing stamens. These floral characteristics facilitate cross-pollination and contribute to the fact that blueberry flowers typically need pollination services provided by bees (Free 1970, McGregor 1976).

Bumblebees are more effective pollinators than are honeybees in both lowbush and highbush blueberries, most likely due to the poricidal dehiscence of blueberry pollen, coupled with the ability of bumblebees to perform buzz pollination (MacKenzie 1994, Stubbs and Drummond 2001, Ratti et al. 2008, Tuell et al. 2009). Bumblebee abundance is often positively correlated with blueberry mass (Ratti et al. 2008); they visit more flowers per minute and deposit more pollen per flower than honeybees; an *Apis mellifera* worker would need to visit a flower four times to deposit the same amount of pollen as a single visit by *Bombus* spp. (Javorek et al. 2002, Tuell et al. 2009).
Early attempts to self-pollinate highbush blueberries failed to produce mature fruit, and experiments using caged blueberry bushes showed that blueberry fruit only matured in cages that contained bees (Free 1970). When self-pollination does occur, few fruits ripen, and they are often smaller, contain fewer seeds and reach maturation later than fruits that were cross-pollinated (Coville 1921, McGregor 1976, Chavez and Lyrene 2009). Therefore, cross-pollination facilitated by bees is essential for maximum blueberry production, and failure to produce good crops and high crop yield is often the result of inadequate pollination (McGregor 1976). Blueberry yield and fruit set increase with bee abundance (by nearly 500% in some cultivars), bee species richness, and flower visitation frequency (Ackermann et al. 2009, Eaton and Nams 2012, Klein et al. 2012). Despite this importance of pollinator abundance and species richness, growers often blame frost or poor weather conditions for their low yields which are, in reality, most likely due to poor insect pollination (Chandler 1943, McGregor 1976).

**Research objectives**

The impact of organic vs. conventional methods on bee communities and pollination success is unclear for most crops, including blueberries. Despite the obvious potential differences in impact on pollinator communities, there is surprisingly little knowledge about a) the relative impacts of conventional and organic farming practices on wild bee diversity in and near most agroecosystems and b) the importance of wild bee diversity for the production of most fruit crops (Kremen et al. 2002).

To test the hypothesis that the abundance, species richness and diversity of native bee species differ between conventional and organic blueberry farms, I sampled bee communities
in fields of both types in Skagit County, WA. In addition, I combined experimental and comparative approaches to determine the degree to which blueberry production may be influenced by the in-field community of native bees. Overall, I predicted that, compared to organic farms, conventional farms would support a lower diversity and abundance of native bee species, and that berry production would be enhanced by increased native bee diversity and/or abundance. This research not only helps improve our understanding of the factors influencing blueberry yield, but more broadly, provides much-needed data to inform decisions regarding the best practices for maintaining native bee diversity and abundance in agricultural landscapes. As such, this research has important implications for both sustainable farming and the conservation of native plant communities that are also reliant on native pollinators.
METHODS

Study sites

I conducted this research during the spring and summer of 2012 on nine highbush blueberry farms in Burlington and Mt. Vernon, both located in Skagit County, Washington (Figure 1). Skagit County is one of the largest agricultural communities west of the Cascades in Washington, with over 90 different crops grown in the county (WSU 2013). Blueberries are one of the most economically important crops grown, as yields and quality are exceptionally high compared to the Midwestern region of the U.S. (another major blueberry-growing region), partially due to cooler summer temperatures (McMoran 2011). To better isolate the effects of farming practices on bee communities, I chose the farms for this study based on proximity to one another, similarity in practices within each category (conventional or organic), and similarity in size (Appendix B). Five of the farms used conventional farming practices while the remaining four farms used organic farming practices (Appendix C). Three of the organic farms and four of the conventional farms were owned and managed by Sakuma Brothers Farms, and the remaining two were each owned by individual farmers.

Floral characteristics can differ substantially among blueberry cultivars, which can affect visit rates and presence of bees (Ehlenfeldt 2001, Courcelles et al. 2013). To eliminate any varietal effects, all fields had the same blueberry cultivar, Duke, which is relatively early-blooming (early spring), starts forming berries in early summer, and ripens in midsummer. This cultivar (like most of the commonly-grown blueberry cultivars) benefits greatly from cross-pollination; fruit set, weight and seed counts all increase with cross pollination (Ehlenfeldt 2001). In addition, I chose this cultivar because it is one of the more
Figure 1. Locations of the nine farms used for this study in Skagit County, Washington. Organic farm sites are represented by green circles (with the prefix “O” in the site name) and conventional farm sites are represented by blue triangles (with the prefix “C” in the site name).
commonly-used cultivars on both conventional and organic farms in Skagit County, and because there is concern among farmers for pollination of this cultivar (potentially because the early bloom period happens during times of cool weather when honeybee activity may be limited (Jones and Sweeney-Lynch 2011)). Poorer weather conditions often seen during springtime can affect yields in early-blooming crops due to the combined effects of weather on bee activity, flower opening, pollen germination, and fertilization (Tuell and Isaacs 2010).

**Assessing land use surrounding farm sites**

Semi-natural habitats can be associated with increased refuge and nesting sites for bees (Kremen et al. 2002, Carré et al. 2009), and given the fact that bees display a wide array of nesting habits, the amount and quality of land available can influence the composition of bee communities in a given area (Eltz et al. 2002, Kremen and Chaplin-Kramer 2007, Carré et al. 2009, Williams et al. 2010). Therefore it was important to assess surrounding land use for all farm sites in this study.

To estimate land use surrounding each of the farm sites, I obtained Google Earth (©2011) aerial images of each site, determined the center of each site, and used the images to categorize land use within a 1km radius of the site center. I categorized all land as agricultural, open with sparse trees, or forested. Agricultural areas included any type of land used for farming, open areas with sparse trees consisted of uncultivated land with isolated trees that did not form a continuous canopy of at least 800 m², and forested areas were those places in which there was continuous tree canopy exceeding 800 m². After categorizing land use, I used Adobe® Photoshop® CS3 to shade the areas with a different color for each land use category. Subsequently, I analyzed the shaded image in ImageJ (Rasband 2012), in which
I determined the number of pixels corresponding to each land use type. Pixel counts formed the basis for subsequent calculations of % cover for each land use category around each study site (Appendix C).

**Data analyses**

I used Student’s t-tests to compare means between organic and conventional farms, or Welch’s t-tests when variances were heteroscedastic. Welch’s t-test is a parametric test, but it does not assume equal variance (Ruxton 2006). To compare the categorical variable, tillage, between the two farm types, I used Pearson’s Chi-squared test with Yates’ continuity correction, which prevents overestimation of significance in small data sets. Specifically, when a cell in a 2x2 matrix has fewer than 5 observations, this correction is recommended (Yates 1934). I used a p-value of ≤ 0.050 to determine significant differences for all tests.

**Bee community structure**

**Methods/experimental design**

To compare the bee communities in conventional and organic blueberry fields, I collected bees in spring 2012 using pan traps featuring 355 ml (12 ounce) plastic bowls (Staples®, Framingham, MA). Bowls were painted UV blue, UV yellow, or white, because previous research has shown that such a combination is the most effective method for trapping a variety of bees in both agricultural and natural habitats, and that these trap colors are complementary, because bee species differ in their color preferences (Droege 2002, Wilson et al. 2008). As suggested by Droege (2010), I used fluorescent paint (Guerra Paint and Pigment, New York, NY) to coat the entire top surface of each bowl.
Each trap consisted of three bowls (one per color) secured on top of a wooden board, held fast to a wooden stake at a level corresponding to the top of the blueberry bushes when they were flowering (about 1.2 meters high) (Figure 2). Each trap was filled with about 300 mL of water and a few drops of blue Dawn Ultra dishwashing liquid (Procter & Gamble, Kansas City, KS). The coloration of the traps apparently resembles that of flowers, luring bees to alight on the soapy water, where they sink (because the soap acts as a surfactant) and drown (Droege 2010).

