Effects of farming practices and landscape composition on wild invertebrate pollinator and bird abundance, richness and health

by

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Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

in the
Department of Biological Sciences
Faculty of Science

SIMON FRASER UNIVERSITY
Spring 2018

Approval

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Degree:	**Master of Science (Biological Sciences)**
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Date Defended/Approved:	April 11, 2018

Abstract

Wildlife biodiversity is threatened by agricultural intensification, which reduces and fragments natural habitat. I examine how farming practices and landscape composition influence wild pollinators and birds that inhabit these ecosystems. I also assess pollen foraging preferences of wild bumble bees and the effect of foraging preferences on their health. Forest cover was the main predictor of wild pollinator and bird abundance and richness, and floral resource availability also increased the abundance and richness of pollinators. There was no effect of farm management type (organic vs. conventional) on abundance or diversity of either pollinators or birds. Bumble bees showed a strong foraging preference for flowers not found on farms, and those collected in natural areas had higher body fat content than bees collected on farms. These results emphasize the importance of the conservation of natural habitat adjacent to agricultural areas for biodiversity, and of floral resources in natural areas for pollinator health.

Keywords: agroecosystem; farm management; biodiversity; landscape composition; organic agriculture; bee health

Acknowledgements

I am grateful to Elizabeth Elle for overwhelming support and mentorship as my supervisor. David Green, thank you for detailed feedback and assistance with writing. Christine Bishop and John Elliott, thank you for supporting the transformation of this project and Leithen M'Gonigle for agreeing to be my examiner.

Field work wouldn't have been possible without the support of blueberry farmers, as well as Metro Vancouver Regional Parks and the City of Abbotsford. I am so grateful for the endless conversations with farmers, especially to Dave Gemmell, who often met me at the farm gate to pull a list of pollinator-related questions from your pocket.

I would like to thank the various funding sources that supported my research: NSERC, Environment Canada, the National Institute of Food and Agriculture, U.S. Department of Agriculture, and Northwest Scientific Association.

The Elle lab provided mentorship, ongoing support and laughs during my time in Vancouver: Sandra Gillespie, Julie Wray, Kyle Bobiwash, Tyler Kelly and Allison Dennert. I want to thank Tony Williams, Allison Cornell and Jeff Yap for sharing their soxhlet lipid extraction methods and lab equipment. A million thank-yous to Tiia Haapalainen for being my right-hand field assistant, and providing your expertise both in the field and in the laboratory for bee identification. I am indebted to Philina English for mentorship in statistics and providing a tall, supportive shoulder when I needed to lean. Thanks to all of my SFU buddies who made the grey days of Vancouver a little brighter, especially Marinde Out, Dan Greenberg, Richard Johnston and also my "bee gals" – Martina Clausen, Ashton Sturm and Erin Udal.

I want to thank Sebastián Pardo for pushing me to be a better grad student and human being. Thank you so much for climbing mountains, chasing insects and birds, growing a beautiful garden, and countless silly moments. You will forever be engrained in my smile lines.

And I will never fully be able to express my gratitude to my family in Spokane: for the outpouring of love I felt from Mom and Dad, and for my brother James for being the pillar who is always there for me.

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Chapter 1.

General Introduction

Global biodiversity is declining at an unprecedented rate (Baillie et al. 2004). The world could lose more than two-thirds of its terrestrial wildlife by 2020 if current extinction trends continue (WWF 2016). Agricultural intensification is one of the major factors influencing biodiversity loss, as natural habitat is lost or fragmented (Tilman et al. 2001b; Tscharntke et al. 2005). Thus, the conservation of biodiversity is essential within human-modified systems, such as farmland. Modern agriculture has seen an increase of field sizes, low crop and vegetation diversity, and the use of pesticides and other chemical inputs (Kennedy et al. 2013). Wildlife conservation of the organisms that inhabit these agroecosystems requires an understanding of the factors that influence the conservation of biodiversity and wildlife health.

Landscape heterogeneity surrounding agro-ecosystems can provide wildlife habitat and resources (Kennedy et al. 2013). Some farms provide a pulse of resources for a short period of time (such as mass-flowering crops for pollinators), and a diverse landscape surrounding farms can provide resources over a temporal and spatial scale. When assessing needs of wildlife in or near agroecosystems, the protection of wild lands is important since many species can not attain all of their habit and food needs from farms (Phalan et al. 2011).

Many local (on-farm) management strategies have been implemented to provide benefits to wildlife, such as integrated pest management and planting hedgerows or meadows along field edges for birds or pollinators. A meta-analysis conducted by Tuck et al. (2014) stated that organic agriculture increases biodiversity, but the increase may depend on the level of agricultural intensification in the area (Kremen et al. 2002). On-farm practices such as the use of pesticides can decrease ecosystem services provided by beneficial insects, including both traditional pesticides that kill insects, and systemic pesticides which can have sub-lethal impacts (Gill and Raine 2014). Therefore it is important to assess wildlife abundance and diversity at the local farm scale as well as landscape-scale to gain a better understanding of preserving wildlife biodiversity and health in our region.

The nutritional needs of floral visitors may not be provided for within agricultural landscapes. Pollen is highly variable in protein content (2.5-61%), depending on plant species and where it is growing (Roulston et al 2000). Bumble bees rely on pollen as a sole protein source, but the connection between bumble bee health and pollen nutrition is unknown. The majority of research on dietary needs for bees is conducted with the managed honey bee (*Apis mellifera*), for which pollen diet deficiency was found to reduce life span (Schmidt et al 1987) and colony growth (Sagili & Pankiw, 2007). Additionally, in a laboratory experiment, honey bees fed a polyfloral diet lived longer when exposed to the parasite *Nosema ceranae* compared to bees fed a monofloral diet (Di Pasquale et al. 2013). The link between diet and health has rarely been considered for wild bees.

As agricultural intensification continues to increase, we need to consider how to conserve wildlife within agricultural landscapes. In this thesis, I focus on two groups of organisms that inhabit agroecosystems: wild pollinators and birds. Bumble bees are important for crop pollination, including my focal crop, highbush blueberry (*Vaccinium corymbosum,* Button & Elle, 2014). Although once very common on blueberry farms in our region (Winston & Graf, 1982; MacKenzie & Winston 1984) the western bumble bee *(Bombus occidentalis*) is in decline, with few individuals observed in the early part of this century (Ratti 2006) and none recently (Button, 2014). Other bumble bees in our region do not appear to be at risk, but a better understanding is needed of their response to local and landscape factors. Some farmland birds such as aerial insectivores depend on a diet of insects and have seen widespread population declines (Nebel et al. 2010; Smith et al. 2015). I include both pollinators and birds in this thesis to assess how different groups of organisms respond to farming practices and landscape composition.

I focus on blueberry farms because this crop is an example of agricultural intensification in the region; land area in BC devoted to blueberry production rose by 75 per cent between 2006 and 2011 (Statistics Canada 2012). BC produces 95% of Canada’s highbush blueberries, and is one of the top three blueberry-producing regions in the world (British Columbia Ministry of Agriculture 2011).

In this thesis, I investigate local and landscape-scale effects on pollinator and bird abundance, richness and health. In Chapter 2, I look at the influence of surrounding landscape cover in addition to local management practices on wild pollinator and bird abundance and richness. In Chapter 3, I investigate foraging preferences of bumble bees found on blueberry forms, and look at effects on bee health as measured by body lipid. These data can be applied by land managers and farmers to preserve natural habitat around farmland for the conservation of wildlife in and around agriculturally-intensive crops in our region.

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Chapter 2.

Landscape composition and farming practice determine abundance and diversity of wild pollinators and birds

Abstract

Land use intensification can alter wildlife communities on farms, potentially reducing the abundance and diversity of beneficial species. We examined how landscape composition surrounding farms and local farm management (non-crop floral resource availability, e.g. ‘weeds’; and pesticide applications) affected abundance and diversity of two focal groups: wild invertebrate pollinators and birds. We compared conventional highbush blueberry farms, organic highbush blueberry farms and natural areas in British Columbia, Canada. We found that forest cover within a one kilometer radius of field sites had a consistently positive effect on wild invertebrate pollinator and bird abundance. In addition, we found that non-crop floral resources increased diversity of wild pollinators, fungicides decreased pollinator richness, and herbicides decreased bird abundance. Although previous studies indicate an average increase in biodiversity on organic farms, we found that forest within a one kilometer radius increases abundance and diversity more than organic farming practice in this crop and our region. We suggest that conservation efforts should focus on preserving the quality and quantity of natural habitat adjacent to agricultural areas as well as providing non-crop floral resources and reducing pesticides at the farm-level.

Introduction

The conversion of natural habitat to human-modified systems is one of the leading causes of biodiversity decline (Tscharntke et al. 2012; Hooper et al. 2012; Regan et al. 2015). The pressure to feed a growing population has resulted in an increase in agricultural intensification, which can be characterized by large field sizes, low crop and vegetation diversity, and the use of pesticides and other chemical inputs (Kennedy et al. 2013). Agricultural intensification may negatively impact biodiversity in two ways: first, through the loss and fragmentation of natural ecosystems across the landscape, since these areas provide habitat and food for wildlife (Krebs et al., 1999; Tilman et al., 2001; Firbank et al., 2008) and second, through the use of pesticides, fertilizers, and other farm management practices, which can have direct negative impacts on wildlife (Björklund et al., 1999, Blacquière and et al., 2012). Wildlife conservation can benefit from both the integration of wildlife habitat within human-modified systems (Tscharntke et al. 2012) and the preservation of natural landscapes adjacent to farms (Phalan et al. 2011; Gabriel et al. 2013).

Natural land adjacent to farms may help buffer impacts of intensive agriculture by providing essential habitat and diverse resources for wildlife (Tscharntke et al., 2005). Diverse resources are available over a longer time scale in natural areas compared to farms which often provide a pulse of resources for a limited time (Benton et al., 2003) or provide fewer resource types (Smith et al. 2010). Landscape heterogeneity can benefit floral visitors by providing a diversity of pollen and nectar resources (Kennedy et al. 2013). In Europe, where decline of farmland birds has been well documented (Donald et al., 2001; Fuller et al., 1995), landscape diversity can be a predictor for the abundance of passerines because diverse landscapes provide food in the form of insects, fruit and seeds (Smith et al., 2010).

Farming practices may influence the suitability of farms as wildlife habitat. Organic farming increases species richness by an average of 30% compared to conventional farming, according to the meta-analysis by Tuck et al. (2014). Organic farming may have less impact on wildlife abundance compared to conventional farming (Bengtsson et al., 2005; Belfrage et al., 2005). This difference between conventional and organic is likely due to a combination of the tendency for organic farms to be smaller and grow more diverse crops on a local-scale, and to prohibit the use of synthetic pesticides (including herbicides, fungicides, and insecticides), although organic pesticides are allowed. Comparing the effect on biodiversity for different farming practices has rarely been examined in berry crops or in British Columbia. Diverse cropping systems may reduce damage by herbivores and increase natural pest predators compared to less diverse agroecosystems (Letourneau et al. 2011). Beneficial insects and wildlife dependent on a diet of insects may be negatively affected by the use of pesticides, whether synthetic or organic (Zhang et al. 2007). Pesticide impacts can go beyond simple mortality. Some can have sub-lethal impacts, for example reducing foraging bumble bee efficiency on complex flowers (eg. Spinosad, an organic pesticide: Morandin et al. 2005). Others can have neurological impacts on invertebrate pollinators that include reduced colony growth, impaired memory and inefficient foraging behavior (e.g. neonicotinoids, a synthetic pesticide; Hallmann et al., 2014; Mason et al., 2013; Pisa et al., 2014). These impacts on individual bees may reduce population growth with the potential for over-arching effects on both abundance and diversity.

As land use for agriculture continues to intensify, it is important to quantify the impact, which may help to better understand how to conserve wildlife within agricultural landscapes. We selected two focal groups of organisms that inhabit agroecosystems in the Pacific Northwest of North America for this study: wild invertebrate floral visitors (hereafter, “pollinators”) and birds. These groups provide essential ecosystem services such as pollination and pest control to farms. Some bees in our region may be experiencing declines (Ratti 2006) but little information is known about population declines of others. In addition, some farmland birds such as aerial insectivores depend on a diet of insects and have seen widespread population declines (Nebel et al. 2010; Smith et al. 2015). Berry production increased at a rate of 76.8% between 2006 and 2011 in British Columbia (Brazelton 2013) and can be pesticide and land-use intensive. Due to the lack of information on how berry farming impacts wildlife, we studied blueberry farms as an agroecosystem of interest.

To evaluate the relative importance of effects from surrounding landscape and farming practices on abundance and biodiversity of our focal groups, we conducted a comparative study on conventional and organic blueberry farms, as well as natural areas. Canada is the third largest producer of highbush blueberries *(Vaccinium corymbosum* L.*)* in the world (Brazelton 2013), with over 800 farms and 11,000 hectares dedicated to blueberry production in British Columbia (BC Blueberry Council 2016). The majority of these farms are concentrated in the lower Fraser River valley, British Columbia. Organic production makes up a small subset of the industry, but is rapidly expanding due to 20 - 100% higher premiums for organic blueberries compared to conventional blueberries (Julian et al. 2011). We included natural areas in our study to provide a reference point for biodiversity in our region and during the season of our survey work.

We asked the following questions:

1. How do surrounding landscape and on-farm practices predict abundance and richness of pollinators and birds?
2. Does abundance and richness of pollinators and birds differ between organic farms, conventional farms, and natural areas?

Methods

Study system and sites

For this study, we included 18 sites: 6 conventionally-grown blueberry farms, 6 organically-grown blueberry farms, and 6 “natural” areas. Sites were distributed throughout the lower Fraser River valley, British Columbia, Canada (Figure 2.1), and we paired the conventional and organic farms as closely as possible for cultivar (paired within cultivar Bluecrop, Duke, Elliot, or Hardiblue), location, surrounding habitat, and size. The organic farms were either certified by an official certification body (Certified Organic Associations of B.C. or Canadian Food Inspection Agency) or followed organic practices by not using synthetic fertilizers or pesticides. The “natural” sites were largely second-growth forests with many flowering shrubs that we surveyed along a path or edge habitat. These areas are managed by Metro Vancouver Regional Parks or the City of Abbottsford. Natural areas were chosen to be near the paired farm sites (less than 20 kilometers away), but all sites were separated by at least two kilometers to minimize the chance that floral visitors might move among sites.

Biodiversity sampling

Invertebrate pollinator abundance and richness

We conducted our field work from April 16 through June 29, 2015 with the blueberry bloom of a given field lasting approximately three to four weeks within that interval. We surveyed floral visitors at each site five times during this time frame, with all three site types in an area surveyed within the same day. We rotated the time of survey to each site between morning, mid-day, and afternoon. Surveys were limited to conditions conducive to insect foraging: mostly/partly sunny, temperatures above 13^{o} C, and low wind. We collected pollinators along three, 50-meter-long transects spaced 25 meters apart, rotating the collector at each transect among survey dates. In farms one of these transects was at the edge of the crop placed along the most natural field edge (a weedy strip or hedgerow), and two transects were in the crop (25 meters from the edge into the crop**,** and 50 meters from the edge). In natural areas the three transects were spaced along an opening, usually a trail. We collected all wild insects contacting the sex organs of flowers (we excluded the managed honey bee, *Apis mellifera)* with nets for 10 minutes per transect per survey date on both crop and non-crop flowers. Butterflies were identified and recorded, but not collected. Insects were pinned and identified to species, or in cases when identification to species was not possible due to the lack of updated keys we identified to genus or morphospecies (Appendix A, Table A1). Some of the collected species may be managed in our region (e.g. *Osmia lignaria*, *Bombus impatiens, and Bombus vosnesenskii)*. Because *O. lignaria* and *B. vosnesenskii* are native species, and *B.impatiens* has become naturalized, management status could not be determined for individual bees, so they were retained in our analysis. For each sampling date, we summed the abundance of netted pollinators and number of species by site for analysis.

Bird abundance and richness

We surveyed birds using a modified version of point counts for farms (Freemark and Rogers 1995). We surveyed each site four times from April 16 through June 29, ensuring all three site types in an area were surveyed within the same day. Two observers concurrently recorded all birds within a 100-meter radius at two stationary points per farm for 10 minutes. Points were located at least 400 meters apart at the field border, where the crop meets the most natural field edge. Three sites (one conventional, one organic and one natural area) were surveyed each day between dawn and 0930, with favorable weather conditions (no rain, wind <13 miles per hour). Each time we performed surveys, we alternated the order of the sites as well as the observer at each point. We excluded waterfowl and flyovers from our analysis. For each sampling date, we summed the abundance of birds observed and number of species by site. Bird species detected at field sites are in Appendix A, Table A2.

Landscape composition

I assessed landscape cover in ArcGIS using the world imagery basemap (ESRI 2016). Polygons of different landscape covers were digitized by hand, due to the lack of quality data and resolution provided by available crop data layers. I drew a 1-km radius circle from the center of the transect 25-meters from the field edge (the center of where I conducted pollinator and bird surveys). A 1-km radius is consistent with other studies assessing how landscape cover affects abundance of multiple taxa (Fahrig et al. 2015, Mallinger et al. 2015, Smith et al. 2010). I used the following landscape categories: blueberry, semi-natural (fallow fields, hay, and urban/suburban gardens), forest canopy (largely mixed conifer and deciduous), annual crops (corn and potatoes), perennial crops (raspberry, cranberry and strawberry), development (houses and roads) and water.

Local Management

Toxicity indices

We calculated toxicity indices for pollinators and birds for each farm using the Environmental Impact Quotient (EIQ) Field Use Rating formula which takes into account the pesticides relative toxicity to bees or birds and the amount of active ingredient applied (Kovach et al. 1992):

Toxicity index = $\Sigma_{i\text{-}j}$ [Rate (mL/acre) * active ingredient (%) * EIQ toxicity value

where i-j are different pesticides as reported from farmers' records (example in Appendix C) and EIQ toxicity values were taken from Kovach et al. (1992) and Eshenaur et al. (2010). Bee EIQ toxicity values for individual pesticides are the product of the active ingredient's acute toxicity to honey bees on a scale of 1-5 (relatively nontoxic = 1(LD_{50} > 100 ug/bee), moderately toxic = 3 (LD_{50} = 2 – 10.99 ug/bee), highly toxic = 5 ($LD_{50} <$ 2 ug/bee) and its plant surface residue half-life on a scale of 1 – 5 (1-2 weeks = 1, 2-4 weeks = 3, >4 weeks = 5; Kovach et al. 1992). Bird EIQ toxicity values for individual pesticides are the product of the active ingredient's 8 day LC_{50} values for mallards (>1000 ppm = 1, 100 – 1000 ppm = 3, 1-100 ppm = 5), its plant surface residue half life, and soil residue half life (< 30 days = 1, 30-100 days = 3, >100 days = 5). Bee and bird EIQ values for pesticides applied to blueberry farms in this study are in Appendix B.