I continuously trapped bees for the majority of the blueberry flowering period in 2012, to obtain a representative sample of the season-wide bee community at each farm. I first deployed traps in early May when the flowers were starting to bloom, and did the final collection in mid-June, when about 90% of berries were forming and fewer than 10% of flowers remained open. Over this period, I collected all bee specimens from the traps on each of five dates (Appendix D); immediately refilling the bowls with fresh soapy water after each collection. The duration of trapping varied among sampling periods, but because I pooled all bee samples for a given trap into a single season-long sample, this variation was unimportant for subsequent analyses.

To characterize the bee communities at each farm, I deployed a cluster of three pan traps (one of each color) at each of eight random locations at each farm site. I randomized trap locations by estimating the combined length of blueberry rows at each site (using Google Earth ©2011 aerial images) and using a random number generator to select the eight locations at which the traps would be placed (Figure 3). Following established sampling recommendations (FAO 2009, Droege 2010), I replaced sample locations if they were within
Figure 2. Pan traps used to collect bees in this study. Stakes held each trap at approximately the height achieved by the blueberry bushes during peak flowering (left). Three differently-colored bowls were put in place (top right) and filled with a water/detergent mixture at the start of the flowering period. At the end of each sampling period, all specimens caught in traps (bottom right) were collected and stored for further processing.
Figure 3. Image of one of the nine farm sites (Organic site O3) used in this study. The locations of the randomly-selected pan trap sampling locations are represented with star symbols. See text for randomization procedure. Image © Google Earth 2012.
5 m of another sampling location to minimize the likelihood that traps would ‘compete’ with each other. All trap stakes were in place by the end of March 2012, to ensure that I could begin trapping as soon as the blueberries began flowering.

I combined pan trapping and capture with nets to sample bee communities, because the two methods often complement each other, resulting in a more representative sample of the resident bee community (Cane et al. 2000, Westphal et al. 2008, Wilson et al. 2008, FAO 2009, Morandin and Kremen 2013). To hand-collect bees, I used aerial nets at each site during conditions when the majority of bees would be out foraging (between 10:00 and 18:00 PDT on clear days, with temperatures above 15.5°C). I hand collected at each site on three occasions (May 19th, May 26th, and June 11th, 2012), with an average of six collectors per session. Collectors haphazardly distributed themselves throughout the study site, and collected all bees seen on blueberry flowers during a 20 minute period at each location. They quickly tallied and release and captured honeybees, to minimize time spent handling these common and easily-identified bees, but all native bees were collected, stored in vials, and transported to a freezer for storage prior to processing and identification. To reduce among-field bias resulting from the impact of temperature and/or time of day on pollinator activity, netting and pan trap collections were sampled in a different order for each collection day.

**Specimen processing and identification**

Prior to processing, I stored all trap-caught specimens at room temperature in 70% ethanol in 50 mL Falcon tubes, but froze hand-collected specimens in dry 50 mL Falcon tubes in a -20°C freezer. Bees caught in traps are often greasy, making them difficult to identify, so prior to identification, I washed and dried the specimens following established
protocols (Droege 2010). First, I placed the specimens from a trap sample or hand collected sample into a glass with warm water, a few drops of blue Dawn Ultra dishwashing liquid (Procter & Gamble, Kansas City, KS), and a magnetic stir bar, and stirred the contents of the glass for approximately 5 minutes. After stirring, I rinsed all of the specimens thoroughly with cold water, and then dried them for approximately 15 minutes in an automatic bee dryer (Appendix E and F) to fluff their body hairs. After drying, I pinned and labeled the bees, sorted them by morphology, and identified them to species using published taxonomic keys (Sandhouse 1941, LaBerge 1964, 1967, 1973, Roberts 1973, Bouseman and LaBerge 1978, LaBerge 1985, McGinley 1986, Gibbs 2010, Koch et al. 2012). At least one voucher specimen of each species is deposited in the Western Washington University Insect Collection, housed in the Biology Department at Western Washington University.

**Data analyses: bee diversity and abundance**

**Univariate analyses.** To compare community composition between organic sites (N = 4) and conventional sites (N = 5), I determined several community metrics for each site. The first index I used was total native bee abundance, as this index provides an estimate of the potential for native bees to contribute to field-wide pollination services. In addition, I chose a suite of indices commonly used in community ecology to examine the richness, diversity, and evenness of the native bee community. My rationale for choosing these indices is that they are commonly used in studies of bee communities (Krebs 1989, MacKenzie and Eickwort 1996, Magurran 2004, Holzschuh et al. 2007, Karunaratne and Edirisinghe 2008, Bates et al. 2011). Thus, these community metrics allow the results of this study to be compared with the results of similar studies. Specifically, in addition to the standard measure of species richness (S, the number of species sampled), I also employed Margalef species
richness \((d)\), which is corrected for sample size (Magurran 2004). I used this measure because some of my bee community samples were rather small, making small sample size effects a concern. The two standard diversity indices I used were 1) the Shannon diversity index \((H')\), which captures both the richness and evenness characteristics of a community; as \(H'\) increases, the diversity also increases (Shannon and Weaver 1949, Krebs 1989, Magurran 2004), and 2) the Simpson diversity index \((D)\), which gives the most abundant species greater weight, while being less sensitive to species richness; as \(D\) increases the diversity decreases (Simpson 1949, Krebs 1989, Magurran 2004). Finally, I used a standard index of evenness, the Pielou evenness index \((J')\), which aims not only to quantify similarities in the relative abundance of species in a community, but also to assess the departure of the observed pattern from the expected pattern in a hypothetical community with maximal evenness (Magurran 2004).

With the exception of total native bee abundance, I calculated all indices using the DIVERSITY function in the statistical program PRIMER V6 (Clarke and Gorley 2006). I used Student’s t-tests to compare mean index values between organic and conventional farms. I used the Welch’s t-test to compare species richness values between the two farm types, because data were non-normal and variances were heteroscedastic. For all tests, used the statistical program R (R Development Core team 2008), with a \(p\) value of \(\leq 0.050\) as the basis for determining significant differences.

**Multivariate analyses.** Although univariate analyses of community indices can provide insight into the structure of communities, community data often have large numbers of species which are each subject to statistical noise and must be analyzed using multivariate
techniques if we are to examine the relationship between communities and environmental variables (Clarke and Warwick 2001). Non-metric multidimensional scaling, also referred to as NMDS (Kruskal and Wish 1978), is a frequently used multivariate method that uses limited assumptions and handles large community data sets (Clarke and Warwick 2001). Rather than analyzing community data directly, this method constructs a similarity matrix based on a chosen distance measure. This method represents measurements of both similarity and dissimilarity among datasets as distances between points in multidimensional space that can be represented in the forms of ordination plots and dendrograms (Clarke and Warwick 2001, Borg and Groenen 2005). Ordination plots of communities can be interpreted by observing the distances between points; the closer two points are to one another, the more similar the two communities are. These similarities are also commonly depicted as dendrograms, generated by first grouping samples with the highest mutual similarities, then gradually lowering the similarity level until the dendrogram includes all of the samples (Clarke and Warwick 2001).