Non-crop floral resources

We conducted vegetation surveys five times on the same days and along the same three transects as pollinator and bird surveys from mid-April through the end of June 2015. We selected 10 survey points at stratified random intervals of 5 meters along each 50-meter-long transect. We used a 25 cm x 2-meter quadrat perpendicular to the transect and quantified the percentage cover by flowers in bloom by species for both shrub and ground vegetation, excluding blueberry flowers.

Statistical Analysis

We conducted all analyses in R (R Core Team 2017). We examined the effects of site type (organic, conventional, natural), surrounding landscape (6 landscape cover categories), and local management (toxicity indices and non-crop floral resources) on the observed abundance and richness of pollinators and birds using general linear mixed models (GLMMs). We included site as a random effect. For analyzing richness, we calculated rarefaction curves and the chao2 estimate of species richness for pollinators and birds using the package 'vegan' (Oksanen et al. 2017), but since results were the same as for observed richness we present analysis of observed richness only. Our data fit a negative binomial probability distribution with a log-link function using 'glmmTMB' (Magnusson et al. 2017).

We first analyzed a model including landscape categories which we predicted to have a positive effect on wildlife, which included: forest, semi-natural habitat and perennial agriculture. Then we analyzed in a separate model the landscape categories which we predicted to have a negative effect on wildlife: blueberry agriculture, development and annual agriculture. We excluded water from our analyses since it comprised a small proportion of the overall landscape composition. For each of these models, we used stepwise deletion of non-significant terms (*P*>0.05) to come up with the simplest model with the fewest explanatory variables. The explanatory variable with the highest *P*-value was removed, and we then tested for loss of explanatory power from the removal of variables by comparing models with and without the variable using analysis of variance (maximum-likelihood fitting). If ANOVA models did not differ significantly the explanatory variable was permanently deleted from the GLMM and we proceeded to the next highest *P*-value and repeated the process (Zuur et al. 2009).

We analyzed in additional GLMMs non-crop floral resources and toxicity indices for pollinators and birds with site as a random effect, but excluded natural sites where pesticides are not used from all analyses of on-farm practices. We predicted non-crop floral resources to have a positive effect on wildlife (directly for pollinators, and through impacts on insect diversity for birds) and toxicity to have a negative effect on wildlife. We analyzed floral resources and toxicity in separate models. We examined both overall pesticide toxicity per farm as well as compound class (fungicide, herbicide or insecticide) toxicity in separate models.

There is some evidence that honey bees can compete with native bees (Thomson 2004). Because we did not know if stocking rates of managed honey bees would vary among farms or between organic and conventional farms prior to the start of the research, we additionally counted all insects on flowers, including honey bees, for 10 minutes per transect per survey date and site. To examine whether there were effects of honey bee abundance on wild pollinator abundance, we used a simple regression model using the lm function in R and extracted the R-squared statistic using the summary function (R Core Team 2017). This relationship was weak ($r^2 = 0.06$), so we interpret differences in wild pollinator abundance and richness (see Results) to be due to factors other than managed honey bee abundance.

Results

Biodiversity sampling

Invertebrate pollinators

We collected a total of 822 individuals from 88 species of wild (non-*Apis*) pollinators. We observed 39 species across all conventional farms, 42 species from all organic farms, and 64 species from all natural areas. We found an average of 3 species per site for conventional farms, 3 species per site for organic farms and 6 species per site for natural areas (Table 2.1). Bumble bees (*Bombus* spp*.)* were the most frequent wild pollinator making up 68% of total pollinators collected at conventional farms, 65% of total pollinators collected at organic farms, and 55% of total pollinators collected in natural areas. Other pollinators detected at sites included (from order of highest to lowest abundance): Syrphidae, Muscoidea*,* *Ceratina* spp., *Halictus* spp., *Osmia* spp., and Lepidopterans (see Appendix A, Table A1) for a complete list of species collected).

Birds

We observed a total of 923 birds from 52 species: 41 species from all conventional farms, 34 species from all organic farms, and 44 species from natural areas. We found an average of 8 species per site for conventional farms, 9 species per site for organic farms and 11 species per site for natural areas (Table 2.1). When separated by foraging guild (De Graaf et al. 1985), insectivores were the most frequent guild, making up 27% of total birds observed at conventional farms, 29% of total birds observed at organic farms, and 42% of total birds observed in natural areas. Other foraging guilds detected at sites included (from order of highest to lowest abundance): omnivores, granivores, frugivores, nectarivores and carnivores. (see Appendix A, Table A2 for a complete list of species observed).

Landscape characteristics

There was considerable variation in the land cover surrounding conventional farms, organic farms and natural areas. Forested area within a 1-km radius of the center of our sites varied between 0 and 47% for conventional farms, between 0.6 – 33% for organic farms, and between 18 and 64% for natural areas (Table 2.2).

Conventional farms had more perennial agriculture and blueberry agriculture within a 1-km radius compared to organic farms (Figure 2.2, Table 2.2). Organic farms had more semi-natural landscape within 1-km compared to conventional farms. Natural areas had more forested landscape and development within 1-km compared to conventional farms and organic farms (Figure 2.2).

Wild pollinator abundance and richness increased with percentage of forest within a 1-km radius (abundance: $z = 3.08$, $P = 0.002$, Figure 2.3; richness $z = 3.24$, $P = 0.001$; Figure 2.4), but no other landscape categories were significant. We found no effect of site type on pollinator abundance ($F = 0.59$, $P = 0.56$) or richness ($F = 0.27$, $P = 0.75$).

Bird abundance and richness also increased with percentage of forest within a 1-km radius (abundance: z = 3.29, *P* = 0.001, Figure 2.5; richness z = 2.61, *P* = 0.009, Figure 2.6) and declined with percentage of annual agriculture within a 1-km radius (abundance: z = -3.21*,* *P* = 0.001, Figure 2.7; richness: z = -2.40, *P* = 0.02*,* Figure 2.8). We found no effect of site type on bird abundance (F = 0.15, *P* = 0.86) or richness (F = 0.05, *P* = 0.95). None of the other landscape categories besides forest and annual agriculture had a significant effect on abundance or richness of birds.

Local Management

Toxicity indices

Toxicity index for pollinators and birds for each site is shown in Table 2.2. We found no association between the bee toxicity index and the abundance or richness of wild pollinators (abundance: z = -0.67, *P* = 0.51; richness: z = -0.99, *P* = 0.32) for conventional and organic farms. We analyzed toxicity for individual compound classes (fungicide, herbicide or insecticide) separately in additional models, and found a negative effect of fungicide toxicity on pollinator richness (z = -2.10, *P* = 0.04*)*. We found no association of bird toxicity with abundance or richness of birds, although there was a trend for a negative effect on abundance (abundance: z = -1.9, *P* = 0.06; richness: z = -1.45, *P* = 0.15). When analyzing compound classes separately, we found a negative effect of herbicide toxicity on bird abundance (z = -3.03, *P* = 0.002*)*

Non-crop floral resources

We found no difference in non-crop floral resources between conventional farms and organic farms, contrary to our expectation (z = 0.54, *P* = 0.59, Table 2.2). Pollinator richness increased with on-farm floral resources (z = 1.95, *P* = 0.05), but we found no effect of floral resources on pollinator abundance (z = 1.35, *P* = 0.18). We found no effect of floral resources on bird abundance (z = 1.31, *P* = 0.19) or richness (z = 0.31, *P* = 0.76).

Discussion

Organic blueberry farming did not significantly increase wild pollinator nor bird abundance and richness in this study. In a recent meta-analysis, organic farming increased species richness by an average of 30% compared to conventional farming (Tuck et al. 2014), and we had anticipated a similar result in our study. However, cropping systems in more agriculturally intense areas may receive more benefit from organic farming for increasing biodiversity. Agriculture comprised an average of 46.1% of the surrounding landscape in our study region (Table 2.2), so may not be of a high enough intensity for organic farming practice to be beneficial. Many organic farms in our study were located in close proximity to conventional farms, such that we expect wildlife to move between farm types and thus be exposed to different farming practices. Finally, organic farming may have a more positive effect in annual cropping systems where farms tend to be locally diverse and crops can be rotated (Birch et al. 2011), in comparison with a perennial crop such as blueberry which is managed very similarly between organic and conventional systems.

Forest cover within a 1-km radius of farms was consistently the most important predictor for abundance and richness of both pollinators and birds. This provides further evidence of the importance of adjacent natural habitat to overall biodiversity in agricultural systems (Chacoff and Aizen 2006; Greenleaf and Kremen 2006; Pickett and Siriwardena 2011). Natural areas provide diverse food and nesting habitat for pollinators (Klein et al. 2007) in comparison with farmland where the soil is frequently disturbed, negatively impacting ground-nesters, and there is limited availability of wood for cavity nesting. Proximity to forest can increase abundance and richness of farmland birds because forests provide a variety of nesting habitats, refuge and food (Reino et al. 2009). Wildlife may be utilizing the pulse of resources present in the farms yet depend on access to forested areas for additional resources (Steffan-Dewenter and Tscharntke 1999).

Annual agriculture in the surrounding landscape negatively affected birds in our study, likely due to the lack of available resources for birds. Bird species that utilize farmland have experienced population declines and range contractions (Fuller et al. 1995) and annual agriculture in our region may not present adequate resources for bird as these areas are characterized by high soil disturbance and bare soil outside of the growing season.

Instead of an overall effect of site type (farming practice), we found specific local management practices to be important for wildlife abundance and diversity. The use of pesticides on farms marginally decreased bird abundance, and we found a negative effect of herbicides on bird abundance and a negative effect of fungicides on bees. The use of herbicides has been linked to grey partridge (*Perdix perdix)* chick decline through the direct toxicity to insect food preferred by the chicks (Freemark and Boutin 1994). Fungicides are sprayed during blueberry bloom when pollinators are foraging, and has been shown to predict pathogen prevalence in bumble bees (McArt et al. 2017) and can act synergistically with insecticides (Brittain and Potts 2011). Surprisingly, insecticide toxicity did not have a negative effect on pollinators or birds, perhaps because some pollinators such as bumble bees may be able to dilute their exposure to pesticides by foraging on off-farm resources (Memmott et al. 2004; Brittain and Potts 2011) and unlike fungicides, insecticides are not sprayed during crop bloom. Our findings highlight that toxicity can vary within and across farming methods, and can outweigh the main comparison of organic vs. conventional farming practice.

Natural areas were included in this study as a reference point for comparison to farms and we expected to find higher abundance and richness of insect pollinators and birds in those sites. Although we did see a trend for higher mean abundance of pollinators and birds in natural areas, none of those differences were significant when controlling for forest cover in the surrounding landscape. We interpret this as farms and the surrounding landscapes in our region providing adequate resources for wildlife during our survey period. In addition, these natural areas were often disturbed edge habitat which may not be ideal habitat for wildlife. Future studies could focus on sampling over a longer season and over multiple years to better evaluate whether farms continue to provide adequate resources outside of when the crop is in bloom.

Both landscape-scale and local management practices are important for abundance and species richness of wild pollinators and birds in our region. Forest in the adjacent landscape was the most important predictor of pollinator and bird abundance and diversity in this study, highlighting the need to conserve natural areas that remain in these agricultural landscapes. Local management practices such as reducing pesticide use and increasing the availability of alternate floral resources should also be considered. Herbicides and fungicides had negative impacts on birds and pollinators in our region which is consistent with other studies highlighting the negative effects of pesticides on biodiversity (Geiger et al. 2010, Henle et al. 2008). In addition, ‘weed’ cover can positively affect wild pollinator abundance, as has been found in my study as well as others (e.g. Morandin & Winston 2005). Both native and non-native species of plants are beneficial to provide alternative food resources for pollinators and birds. Therefore, conserving wild areas adjacent to farms as well as maintaining beneficial on-farm practices for the preservation of biodiversity on farm should be beneficial for biodiversity and potential pollination services. We present novel findings about the importance of conserving forest in the surrounding landscape for the benefit of wild pollinators and birds for blueberry farms in this region. The integration of conservation between human modified systems and natural areas is important for the future of wildlife as human pressures are likely to increase with time in our study area.

Figures

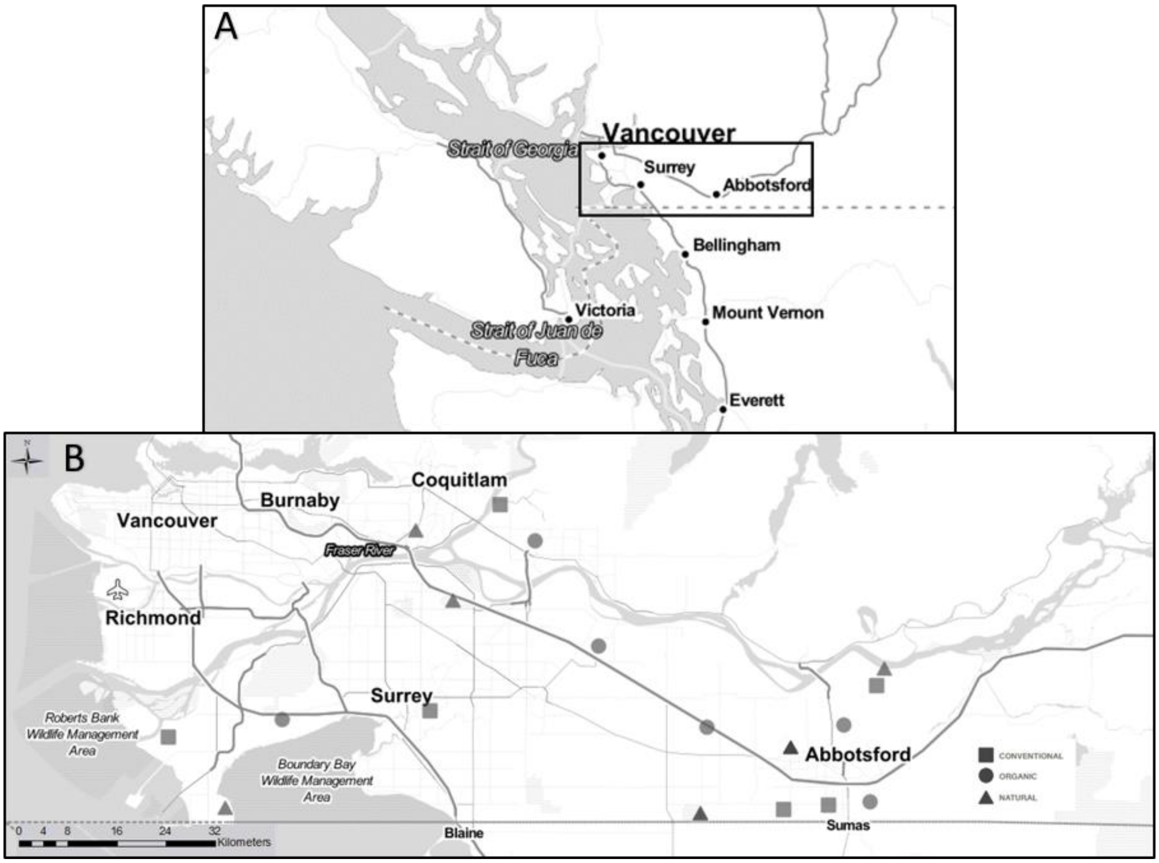

Figure 2.1. **A.** Overview of study area. **B**. Field study locations of 18 sites in the lower Fraser River valley, British Columbia. Squares indicate conventional blueberry farms, circles indicate organic blueberry farms, and triangles indicate natural areas.

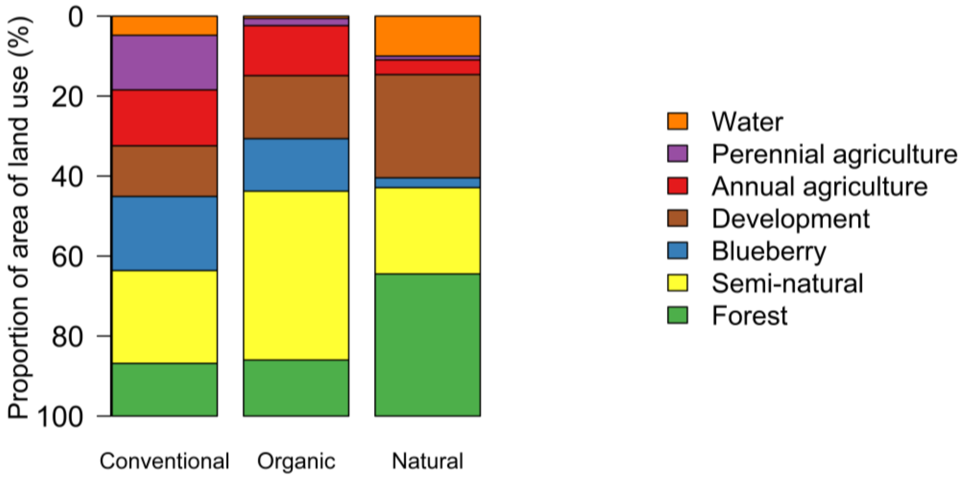

Figure 2.2. Proportion of area in different land use categories (%) within a 1-kilometer radius of study sites: conventional blueberry farms, organic blueberry farms, and natural areas in the lower Fraser River valley, British Columbia for n=6 sites for each site type.