I conducted all NMDS analyses for this study using the statistical program PRIMER V6 (Clarke and Gorley 2006), generating similarity matrices for bee abundance from raw counts of native bee species at each site. Using these matrices, I then generated an ordination plot and dendrogram using the Bray-Curtis similarity distance. I chose the Bray-Curtis similarity distance for all NMDS analyses because it delivers robust and reliable results, and is commonly used to examine relationships in ecological data, more specifically, when examining species counts and communities (Bray and Curtis 1957, Clarke and Warwick 2001). Subsequently, I used the SIMPER feature within PRIMER V6 (Clarke and Gorley
(organic and conventional) and to the dissimilarity between groups.

**Land use and native bee community integrity.** I created simple scatterplots to visually assess possible relationships between bee community measures (native bee abundance, honeybee abundance, diversity ($H'$), diversity ($D$), Margalef native bee richness ($d$), standard native bee species richness ($S$), and evenness ($J'$)) and the percentage of surrounding forested areas within a 1 km radius of each farm, tillage, and farm size. I chose to visually assess these relationships because the sample size (number of farm sites) used for this study was too small to enable me to analyze these relationships using generalized linear mixed models (Bolker 2008).

In addition, I used a scatterplot-based approach to investigate the integrity of the native bee communities in Skagit County blueberry farms, compared to previously-published surveys of native bee communities found in other habitats in the region (Appendix G). Specifically, I used this approach to compare the bee communities I sampled with those sampled in other agricultural landscapes, natural landscapes, and urban landscapes in the Pacific Northwest and western Canada to determine the relative diversity and abundance of native bees at my sites were. Because the degree of bee sampling varies across studies, and sampling effort impacts estimates of diversity and abundance, I created scatterplots depicting the relationship between native bee abundance, native bee species richness, and either total trap hours, or total person hours of netting for eight studies, including this study. The number of bee community surveys in this region is rather modest, so I used these plots for visual
comparisons, and did not statistically analyze the data to tease apart the effects of habitat category and sampling effort on bee community metrics.

Impacts on blueberry yield

Manipulative experiment analyses: pollination services and blueberry production

To determine if blueberry production is pollen limited and if pollinator exclusion influences the mass/seed number of blueberries, I manipulated access to pollination for individual flowers, and studied the impacts on berry production. Due to time constraints, I performed this experiment in only one of the nine fields in which I had also sampled the bee community. I performed this experiment at site O1 because I expected that this site would have high pollinator diversity, given that it is an organic farm with some forested areas nearby, thus maximizing the likelihood of seeing an impact of pollinator removal on berry production.

At the experimental site, I randomly selected individual blueberry bushes for inclusion in the experiment, and for those bushes, randomly determined if the experimental flowers would be from an upper or lateral branch of the bush. I randomly assigned experimental flowers (one per bush) to one of three treatments (N=40/treatment): 1) negative control flowers, which remained bagged together with the other flowers in its cluster (comprised of 10-12 flowers) in green mesh bags for the entire experiment, to provide an estimate of berry production in the absence of pollinators (i.e., self-pollination), 2) positive control flowers, which remained freely available to pollinators throughout the study, and 3) hand-pollinated flowers, which were bagged continuously, except when they were being
hand pollinated. I placed bags over the appropriate flower clusters in March, prior to the onset of blooming, to ensure that no pollinators had access to the bagged flowers (Figure 4). When the flowers were in bloom, I returned to perform hand pollination. For the hand-pollinated flowers, I collected pollen in a small bowl by placing an electric toothbrush above blueberry flowers on at least 50 different plants to shake free the pollen and generate sufficiently diverse pollen pool to ensure cross-pollination. Subsequently, I used a small paintbrush to thoroughly coat the stigmas of the hand-pollinated flowers with this pollen mixture, marked the treated flower by loosely tying a red thread to its pedicel, and replaced the mesh bag. All hand-pollinated flowers remained bagged until blueberries were ripe. Flower clusters that were always available to pollinators were bagged after they had finished flowering, to prevent berry loss.

On July 23, 2012 (when berries were at peak ripening, and two days prior to picking by farm workers), I collected bagged blueberries from all of the experimental flowers at the study site by removing bags from each cluster, picking and counting all ripe berries were, and counting the aborted flowers in each cluster. For the hand-pollinated treatments, I collected only the marked berry that I had previously hand pollinated (or it was noted that the flower aborted, as appropriate). I refrigerated all collected berries overnight in 50 mL Falcon tubes prior to processing. For the positive and negative controls, I randomly selected one berry to analyze from those that I had collected from each experimental cluster. This subsampling was done to have sample sizes consistent across treatments, since in the hand-pollination treatment, I had only hand pollinated one flower per cluster. The day after collection, I determined the wet mass of each selected berry with an analytical balance, and measured its diameter with digital
Figure 4. Bagged cluster of budding flowers prior to bloom (top panel). Bagged cluster of blueberries near peak ripening, negative control (bottom panel).
calipers. Subsequent to these initial measures, I individually froze the selected berries at -20 ºC in Falcon tubes until later seed counts.

To count the seeds in each berry, I thawed the 50 mL Falcon tubes in warm water, shook the tubes vigorously for approximately 30 seconds to separate the pulp and skin from the seeds, and poured the contents of the tube into a small white bowl for viewing under a dissecting microscope. Under magnification, I separated the seeds from the pulp and obtained separate counts of both large, well-developed viable seeds, and small, poorly-developed unviable seeds (Ehlenfeldt and Martin 2010).

**Comparative analysis of field-wide blueberry production**

To determine the average blueberry mass, seed count and abortion rate for each farm, I harvested berries from all nine study sites on July 24, 2012. At each site, I collected berries from clusters (one cluster per bush) on the upper branches of each of eight randomly-selected bushes per site (sampled bushes were directly across from each randomized pan trap location, in the adjacent row of bushes). In addition to collecting and counting the berries, I also counted the aborted flowers in each sampled cluster. I used the same berry analysis methods for this experiment as I did for the manipulative experiment, with the exception that I measured and counted seeds of all berries collected from clusters (rather than randomly selecting one berry per cluster).

**Data analyses: blueberry yield**

To compare the average mass and diameter of berries between the three experimental treatments (positive control, negative control, and hand-pollinated), I performed Student’s t-
tests. However, I used Welch’s t-tests to compare seed counts and berry abortion rates, because data were non-normal and variances were heteroscedastic. For this reason I also used Welch’s t-tests to compare the average mass, diameter, seed counts, and berry abortion rates among organic and conventional farms. To determine if there were any relationships between berry yield (berry mass, diameter, seed counts and abortion rates) and bee community structure (diversity, richness, evenness, native bee abundance, and honeybee abundance), I performed Pearson’s product-moment correlations. For this latter analysis, I pooled data for both farm types into a single analysis to determine overall effect of community measures on berry yield. I used a p value of ≤ 0.050 to determine significant differences for all tests, and performed all data analyses using the statistical program R (R Development Core Team 2008).
RESULTS

Study sites

The average size and elevation of the farm sites used in this study did not significantly differ between organic and conventional farms (Appendix B). Similarly, tillage, the distance to the nearest woodlot, percentage of sparsely-treed open areas, and the amount of forested and cultivated land, did not differ between the two farm types (Appendix C).