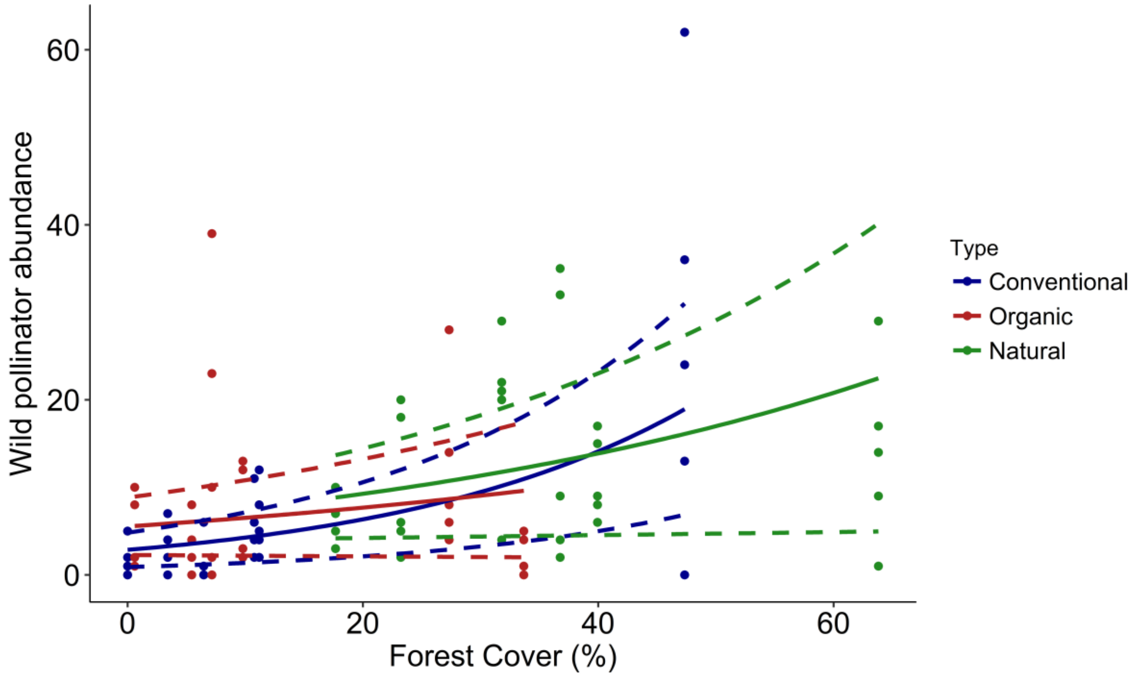

Figure 2.3. Wild pollinator abundance increases with percent forest cover (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled five times in the lower Fraser River Valley, British Columbia (*z* = 3.08, *P* = 0.002). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

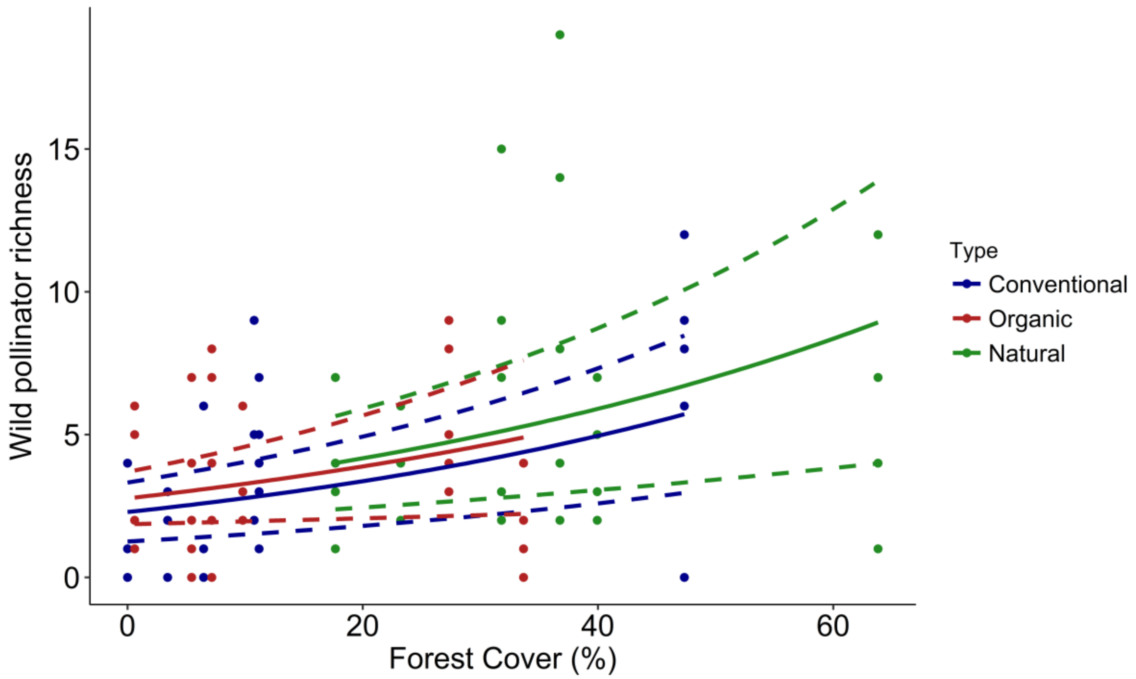

Figure 2.4. Wild pollinator species richness increases with forest cover (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled five times in the lower Fraser Valley, British Columbia (z = 3.24, *P* = 0.001). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

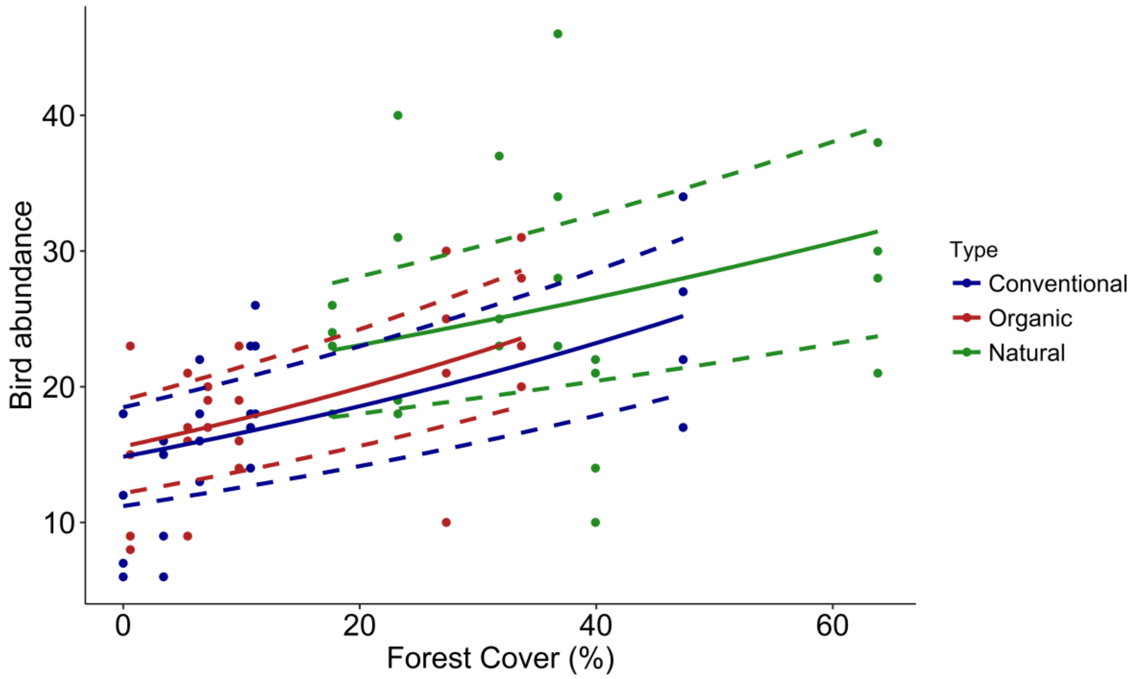

Figure 2.5. Bird abundance increases with percent forest cover (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled four times in the lower Fraser River Valley, British Columbia (z = 3.29, *P* = 0.001). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

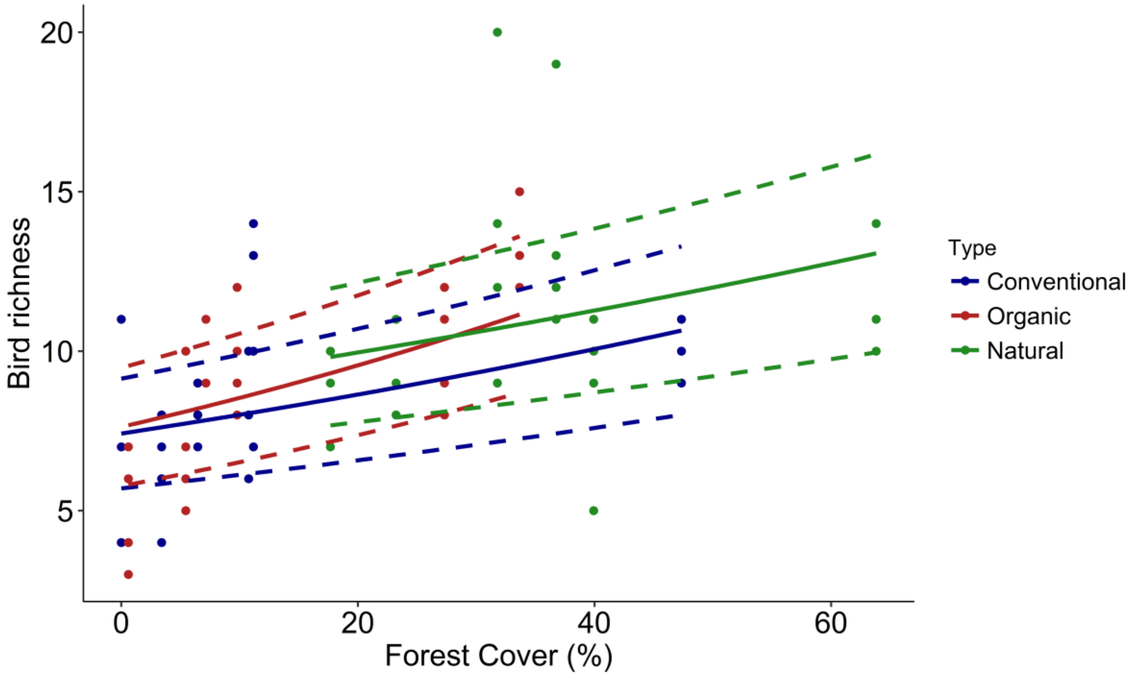

Figure 2.6. Bird species richness increases with percent forest cover (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled four times in the lower Fraser River Valley, British Columbia (z = 2.61, *P* = 0.009). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