Bee sampling

Collectively, pan-trapping and netting at the nine sites yielded a total of 6,565 specimens (6,227 via trapping and 338 via netting). Non-native honeybees (*Apis mellifera*) accounted for 6,132 of these individuals (3,721 at conventional sites, and 2,411 at organic sites), while the remaining 433 individuals (359 collected at organic farm sites, and 74 collected at conventional farm sites) were from native species. I identified all but five individuals to species; identifying the remaining individuals to subgenus (*Lasioglossum* (Dialictus) spp. (two morphospecies), *Lasioglossum* (Evylaeus) sp., and *Andrena* (Trachandrena) sp.). Including these three subgeneric categories; I collected a total of 19 species (Appendix H), representing four families (Apidae, Halictidae, Megachilidae, and Andrenidae; Appendix I). Approximately 89% of all native bee species collected in this study were bumblebees (*Bombus* spp.), in the family Apidae (Appendix J). Bees in the Halictidae and Andrenidae made up approximately 6% and 5% of the total respectively, while I collected only a single specimen from the Megachilidae (*Osmia lignaria*) (<1%).
Bumblebees made up approximately 90% of the native bees collected at organic farm sites, and 84% of native bees collected at conventional farm sites.

**Bee abundance and diversity**

Overall, there was a higher abundance of native bees on organic farms compared to conventional farms, while honeybee abundance did not differ between the two farm types (Figure 5). These patterns were mirrored by results of capture rates (Appendix K). Organic site O1 had the highest abundance and capture rate of native bees, while conventional site C2 had the lowest (Appendix L). Native bee diversity (both Shannon and Simpson indices) did not differ between organic and conventional farms (Figure 6). Conventional site C2 had the lowest diversity, while organic site O3 had the highest.

There was a nonsignificant trend for greater native bee species richness at organic farm sites than at conventional farm sites (Figure 6). Organic farm site O3 had the highest species richness, while conventional farm site C2 had the lowest. However, this trend was not apparent in the Margalef richness index, which corrects for different sample sizes (Figure 6). I also found that conventional farms had a higher evenness of native bee species than organic farms (Figure 6), with conventional farm site C2 having the highest evenness, and organic farm site O1 having the lowest.

**Community composition**

NMDS analyses revealed two very distinct groups of bee communities based on species-specific native bee abundances (Figures 7 and 8). One cluster contained four of the
Figure 5. Native bee and honeybee abundance for both conventional and organic farm sites. Error bars represent standard error. The abundance of native bees differed between the two farm types ($t = -3.78$, $df = 7$, $p = 0.007$), while that of honeybees did not ($t = 0.90$, $df = 7$, $p = 0.40$). Stars indicate significance.
Figure 6. Average native bee community measures for both conventional and organic farm sites; a) Shannon diversity ($H'$) ($t = -0.17$, df = 7, $p = 0.87$) b) Simpson diversity ($D$) ($t = 0.30$, df = 7, $p = 0.77$) c) Margalef richness ($d$) ($t = -0.81$, df = 7, $p = 0.45$) d) species richness ($S$) ($t = -2.31$, df = 7, $p = 0.05$) and e) Pielou’s species evenness ($J'$) ($t = 4.71$, df = 7, $p = 0.002$). Error bars represent standard error. Stars indicate significance.
Figure 7. Bray-Curtis similarity NMDS plot displaying the ordination of farm sites based on similarity in native bee community composition. Analysis displays 30, and 60 percent similarity contours (displayed in blue, and pink respectively). The stress value for this analysis was 0.01, indicating that this is an excellent representation of the similarities among farm sites.
Figure 8. Hierarchical cluster analysis displaying similarities between farm sites based on native bee community composition. Scale bar is a percentage of similarity based on the Bray-Curtis similarity distance.
five conventional sites, while the other cluster contained all four organic sites and one conventional site. Three of the four organic sites clustered very closely together. The fact that organic site O4 clustered with these sites despite having large geographical separation (see Figure 1) indicates that the clustering was not solely due to geographic proximity.

Three species (*Bombus flavifrons* Cresson, *Bombus melanopygus* Nylander, and *Bombus mixtus* Cresson) contributed most to the average similarity in community composition within each farm type (Table 3). Six species (*Andrena hemileuca* Viereck, *Bombus flavifrons*, *Bombus melanopygus*, *Bombus mixtus*, *Bombus vosnesenskii* Radoszkowski, and *Lasioglossum laevissimum* Smith) contributed most to the average dissimilarity in community composition between farm types (Table 4).

**Land use and native bee community integrity**

Visual comparisons of scatterplots suggest that the percentage of surrounding forested areas within a 1 km radius of each farm site was generally low for the conventional farms in this study, and variable for the organic farms. However, across the entire range of surrounding forest cover, there was no strong pattern of increasing native bee richness, diversity, or evenness with increasing surrounding forest (Figure 9). Farm size did not appear to have a strong influence on bee community metrics, and spanned a similar spectrum for both organic and conventional farms. However, for a given farm size, organic farms generally had greater native bee abundance and lower native bee evenness, compared to conventional farms, but there were no consistent differences for richness or diversity between farm types (Figure 10). There were no obvious differences in bee community structure
Table 3. The three species that contributed most to the average similarity in native bee community composition within each farm type (conventional farm sites and organic farm sites; 41.8% and 52% respectively). Average abundance represents the number of bee specimens caught per site. Contribution percent refers to the percent that each listed species contributed to the average similarity in native bee community composition among conventional and organic sites. Cumulative percent refers to the combined percentage that all species together contributed to the average similarity in native bee community composition among conventional and organic sites.

<table>
<thead>
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<th>Species</th>
<th>Average Abundance</th>
<th>Contribution %</th>
<th>Cumulative %</th>
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Table 4. The six species that contributed most to the average dissimilarity (76.5%) in native bee community composition between farm types (conventional farm sites and organic farm sites). Average abundance represents the number of bee specimens caught per site. Contribution percent refers to the percent that each listed species contributed to the average dissimilarity in native bee community composition between farm types. Cumulative percent refers to the combined percentage that all species together contributed to the average dissimilarity in native bee community composition between farm types.

<table>
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<th>Average Abundance in Organic</th>
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Figure 9. Relationship between the percentage of surrounding forested area within a 1 km radius of each farm site and a) native bee abundance b) honeybee abundance, and several metrics of native bee community structure including c) Shannon diversity ($H'$) d) Simpson diversity ($D$) e) Margalef richness ($d$) f) species richness ($S$) and g) Pielou evenness ($J'$) for both conventional and organic farms.
Figure 10. Relationship between farm size (ha) and a) native bee abundance b) honeybee abundance, and several metrics of native bee community structure including c) Shannon diversity ($H'$) d) Simpson diversity ($D$) e) Margalef richness ($d$) f) species richness ($S$) and g) Pielou evenness ($J'$) for both conventional and organic farms.
between tilled and untilled conventional farms. However, organic farms (all of which were not tilled) apparently had higher native bee abundance and species richness, but lower evenness compared to untilled conventional farms (Figure 11).

Several trends emerged when comparing native bee abundance and richness from this study to those from other surveys of bee communities in the region. In general, surveys in natural and urban landscapes yielded relatively high native bee abundance and richness compared to this study and other studies in agricultural landscapes (Figure 12). Furthermore, after correcting for the number of native bees in a sample, it appears that bee communities in agricultural settings in this region have low species richness compared to the communities in natural habitats. By comparing the results of hand-collection based surveys, these apparent impacts of land use are evidently not an artifact of consistently different sampling effort (person hours of netting) across habitat types (Figure 13). This study had substantially more trapping effort than other bee surveys in natural and managed habitats in the region, but yielded lower native bee abundance and richness than those surveys found (Figure 14).

**Blueberry yield**

**Manipulative experiment**

Many of the berries in the hand-pollination treatment did not form, indicating that the hand pollination did not yield maximal berry production. Thus, I am unable to reach conclusions regarding pollen limitation by comparing the results of this treatment with the positive control treatment. However, comparisons of the positive and negative controls are useful for assessing the degree to which blueberries benefit from outcrossing at the study
Figure 11. Relationship between tillage (yes or no) and a) native bee abundance b) honeybee abundance, and several metrics of native bee community structure including c) Shannon diversity ($H'$) d) Simpson diversity ($D$) e) Margalef richness ($d$) f) species richness ($S$) and g) Pielou evenness ($J'$) for both conventional and organic farms.
**Figure 12.** Relationship between native bee abundance and native bee species richness ($S$) for eight studies (some studies span over two years and different landscape types and are represented by multiple data points) investigating bee communities in Washington, Oregon, and Western Canada (Appendix G). Urban landscapes are represented by an X, natural landscapes are represented by open circles, cultivated landscapes are represented by black closed circles, and the plus symbol represents this study.
Figure 13. Relationship between native bee species richness ($S$) (top), native bee abundance (bottom), and person hours of netting for four studies (some studies span over two years and different landscape types and are represented by multiple data points) investigating bee communities in Washington, and Western Canada (Appendix G). Urban landscapes are represented by an X, natural landscapes are represented by open circles, cultivated landscapes are represented by black closed circles, and the plus symbol represents this study.
Figure 14. Relationship between native bee species richness ($S$) (top), native bee abundance (bottom), and total trap days (calculated as number of traps x number of sites x number of days) for four studies (some studies span over two years and different landscape types and are represented by multiple data points) investigating bee communities in Washington, and Oregon (studies listed in Appendix G). Natural landscapes are represented by open circles, cultivated landscapes are represented by black closed circles, and the plus symbol represents this study.
sites. Open pollinated berries were 34% larger in mass, 29% larger in diameter, and had 12% more seeds compared to berries that excluded pollinators (Figure 15). Furthermore, flowers that did not have access to pollinators were approximately 9 times more likely to abort compared to flowers that were open to pollinators (Figure 15).

**Field-wide blueberry yields**

Conventional and organic farms did not differ in the mass or diameter of berries (Figure 16). However berries from conventional farms had significantly more seeds than berries from organic farms (Figure 16). Blueberry abortion rates did not differ between the two farm types (Figure 16). Berry mass increased with berry diameter, but berry mass was not correlated with any measure of bee diversity, richness, or evenness, or with the abundance of either native bees or honeybees (Figure 17). Similarly, neither berry diameter (Figure 18) nor seed count per berry (Figure 19) were correlated with bee community metrics or measures of bee abundance.
Figure 15. Average a) berry mass (g) ($t = -3.32$, df = 7, $p = 0.013$) b) seed count ($t = -3.68$, df = 7, $p = 0.0079$) c) berry diameter (mm) ($t = -3.51$, df = 7, $p = 0.0099$) and d) percent of aborted berries ($t = 4.43$, df = 7, $p = 0.0030$) for ‘Duke’ variety blueberries for the two experimental treatments used in this study. Excluded Pollinators treatment represents berries that were bagged and never open to pollinators (n=27) and the Open Pollinated treatment represents berries that were never bagged (n=37). This experiment took place in a single organic farm, site O1. Error bars represent standard error. Stars indicate significance.
Figure 16. Average a) berry mass (g) \((t = 0.74, df = 7, p = 0.48)\) b) seed count \((t = 2.58, df = 7, p = 0.036)\) c) berry diameter (mm) \((t = 0.82, df = 7, p = 0.44)\) and d) percent of aborted berries \((t = -0.30, df = 7, p = 0.77)\) for ‘Duke’ variety blueberries for both conventional \((n = 5,\) average number of berries sampled per site = 45.8) and organic farm sites \((n = 4,\) average number of berries sampled per site = 46.2). Error bars represent standard error. Stars indicate significance.
Figure 17. Pearson product-moment correlations between pooled average berry mass (g) and 
a) berry diameter (mm) \( (r = 0.95, n = 9, p < 0.001) \) b) seed count \( (r = 0.19, n = 9, p = 0.63) \) c) native bee Simpson’s diversity \( (D) \) \( (r = 0.06, n = 9, p = 0.88) \) d) native bee Shannon diversity \( (H') \) \( (r = -0.19, n = 9, p = 0.63) \) e) native bee species richness \( (S) \) \( (r = -0.17, n = 9, p = 0.67) \) f) native bee Margalef richness \( (d) \) \( (r = -0.41, n = 9, p = 0.27) \) (d) g) native bee Pielou’s evenness \( (J') \) \( (r = -0.11, n = p p = 0.77) \) h) honeybee abundance \( (r = -0.22, n = 9 p = 0.56) \) and i) native bee abundance \( (r = 0.04, n = 9, p = 0.92) \).
Figure 18. Pearson product-moment correlations between pooled average berry diameter (mm) and a) seed count ($r = 0.29, n = 9, p = 0.46$) b) native bee Simpson’s diversity ($r = 0.12, n = 9, p = 0.76$) (D) c) native bee Shannon diversity ($H'$) ($r = -0.26, n = 9, df = 7, p = 0.49$) d) native bee species richness ($S$) ($r = -0.35, n = 9, p = 0.35$) e) native bee Margalef richness (d) ($r = -0.44, n = 9, p = 0.24$) f) native bee Pielou’s evenness ($J'$) ($r = 0.08, n = 9, p = 0.85$) g) honeybee abundance ($r = -0.12, n = 9, p = 0.75$) and h) native bee abundance ($r = -0.11, n = 9, p = 0.77$).
Figure 19. Pearson product-moment correlations between pooled average seed counts and a) native bee Simpson’s diversity ($D$) ($r = -0.002$, $n = 9$, $p = 0.99$) b) native bee Shannon diversity ($H'$) ($r = 0.03$, $n = 9$, $p = 0.93$) c) native bee species richness ($S$) ($r = -0.34$, $n = 9$, $p = 0.37$) d) native bee Margalef richness ($d$) ($r = 0.21$, $n = 9$, $p = 0.59$) e) native bee Pielou’s evenness ($J'$) ($r = -0.08$, $n = 9$, $p = 0.83$) f) honeybee abundance ($r = 0.43$, $n = 9$, $p = 0.25$) and g) native bee abundance ($r = 0.02$, $n = 9$, $p = 0.96$).
DISCUSSION

Overview

The results of this study reveal farming methods influence the community of native bees in blueberry fields. In particular, this study documented substantially greater native bee abundance in organic blueberry fields compared to conventional blueberry fields. Moreover, although diversity measures generally did not differ between farm types, native bee community composition varied with farming methods, with those differences most strongly driven by greater bumblebee abundance in organic fields. However, comparing the results of this study to those of other bee surveys in natural and managed habitats, the abundance and species richness of bees in lowland Skagit County blueberry fields was rather low, regardless of farming methods. A manipulative pollination experiment confirmed previous results (Free 1970, McGregor 1976, Ackermann et al. 2009, Chavez and Lyrene 2009) showing that blueberry production is highly dependent on access to pollinators. Despite this reliance on pollinators, there was no evidence that average blueberry mass was related to the diversity and/or abundance of native bees. Taken together, the results of this study have important implications for both agriculture and conservation.

Effects of farming practices on native bee communities

Organic farms may provide more suitable habitats for bees and have higher bee diversity because these farms use less intensive methods compared to conventional farms (Bengtsson et al. 2005). These consequences are expected in part because chemical herbicides reduce the availability of floral resources (Krauss et al. 2011, Edesi et al. 2012, Batary et al. 2013, Ferreira et al. 2013). In addition, pesticides used in conventional farms
directly harm pollinators (Gonzalez-Varo et al. 2013). However, although many different pollinators do indeed benefit from organic farming practices compared to conventional practices, this is not always the case, and the consequences of farming methods may be taxon dependent (Brittain et al. 2010). Nonetheless, several large literature reviews of organic and conventional farm comparisons have revealed one common trend: organic farm management generally enhances native bee abundance and/or richness (Bengtsson et al. 2005, Hole et al. 2005, Kennedy et al. 2013). Organic farming practices increase pollinator abundance and richness in a wide variety of crops including canola, strawberry, triticale, and mango (Morandin and Winston 2005, De Siqueira et al. 2008, Krauss et al. 2011, Andersson et al. 2012). In the extreme, native bee visits to flowers may be reduced in conventional farms to less than 50% of the visits in organic farms, due to the spraying of pesticides during flowering in the conventional farms (De Siqueira et al. 2008). The effects of organic practices can reach beyond the farm; fallow strips adjacent to organic wheat fields had greater species richness and abundance of bees than those adjacent to conventional wheat fields (Holzschuh et al. 2008).