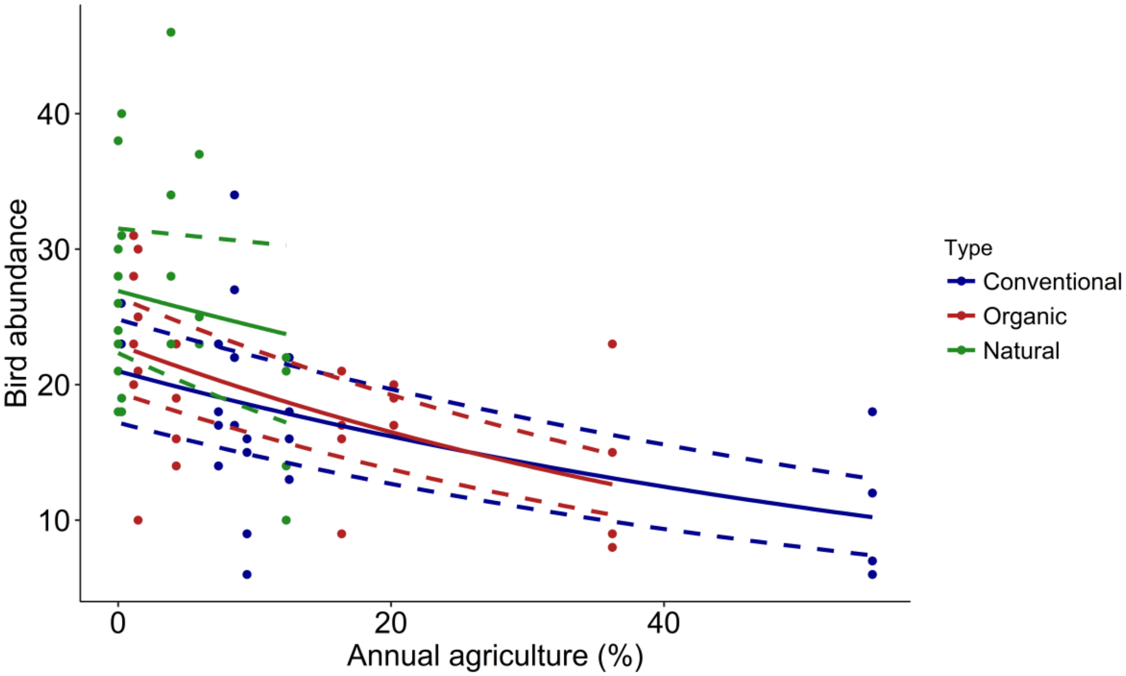

Figure 2.7. Bird abundance decreases with percent of annual agriculture (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled four times in the lower Fraser River Valley, British Columbia (z = -3.21, *P* = 0.001). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

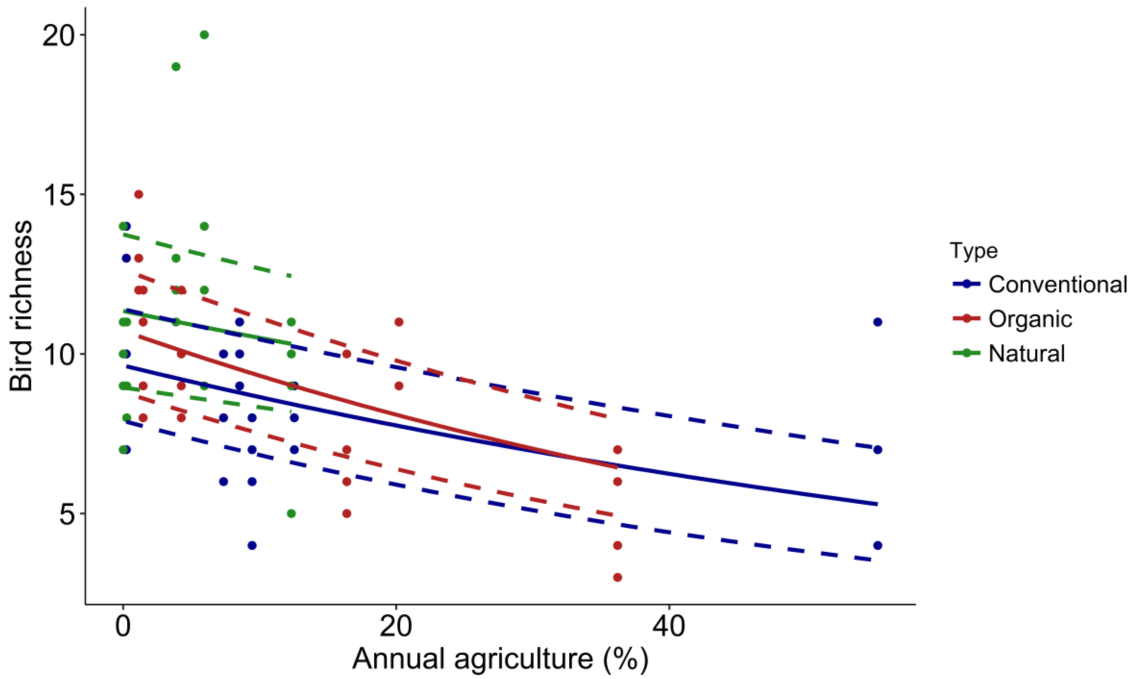

Figure 2.8. Bird richness decreases with percent of annual agriculture (1-km radius) for three site types (N = 6 of conventional farms, organic farms, and natural areas) sampled four times in the lower Fraser River Valley, British Columbia (z = -2.40, *P* = 0.02). Site was included as a random effect in the model. Points represent raw data points, lines represent predicted values and dashed lines indicate 95% confidence intervals.

Tables

Table 2.1. Abundance and richness of pollinators and farmland birds for 18 field sites in the lower Fraser River valley, British Columbia. Site names with C = Conventional blueberry farms, O = Organic blueberry farms, N = Natural areas. Pollinator species is the average number of wild invertebrate pollinator species across the 5 site visits. Pollinator abundance is the average number of netted wild invertebrate pollinators. Bird species is the average number of bird species. Bird abundance is the average number of birds observed.

Site Name	*Location*	*Cultivar*	*Poll spp*		*Poll abun*		*Bird spp*		*Bird abun*	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE
C1	Abbotsford	Duke	1.4	0.48	1.4	0.48	7.8	0.20	17.2	0.77
C2	Matsqui Flats	Elliott	7.0	0.82	27.0	4.32	9.8	0.20	25.0	1.48
C3	Aldergrove	Bluecrop	4	0.56	5.4	0.63	8.5	0.39	18.0	0.76
C4	Langley	Bluecrop	1.6	0.28	2.6	0.54	6.3	0.35	11.5	0.98
C5	Maple Ridge	Bluecrop	4	0.41	6.2	0.71	11	0.65	23.2	0.77
C6	Delta	Hardiblu	1.4	0.28	1.8	0.35	6.5	0.68	10.8	1.12
Mean			3.2	0.59	7.4	2.36	8.3	0.48	17.6	1.43
O1	Abbotsford	Duke	3.0	0.43	4.4	0.78	5.0	0.37	13.8	1.41
O2	Matsqui Flats	Elliott	4.2	0.61	14.8	2.97	9.5	0.20	18.2	0.31
O3	Abbotsford	Bluecrop	2.2	0.33	3.0	0.43	13.0	0.29	25.5	1.01
O4	Surrey	Bluecrop	5.8	0.47	12.0	1.77	10.0	0.37	21.5	1.74
O5	Pitt Meadows	Bluecrop	3.2	0.30	6.4	1.02	9.8	0.35	18.0	0.80
O6	Delta	Hardiblu	2.8	0.51	3.2	0.55	7.0	0.44	15.8	1.02
Mean			3.53	0.47	7.3	1.63	9.0	0.54	18.8	1.29
N1	Abbotsford	n/a	3.2	0.46	6.0	0.48	9.0	0.29	22.8	0.70
N2	Matsqui Flats	n/a	7.2	0.95	19.2	1.68	13.8	0.95	27.0	1.37
N3	Aldergrove	n/a	9.4	1.29	16.4	2.89	13.8	0.73	32.8	2.02
N4	Surrey	n/a	6.2	0.75	14.0	1.89	11.2	0.39	29.2	1.43
N5	Coquitlam	n/a	3.2	0.33	10.2	1.5	9.8	0.31	27.0	2.14
N6	Delta	n/a	4.4	0.43	11.0	0.87	8.8	0.54	16.8	1.17
Mean			5.6	0.82	12.8	1.77	11.0	0.60	25.9	1.73

Table 2.2. Surrounding landscape proportions for 18 sites in the the lower Fraser River valley, British Columbia. (n = 6 sites for each site type) within a 1-kilometer radius surrounding sites.