In the present study, nearly five times more native bees were collected on organic farm sites compared to conventional farm sites, but the two farm types did not differ significantly in honeybee abundance, or in native bee diversity and richness. Nonetheless, the results from the NMDS cluster analysis indicated two distinct clusters; one cluster containing all but one of the conventional sites, and the other cluster containing the remaining conventional site and all four organic sites. This clustering suggests that bee community composition is influenced by farm type. Geographic proximity could drive some of these similarities, but the available evidence suggests otherwise. For example, organic site O4 did
not cluster with conventional site C5. These two farms were only 25m apart, separated by a road, and were consequently very similar in the percentage of surrounding forested area (0.02% and 0.10% respectively). However, the two farms ordinated in different clusters, suggesting that farm management is likely the main driver of the differences in bee abundances observed. For all comparisons, similar patterns emerged when the analyses included only the seven farm sites managed by Sakuma Brothers Farms, though in some cases, statistically significant differences were reduced to nonsignificant trends in the reduced dataset. Thus, the effects of farming methods on bee communities are not likely due to farming method being confounded by the host of other potential differences associated with individual farmers.

The differences in native bee community structure in organic vs. conventional blueberry fields was primarily driven by a suite of bumblebee (Bombus) species that were substantially more abundant in organic fields than in conventional fields. This result is troubling, particularly given that, due to their buzz pollination, bumblebees are much more effective than honeybees at pollinating blueberries (MacKenzie 1994, Stubbs and Drummond 2001, Ratti et al. 2008, Tuell et al. 2009)). The relatively high impact of conventional blueberry farming on bumblebees shown here may be due to a dearth of resources in conventional fields outside of the period of blueberry blooming, due to applications of herbicides. Bumblebees store only a few days’ worth of resources, meaning they require a continuous supply of nectar and pollen during times when the colony is active, a period often extending well before and after the bloom period of the crop (Kells et al. 2001). In addition, applications of pesticides in early spring may jeopardize bumblebee queens (Thompson and Hunt 1999, Rao 2011). Bumblebee queens actively search for nest sites and forage well
before peak blueberry bloom, so they are at an increased risk of exposure to pesticides, since
the fields are actively sprayed early in spring before expensive honeybee hives are placed on
the farms.

**Landscape effects on native bee communities**

Some research has suggested that the impact of the surrounding landscape is much
stronger than that of in-field management practices (Brittain et al. 2010). Both the quality and
quantity of available habitat in agroecosystems can influence native pollinator communities
Ferreira et al. 2013). Wild bee visitation increases with an increasing proportion of semi-
natural habitat surrounding farms, and in some cases, wild bee species only visit flowers in
orchards with adjacent semi-natural habitat (Klein et al. 2012, Smith et al. 2013). The
response of pollinators to the availability of semi-natural habitats surrounding farms is taxon-
specific (Ekroos et al. 2008, Gabriel et al. 2010, Holzschuh et al. 2010), but overall it is clear
that distance from semi-natural habitats can play a key role in pollinator visitation to crop
plants.

The design of this study precluded formally examining the effects of surrounding land
use on native bee diversity and abundance. However, surrounding land use likely does not
explain the differences observed between bee communities in organic vs. conventional fields.
In particular, there were no consistent differences in surrounding land use, in terms of the
amount of forested area, between the two categories of farms. In addition, none of the
measures of bee community structure varied consistently with the amount of forested area
near the study sites.
Native bee community integrity

Taken together with the results from other pollinator surveys in the Pacific Northwest, native bee communities on farms are depauperate, compared to communities in natural or urban habitats. In particular, both the abundance and species richness of native bees is generally lower on agricultural lands. Furthermore, richness estimates in this study were low for agricultural samples, even after correcting for sample size. This pattern is consistent with the low numbers of native bees and low bee species richness found in this study. Indeed, despite a much more intensive trapping effort than was used in other pollinator sampling studies on farms in the region, I found relatively few total native bees and low species richness.

A variety of reasons may underlie the generally depauperate nature of bee communities on farms. The application of pesticides and herbicides may reduce bee numbers, as can tilling (Shuler et al. 2005, Carré et al. 2009, Gonzalez-Varo et al. 2013). In addition, agricultural landscapes often support very little semi-natural habitat, and have reduced habitat heterogeneity (Kremen et al. 2002). Because the nesting requirements of bees vary markedly among species, having a variety of potential nesting habitats is important for supporting high bee species richness (Eltz et al. 2002, Kremen and Chaplin-Kramer 2007, Carré et al. 2009, Williams et al. 2010).
Effects of farming practices on pollination services

For many crops (even those capable of self-pollination), yields increase with insect pollination (Klein et al. 2007, Courcelles et al. 2013). The results of this study support previous findings (Coville 1921, Ehlenfeldt 2001, Chavez and Lyrene 2009, Ehlenfeldt and Martin 2010), that blueberries rely heavily on pollination services for proper berry formation. Despite this reliance on pollinators, I found no relationship between native bee abundance/diversity and blueberry yield. This lack of correlation has been observed in previous blueberry studies (Ackermann et al. 2009). I also found that there was no difference between organic and conventional farms in average berry mass, diameter, and abortion rates, despite the fact that organic farm sites had a significantly higher abundance of native bees than conventional farm sites. Similar results have been seen in almonds, where organic farming increased the frequencies of wild bee and hoverfly visits but did not increase fruit set (Klein et al. 2012).

The lack of concordance between native bee abundance and blueberry yield could arise for several reasons. First, other aspects of organic vs. conventional farming may have overridden any effects of pollinators. For example, the use of pesticides and herbicides may improve growing conditions for berries on conventional farms, while similarly high yields on organic farms may be due to higher native bee abundances. Another possible explanation is that honeybees saturated each of the farm sites in my study. I did not find a significant difference in the abundance of honeybees on the two farm types, and all nine of the farms used in this study rented managed honeybees for pollination services. Therefore, it could be that there were more than enough honeybees available to adequately pollinate these crops,
masking any potential differences that would have resulted if the only pollinators had been native bees. A third possible explanation for the lack of relationship between native bee abundance and pollination services may be that there were too few native bees on any farm type to have a meaningful impact on pollination and berry yield. The native bee community in these fields may have been so depauperate that even in the fields with the most vigorous native bee communities, those bees did not contribute much to pollination. Even though bumblebees and other native bees are known to be more efficient, if too few of them are present, the higher abundances and visitation rates by honeybees may drive fruit set (Courcelles et al. 2013). These three explanations are not mutually exclusive, and all three may explain the apparent disconnect between native bee communities and pollination services in lowland NW Washington blueberries.

**Future studies**

To ensure sustainable blueberry production in the event that honeybees are in short supply, several key questions require attention. How diverse and abundant must native bee communities be to supply adequate pollination in the absence of honeybees? Why does organic farming have less of an impact on native bee abundance in general and bumblebee abundance in particular? How can we modify our conventional farming strategies to embrace the aspects of organic farming that enable healthier pollinator communities? Perhaps most importantly, it is critical that we determine why the bee communities in agricultural settings are generally depauperate and what steps can be taken to increase the species richness and abundance of native bees in these landscapes.
CONCLUSIONS

Honeybee populations are declining rapidly and may not be a sustainable source of pollination services, and consequently, the potential importance of native pollinators continues to increase. Determining what factors influence native pollinator communities and how we can adopt practices that support thriving pollinator communities is of paramount importance, since many of the commercial crops grown depend on pollination for proper fertilization. In this study, I found that native bee communities in blueberry fields are influenced by differences between organic and conventional farming methods. However, regardless of farming methods, the diversity and abundance of native bee communities on these farms is rather low. Further research should focus on understanding the factors underlying these patterns. Crops are not the only plants depending on bees for pollination; much of our diverse native flora would be gone if not for the pollination services performed by native bees. Thus, for the sake of sustainable agriculture and for the maintenance of regional biodiversity, we must strive to better understand the factors influencing our native pollinator communities and the steps we can take to improve the condition of those communities in agricultural landscapes.
REFERENCES


McGregor, S. E. 1976. Insect pollination of cultivated crop plants. USDA.


Rao, S. 2011. Enhancement of pollination by native bees in blueberries and cranberries. SW08-056, Oregon State University, Corvallis, OR.


APPENDICES

Appendix A

The seven currently recognized families of bees and their characteristics (Michener 2007, Moisset and Buchmann 2011).

Permission was given for use of photos provided by: Dr. Laurence Packer (Packer 2013)

<table>
<thead>
<tr>
<th>Family</th>
<th>Subfamilies</th>
<th>Description</th>
<th>Sociality</th>
<th>Nesting Habits</th>
<th>Species Example</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andrenidae</td>
<td>Alocandreninae, Andreini, Panurginae, Oxaeninae</td>
<td>Small to moderate in size. The presence of two sutures below each antenna is a distinguishing characteristic. Commonly known as miner bees due to their nesting habits. Found on all continents except Australia.</td>
<td>Solitary</td>
<td>Ground-nesters</td>
<td>Pseudopanurgus rudbeckiae</td>
<td><img src="image1.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Apidae</td>
<td>Apinae, Nomadinae, Xylocopinae</td>
<td>Largest and most diverse family, with the largest number of tribes. The only unique distinguishing character is having 4 or more ovarioles per ovary. The commonly known European Honey bee is within this family. Found throughout the world.</td>
<td>Solitary Eusocial (highly and primitive) Cleptoparasitic</td>
<td>Ground-nesters Hole-nesters</td>
<td>Bombus pensylvanicus</td>
<td><img src="image2.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Colletidae</td>
<td>Colletinae, Diphaglossinae, Xeromelissinae, Hylaeinae, Euryglossinae</td>
<td>Morphologically diverse family. Bilobed glossa (mouthparts) distinguish them from all other bees. Commonly known as cellophone bees due to the cellophane-like cell lining of nests. Found throughout the world but most abundant in Australia and South America.</td>
<td>Solitary Cleptoparasitic</td>
<td>Ground-nesters Hole-nesters</td>
<td>Cepoecolana fulvicollis</td>
<td><img src="image3.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Halictidae</td>
<td>Rophitinae, Nomioi, Nomioni, Halictinae</td>
<td>Includes some of the most common bees, that are usually small to medium in size. Commonly known as sweat bees due to their attraction to perspiration. Found in temperate areas of the world.</td>
<td>Solitary (some share entrances to nests) Eusocial (primitive) Cleptoparasitic</td>
<td>Ground-nesters Hole-nesters</td>
<td>Agapostemon sericeus</td>
<td><img src="image4.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Megachilidae</td>
<td>Fidellinae, Megachilinae</td>
<td>Distinguishing characters include a rectangular shaped labrum and having the scopa (pollen carrying surface) on the underside of the abdomen. Also known as mason bees and leafcutter bees due to the materials used to build their nests. Found throughout the world.</td>
<td>Solitary Cleptoparasitic</td>
<td>Ground-nesters Hole-nesters</td>
<td>Hoplitis fulgida</td>
<td><img src="image5.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Melittidae</td>
<td>Dasypodainae, Meganomiinae, Melittinae</td>
<td>Small and uncommon family, consisting of only 4 genera. Small to moderate in size. Found primarily in the temperate regions of the Northern Hemisphere and Africa.</td>
<td>Solitary</td>
<td>Ground-nesters</td>
<td>Meganomia gigas</td>
<td><img src="image6.jpg" alt="Photo" /></td>
</tr>
<tr>
<td>Stenotritidae</td>
<td>None</td>
<td>Sister taxon of Colletidae family. Comprises two genera of moderate to large, robust, hairy, fast flying bees. Only found in Australia.</td>
<td>Solitary</td>
<td>Ground-nesters</td>
<td>Ctenocolletes smaragdinus</td>
<td><img src="image7.jpg" alt="Photo" /></td>
</tr>
</tbody>
</table>
Appendix B

Farm type, location and elevation of sites used in this study. Farm type is either organic (certified USDA organic) or conventional. All sites are located in Skagit County, Washington and were sampled during spring/summer 2012. Organic farm sites are represented with the prefix “O” in the site name and conventional farm sites are represented with the prefix “C” in the site name. Student’s t-tests were used to compare means between organic and conventional farms for both farm size (t= 0.62, df= 7, p = 0.55) and elevation (t= 1.26, df= 7, p = 0.25).

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Coordinates</th>
<th>Size (Ha)</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Burlington</td>
<td>48.503°, -122.370°</td>
<td>8.09</td>
<td>7.01</td>
</tr>
<tr>
<td>C2</td>
<td>Burlington</td>
<td>48.503°, -122.363°</td>
<td>15.18</td>
<td>6.71</td>
</tr>
<tr>
<td>C3</td>
<td>Mt. Vernon</td>
<td>48.426°, -122.430°</td>
<td>3.04</td>
<td>3.35</td>
</tr>
<tr>
<td>C4</td>
<td>Burlington</td>
<td>48.511°, -122.398°</td>
<td>6.47</td>
<td>7.62</td>
</tr>
<tr>
<td>C5</td>
<td>Mt. Vernon</td>
<td>48.444°, -122.452°</td>
<td>4.05</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>Mean (± SE)</td>
<td></td>
<td>7.37 ± 2.15</td>
<td>5.30 ± 1.14</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>Burlington</td>
<td>48.493°, -122.408°</td>
<td>10.12</td>
<td>3.35</td>
</tr>
<tr>
<td>O2</td>
<td>Burlington</td>
<td>48.495°, -122.403°</td>
<td>5.95</td>
<td>3.96</td>
</tr>
<tr>
<td>O3</td>
<td>Burlington</td>
<td>48.500°, -122.413°</td>
<td>2.27</td>
<td>5.18</td>
</tr>
<tr>
<td>O4</td>
<td>Mt. Vernon</td>
<td>48.442°, -122.453°</td>
<td>4.05</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>Mean (± SE)</td>
<td></td>
<td>5.60 ± 1.68</td>
<td>3.43 ± 0.83</td>
</tr>
</tbody>
</table>
Appendix C

Pesticide and herbicide use, tillage, and percentages of land area within 1km radius of middle of site that is forested, in agriculture, or open, with sparse trees. All sites are located in Skagit County, Washington and were sampled during Spring/Summer 2012. Organic farm sites are represented with the prefix “O” in the site name and conventional farm sites are represented with the prefix “C” in the site name. A Chi-Squared test was used to compare tillage (X-squared= 1.4, df= 1, p = 0.24) between organic and conventional farms. I used a Student’s t-test to compare means between organic and conventional farms for distance to nearest woodlot (t= 1.18, df= 7, p = 0.28), while Welch’s t-tests were used (due to heteroscedasticity) for surrounding % of forested (t=-1.92, df= 3.33, p = 0.14), % of agriculture (t=2.19, df= 3.16, p = 0.11), and % of sparsely treed (t=-2.61, df= 3, p =0.08) land.