Site Name	*% forest*	*% semi-natural*	*% blueberry*	*% perennial*	*% annual*	*% development*	*% water*
C1	6.5	16.7	7.0	34.0	12.54	16.76	6.56
C2	47.3	19.7	21.6	0	8.52	2.83	0
C3	10.8	20.2	16.9	28.0	7.35	16.72	0
C4	3.4	27.0	41.5	3.77	9.45	12.21	2.58
C5	11.2	32.9	16.1	6.52	0.24	14.74	18.27
C6	0	22.5	8.0	0	55.27	12.74	1.42
Mean	13.2	23.2	18.5	12.1	15.6	12.7	4.81
SE	6.55	2.23	4.77	5.69	7.53	1.97	2.66
O1	0.6	46.3	10.0	0	36.22	6.83	0
O2	7.2	35.2	23.6	0.90	20.20	12.89	0.05
O3	33.7	39.4	13.2	1.02	1.13	11.35	0.20
O4	27.3	54.6	3.5	0	1.46	12.52	0.59
O5	9.8	43.9	2.5	0	4.26	37.81	1.73
O6	5.4	33.9	26.0	4.3	16.38	13.12	0.85
Mean	14	42.2	13.1	1.04	13.3	15.8	0.57
SE	5.03	2.93	3.75	0.64	5.23	4.19	0.25
N1	17.7	2.5	0	0	0	77.79	2.00
N2	31.8	15.7	5.6	0	5.94	3.36	37.61
N3	36.8	34.9	9.1	5.47	3.87	9.33	0.53
N4	63.8	15.6	0	0	0	20.63	0
N5	23.2	47.3	0	0	0.26	24.96	4.28
N6	39.9	13.5	0	0	12.32	18.73	15.50
Mean	35.5	21.6	2.5	0.91	3.73	25.8	10.0
SE	6.12	6.20	1.5	0.85	5.23	10.1	5.57

Table 2.3. Local farm management metrics for 18 sites in the the lower Fraser River valley, British Columbia. (n = 6 sites for each site type). Bee and bird toxicity is the total toxicity index for the site calculated from growers spray records for 2015. Floral resources is the average of the non-crop flowers in bloom (%) for 5 site visits.

Site Name	*Bee toxicity*	*Bird toxicity*	*Floral resources*
C1	4.1	2.90	1.9
C2	5.69	2.60	58.5
C3	2.31	1.93	60.1
C4	9.48	6.47	4.9
C5	4.46	2.06	5.0
C6	6.67	4.13	19.8
Mean	5.45	3.35	25.0
SE	0.94	0.65	7.57
O1	0	0	92.8
O2	1.21	0.24	41.7
O3	0	0	3.9
O4	0	0	68.7
O5	0	0	64.4
O6	0	0	4.3
Mean	0.20	0.04	46.0
SE	0.19	0.04	10.1

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Chapter 3.

Wild bumble bee foraging preferences and fat content in highbush blueberry *(Vaccinium corymbosum)* agro-ecosystems

Abstract

Agricultural intensification can negatively impact the availability and quality of resources for pollinators. Bees source all of their protein from pollen, yet protein content varies considerably by plant species, and highly nutritious plant species may be unavailable or limited in agricultural landscapes. Although honey bee (*Apis mellifera)* nutrition is well studied, very little is known about wild bumble bee (*Bombus* spp.) foraging preferences and nutrition in these landscapes. To explore this relationship, we analyzed pollen collected by bumble bees captured on highbush blueberry (*Vaccinium corymbosum)* conventional farms, highbush blueberry organic farms, and nearby natural areas in the lower Fraser River valley in British Columbia. We identified corbicular pollen collected from three species of common bumble bees (*Bombus mixtus, B. flavifrons, B. melanopygus)* and measured bee fat content as an indicator of health. Our results indicate that bumble bees supplement their diet with non-crop resources including pollen from plant species not found on farms. Bees netted in natural areas had higher estimated pollen protein content in corbicular pollen, and higher body fat content than those collected on farms, although there was no relationship between pollen richness or estimated pollen protein and relative fat content of bumble bees. Although organic farms had more non-crop flowers on site than conventional farms, we found no difference in pollen richness or bee fat content between farm types. These findings emphasize the importance of resource availability and quality for bees in agro-ecological landscapes.

Introduction

The rise in intensive agriculture, and associated land-use change is a major cause of habitat loss and fragmentation globally (Tilman et al. 2001b; Defries et al. 2004; Foley et al. 2005) and habitat loss has led to declines of wild invertebrate pollinators within agricultural landscapes (Cunningham 2000, Aizen et al. 2002, Klein et al. 2002, Kremen et al. 2002 b, Steffan-Dewenter et al. 2002, Klein et al. 2003, Ricketts 2004). Although mass-blooming crops can provide pollen and nectar resources for pollinators, their short bloom time reduces the benefit of these crops as minimal resources are available in the landscape when crops are not in bloom (Kremen 2002, Wesphal et al 2013). Weedy species on farms offer alternative forage for pollinators (Morandin and Winston 2005). Bees also forage away from agricultural areas by collecting off-farm pollen resources to provision on-farm nests (Bobiwash et al. 2018), or by foraging in rural landscapes with higher resource diversity compared to farms (Couvillon et al. 2014). Such foraging decisions can have implications for the crops that rely on bees for pollination (Walther-Hellwig and Frankl 2000), and are also expected to be related to the nutritional status of bees (Naug 2009).

Pollen is an important component of bee nutrition, but is known to vary in protein content (2.5 – 61%, Roulston and Cane 2000), lipid composition, vitamin/mineral content, and amino acid composition (Goulson et al. 2015). Bees rely exclusively on pollen for protein to feed developing larvae (Hydak 1970) and have been shown to prefer pollen with higher protein content (Robertson et al. 1999). Pollen that contains less than 20% crude protein content is considered a low-quality pollen for honey bee colony health (Somerville 2005), and has been found in pollinator-dependent crops like sunflower (Nicolson and Human 2013), blueberry, and buckwheat (Somerville 2005). Central-place foraging bees with nests in or near these low-protein crops will need to forage off-farm to meet their protein needs. We used crude protein content values from the existing literature to assess foraging preferences of wild bumble bees that forage or nest on farms and in natural areas within agricultural landscapes.

The type and range of available floral resources may affect bee health beyond the simple metric of available protein, although this has rarely been studied in wild bees (Goulson et al. 2015). Lipids are also essential to the functioning and development of bees, and lipid content of pollen ranges between 0.8% and 18.9% among different floral resources (Roulston and Cane 2000). The fat body in insects synthesizes and accumulates lipid reserves as well as carbohydrates, amino acids and other metabolites (Arrese and Soulages 2010). Because the fat bodies store and utilize energy, detoxify waste products (Arrese and Soulages 2010), synthesize immunoproteins (Amdam and Omholt 2002) and can be considered an indirect proxy for immunocompetence in honey bees (Wilson-Rich et al. 2009; Alaux et al. 2010), fat content is a realistic indicator of body condition and health in bees. In this study, we use fat content as a metric to measure health of individual bees. This is because colony-level metrics are not feasible with bumble bees whose nests are challenging to locate.

Differences in farm management, for example conventional vs. organic, may impact foraging choices and wild bee nutrition. Organic farms typically have smaller field sizes (and therefore more edge habitat) and grow more diverse crops on a local-scale (Norton et al. 2009). This may provide a range of nutritional options over a longer temporal scale than is typical for conventional farms (Gabriel et al. 2013). In addition, the amount of non-crop floral resources can be higher on organic farms (Morandin and Winston 2005). Few studies have looked at how farm type effects wild bee nutrition and health.

We ask the following questions:

1. Which pollen types do wild bumble bees collect for nest provisioning, and is this different from the resources available on the farm?
2. Are there differences in pollen collected by bees found on different site types within agricultural landscapes, and is this related to protein content of pollen?
3. Does pollen diversity or protein content of pollen affect the fat content of bumble bees foraging in different site types?

Methods

Study sites

We studied 18 sites distributed throughout the lower Fraser River valley, British Columbia: 6 conventionally-grown blueberry farms, 6 organically-grown blueberry farms and 6 “natural” areas. We worked on blueberry farms because this mass-blooming crop is known to have low pollen protein content of 13.9%, below the minimum level of 20% crude protein required to meet nutritional requirements of honey bees (Somerville 2001). Honey bee colonies foraging on monocultures of lowbush blueberry (*Vaccinium angustifolium)* exhibited a reduction in brood rearing compared to non-*Vaccinium* fields in Québec (Girard et al. 2012). We considered different site types because management differences among farms are often related to differences in the availability of on-farm resources for bees (ie pollen from weeds), and weed cover is often higher on organic farms (Morandin and Winston 2005). The organic farms were either certified by an official certification body (Certified Organic Associations of B.C. or Canadian Food Inspection Agency) or followed organic practices by not using synthetic fertilizers or pesticides. We paired the conventional and organic farms as closely as possible for cultivar (paired with cultivar Bluecrop, Duke, Elliot, or Hardiblue), location, surrounding habitat and size. Our "natural" sites were largely second-growth forests with many flowering shrubs, managed by Metro Vancouver Regional Parks or the City of Abbotsford. Natural areas were chosen to be near the paired farm sites (less than 20 kilometers) but all sites were separated by at least two kilometers to minimize the chance that floral visitors might move among sites.