<table>
<thead>
<tr>
<th>Farm</th>
<th>Synthetic Pesticides and Herbicides</th>
<th>Tillage</th>
<th>Distance to Nearest Woodlot (m)</th>
<th>% Forested</th>
<th>% Agriculture</th>
<th>% Sparsely Treed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>yes</td>
<td>yes</td>
<td>2138</td>
<td>5.5</td>
<td>94.5</td>
<td>0</td>
</tr>
<tr>
<td>C2</td>
<td>yes</td>
<td>yes</td>
<td>2673</td>
<td>2.2</td>
<td>97.8</td>
<td>0</td>
</tr>
<tr>
<td>C3</td>
<td>yes</td>
<td>no</td>
<td>605</td>
<td>3.5</td>
<td>96.5</td>
<td>0</td>
</tr>
<tr>
<td>C4</td>
<td>yes</td>
<td>yes</td>
<td>375</td>
<td>6.2</td>
<td>93.8</td>
<td>0</td>
</tr>
<tr>
<td>C5</td>
<td>yes</td>
<td>no</td>
<td>1647</td>
<td>0.1</td>
<td>99.9</td>
<td>0</td>
</tr>
<tr>
<td>Mean (± SE)</td>
<td></td>
<td></td>
<td>1488 ± 439.9</td>
<td>3.5 ± 1.1</td>
<td>96.5 ± 1.1</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Organic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>no</td>
<td>no</td>
<td>223</td>
<td>20.8</td>
<td>57.4</td>
<td>0</td>
</tr>
<tr>
<td>O2</td>
<td>no</td>
<td>no</td>
<td>583</td>
<td>11.6</td>
<td>77.8</td>
<td>21.8</td>
</tr>
<tr>
<td>O3</td>
<td>no</td>
<td>no</td>
<td>244</td>
<td>18.6</td>
<td>65.4</td>
<td>10.6</td>
</tr>
<tr>
<td>O4</td>
<td>no</td>
<td>no</td>
<td>1981</td>
<td>0.02</td>
<td>99.98</td>
<td>16</td>
</tr>
<tr>
<td>Mean (± SE)</td>
<td></td>
<td></td>
<td>758 ± 416.0</td>
<td>12.8 ± 4.7</td>
<td>75.1 ± 9.3</td>
<td>12.1 ± 4.6</td>
</tr>
</tbody>
</table>
Appendix D

Dates on which pan traps were deployed (filled with soapy water) and their contents collected. Total duration represents the length of each trapping period (across the five trapping periods, trapping was continuous from May 9 to June 13, 2012).

<table>
<thead>
<tr>
<th>Date traps were filled</th>
<th>Date specimens were collected</th>
<th>Total Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/9/2012</td>
<td>5/14/2012</td>
<td>5 days</td>
</tr>
<tr>
<td>5/14/2012</td>
<td>5/16/2012</td>
<td>2 days</td>
</tr>
<tr>
<td>5/16/2012</td>
<td>5/20/2012</td>
<td>4 days</td>
</tr>
<tr>
<td>5/20/2012</td>
<td>5/31/2012</td>
<td>11 days</td>
</tr>
<tr>
<td>5/31/2012</td>
<td>6/13/2012</td>
<td>13 days</td>
</tr>
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</table>
Appendix E

Schematic drawing of automatic bee dryer that was used for this project. Materials used to build the dryer included: One 80 mm diameter computer fan, PVC pipe, wood, a MDF board and an AC adapter. A small wood box enclosed the MDF board as well as the switch that controlled the power to the fan. PVC pipe was then attached to the box above the fan. When the dryer is turned on, the fan blows air up throughout the PVC pipes. Bees are placed in the pipe, which is sealed with mesh, the dryer is turned on, and air flows through the pipe drying the bees and fluffing their body hairs.

Design and construction provided by Jon E. Fabian from the engineering department at Western Washington University.
Appendix F

Automatic bee dryer used to dry specimens after collection and washing. See text for washing and drying procedures
Appendix G

Native bee abundance and species richness for this study, and seven additional bee surveys at various locations in the Pacific Northwest and western Canada.

<table>
<thead>
<tr>
<th>Location</th>
<th>Habitat</th>
<th>Sites Sampled</th>
<th>Years of Study</th>
<th>Sampling Method</th>
<th>Sampling Effort</th>
<th>Native Bee Abundance</th>
<th>Native Bee Species Richness</th>
<th>Author</th>
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<td>9</td>
<td>1</td>
<td>Net</td>
<td>54 person hours</td>
<td>338</td>
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<td>Pan Traps</td>
<td>2520 trap days</td>
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<td>2</td>
<td>Blue Vane Traps</td>
<td>188 trap days</td>
<td>488</td>
<td>47</td>
<td>Bergh, 2011</td>
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<td>Organic and conventional blueberry agroecosystems</td>
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<td>2</td>
<td>Blue Vane Traps</td>
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<td>152</td>
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<td>2</td>
<td>Blue Vane Traps</td>
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<td>532</td>
<td>33</td>
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Appendix H

80
Photographic plate showing one representative specimen for each species sampled in this study.

Appendix I
The number of individuals, by species, sampled at each study site. Organic farm sites are represented with the prefix “O” in the site name and conventional farm sites are represented with the prefix “C” in the site name. Species are arranged by family (bold) and subfamily (underlined).

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<td>897</td>
<td>730</td>
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<td>428</td>
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</table>

Appendix J
Relative taxonomic abundance of native bee species collected at each blueberry (‘Duke’ variety) farm site in Skagit County, Washington. Farm sites are arranged by type (Organic and Conventional). Bees were collected using pan traps and hand netting. Pan traps were left out continuously for the majority of the flowering season (blueberries were in bloom from May to early June) and hand netting was conducted three times per farm to supplement pan traps. Species in the genus *Bombus* are represented by shades of blue, species in the genus *Lasioglossum* are represented by shades of purple, species in the genus *Halictus* are represented by shades of pink, species in the genus *Agapostemon* are represented by shades of green, species in the genus *Osmia* are represented by shades of yellow, and species in the genus *Andrena* are represented by shades of turquoise.

![Relative Native Bee Abundance (%)](image)

**Appendix K**

83
Capture rates (calculated as bees per trap per day) for both native bees and honeybees for both conventional and organic farm sites. Error bars represent standard error. Native bee abundance/capture rate was significantly different between organic and conventional farms, whereas honeybee abundance did not differ between the two farm types. Stars indicate significance.
Relationship between farm site and native bee abundance, two measures of diversity (Shannon index and Simpson index), species richness (both the Margalef richness corrected for sample size and the total number of different species present), and evenness (Pielou). All sites are located in Skagit County, Washington and were sampled during May-June 2012. Organic farm sites are represented with the prefix “O” in the site name and conventional farm sites are represented with the prefix “C” in the site name.

<table>
<thead>
<tr>
<th>Farm</th>
<th>Native Bee Abundance</th>
<th>Honeybee Abundance</th>
<th>Species Richness ($S$)</th>
<th>Margalef Richness ($d$)</th>
<th>Shannon Diversity ($H'$)</th>
<th>Simpson Diversity ($D$)</th>
<th>Pielou Evenness ($J'$)</th>
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<tr>
<td>C1</td>
<td>16</td>
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