Bumble bee collection

We focused on bumble bees (*Bombus* spp.) as these are the main wild pollinators of blueberry in British Columbia (Button and Elle 2014). They are central-place foragers that nest on or underground, with typical colony sizes ranging from 50 – 200 individuals, and development of new workers taking approximately two weeks (Goulson et al. 2001). In bees, fat content is determined by the resources fed to developing larvae, with adult fat content declining for the duration of the bee's life (O'Neill et al. 2015). Thus we considered bees collected near to the middle or end of the blueberry bloom to have been likely fed from resources including blueberry. We net collected 256 worker bumble bees of the three most abundant species (*Bombus mixtus, B. flavifrons, and B. melanopygus*) over a 10 day period in early May. The collection period was restricted to this short time frame because bee lipid content fluctuates considerably throughout the season. Bees were stored at -80 C (after corbicular pollen was removed) until lipid analysis was conducted.

Pollen collection and identification

We removed both corbicular pollen loads from each bee, suspended the pollen in 95% ethanol, vortexed the samples, and then pipetted a sub-sample onto a microscope slide following the methodology of Güler and Sorkun (2007). Fuchsine gelatin was added to the slide to dye the pollen grains for ease of identification. One observer counted and identified all pollen grains to reduce observer bias. Each pollen grain was identified to the lowest taxonomic level possible under 400 x magnification, using a reference library from our laboratory, as well as Hodges (1952) and a pollen atlas (Crompton and Wojtas 1993). In most cases the lowest taxonomic level possible for pollen identification is genus, and in some cases it is family. I counted 100 pollen grains along a randomly selected transect on the slide. In a sample of 256 bees, I included 17 slides that had between 51 and 100 grains (and analyzed as a proportion) but discarded any slides with a pollen count of <50 (12 slides) for a total of 244 bees. If any pollen type was observed only once, that count was excluded from further analysis as it may be due to contamination (Westrich and Schmidt 1986).

Floral resource quantification

We conducted vegetation surveys five times, approximately weekly, to include the blueberry bloom and shortly after. We selected 10 survey points at stratified random intervals of 5 meters along each of three transects. In farms, transects were located at the field edge, 25 m and 50m into the crop. In natural areas, transects were normally located along an edge or path. We used a 25-cm by 2-meter quadrat perpendicular to the transect to quantify the percentage of flowers in bloom by species, including both ground vegetation in our counts, and so including blueberry flowers on farms.

Estimate of pollen protein collected per bee

We compiled crude protein percentage for the pollen types identified in corbicular loads from the references listed in Table 3.1. Where the protein percentage was not known, we used values from a congener or another member of the plant family if available, or in a few cases where there was no information we used the average crude protein across all plant species (25%, Somerville 2005). We estimated the amount of total protein content per 100 pollen grains by multiplying the proportion of each pollen type collected by the crude protein content of that type, and summing across different pollen types for each bee.

Body size and lipid measurements

We measured the inter-tegular (IT) span and body lipid content of the same bumble bees that we used for pollen analysis. IT-span is the distance between the nearest edges of the tegulae. This is a standard index of bee size, and a good estimator of dry body weight (Cane 1987; Bullock 1999; Hagen and Dupont 2013) and foraging range (Greenleaf et al., 2007). A single observer measured IT-span in millimeters using digital calipers under a dissecting microscope to reduce observer bias.

We quantified body lipid content using a soxhlet apparatus with petroleum ether extraction. This solvent has been used for fat extraction in solitary bees (O’Neill et al. 2015) and wasps (Strohm 2000). Petroleum ether extracts neutral, non-structural lipids which are the stored energy reserves and regularly measured in insects (Williams et al. 2011). We placed individual bees in plastic trays of known weight, dried in a 60C oven and weighed on an analytical balance. The samples were then crushed in individual filter paper envelopes and loaded into the soxhlet for 6 hours. After lipid extraction, samples were weighed again. To calculate the mass of lipid per bee we measured the difference between post-extraction dry mass and pre-extraction dry mass. We measured the proportion of fat by taking the absolute fat content and dividing it by the mass of the bee. One outlier of a bee with 40% fat was removed from analysis, as this bee was likely a queen (since queens have higher fat content) and our study investigated foraging worker bumble bees.

Analysis

All analyses were run in R (R Core Team 2017). To compare the corbicular pollen types collected by bees with floral resources present at each site, we performed three separate Pearson’s Chi-squared tests (R package ‘MASS'), one for each site type: conventional blueberry farms, organic farms, and natural areas. Since pollen types can be identified only to genus or family, we combined our floral resource data to match the pollen types.

To examine whether bees from the three site types differed in the proportion of different pollen types collected, we summed pollen types across all bees from each of the three site types and ran a Pearson’s Chi-squared test. To evaluate whether individual bees from the site types differed in the richness of pollen collected, the amount of protein in collected pollen, or their IT-span, we used linear mixed effects models (‘lme4’, Bates et al. 2015) with site type as a fixed effect, and site and bumble bee species as random effects. For those models for which there was a significant effect of site type (using ANOVA type III Satterthwaite approximations) we tested how the site types differed using post-hoc Tukey tests.

To assess which factors had an effect on fat content of bees, we used a linear mixed effects model ('lme4', Bates et al. 2015) to identify the effects of site type, pollen diversity, and pollen protein content, with site and bumble bee species as random effects. We expected that bees foraging in landscapes where they could collect more pollen types or more total protein would have higher fat content. This expectation assumes that the resources available to adult bees are similar to the resources available when they were fed as larvae. We controlled for size of bee in the model by including IT-span in the model, as bees of differing sizes are likely to forage over different ranges.

Results

Blueberry pollen comprised 45% of total pollen found in corbiculae of three bumble bee species collected on conventional farms, 67% of pollen on bees from organic farms and 1% of pollen on bees from natural areas (Figure 3.1). Rosaceae pollen from shrubs was also common, comprising 32% of total pollen found on bees from conventional farms, 11% of pollen on bees from organic farms and 74% of pollen found on bees from natural areas. This pollen is most likely from salmonberry *(Rubus spectabilis)* or trailing blackberry *(Rubus ursinus)* due to bloom time in our region. The pollen types collected from bees were significantly different from the floral resources available at the three site types (conventional: $\chi2 = 1321.4$, $P < 0.0001$; organic: $\chi2 = 1204.7$, $P < 0.0001$; natural: $\chi2 = 825.2$, $P < 0.0001$, Figure 3.1).

Bumble bees from the three different site types differed in the proportion of pollen collected from different plant species ($\chi2 = 123.56$, $P < 0.0001$, Figure 3.1). Site type did not have an effect on pollen richness collected by individual bees (F= 1.28, $P = 0.31$; means in Table 3.1). Pollen protein content differed among site types (F= 12.29, $P = 0.0008$). We found higher pollen protein content in corbicular loads from bees collected from natural areas compared to conventional farms (z = 3.92, $P = 0.0002$) and organic farms (z = 4.50, *P* <0.0001). There was no difference in pollen protein content in corbicular loads from organic vs. conventional farms (z = -0.64, *P* = 0.52).

Fat content of bees also differed among site types (F= 3.85, *P* = 0.045; Table 3.1). Bees from natural areas had higher mean fat content compared to conventional farms (z = 2.62, *P* = 0.03), but not organic farms (z = 1.98, *P* = 0.10). There was no difference in fat content of bees collected from the two farm types (z = 0.44, *P* = 0.66).

Total estimated protein content in pollen loads did not have an effect on fat content of bees (F = 0.41, *P* = 0.41; Table 3.1). There was no significant effect of pollen richness per bee on fat content (F = 2.46, *P* = 0.12, Figure 3.2).

We found no effect of site type on mean IT-span (F= 2.26, *P* = 0.14). We found a negative relationship between fat content and IT-span, with a 3.9 % (SE:1.07) decrease in mean fat content for every mm increase of mean IT-span (*P* = 0.004, Figure 3.3).

Discussion

Bumble bees are preferentially foraging on particular pollen types, and these differ from the floral resources found at the site-level. In natural areas, bees collect more from shrub Rosaceae and less from tree Rosaceae than the relative availability of these resources. Collection of Rosaceae pollen likely indicates that bees may be supplementing their diet with off-farm resources, most likely with native salmonberry (*Rubus spectabilis)* or trailing blackberry (*Rubus ursinus)* neither of which is commonly present on farms. Blueberry flowers present a pulse of floral resources, but our data suggests they may not be attractive for pollinators, which likely has implications for the pollination of this crop.

Bumble bee foraging strategies for preferred pollen types may be based on nutritional requirements such as the amount of crude protein found in pollen. The average crude protein content of pollen is between 20-25%, with any pollen source lower than 20% considered a low protein pollen, and any pollen source above 25% considered above average quality pollen (Somerville 2001). The low-protein content of blueberry pollen (13.9%, Somerville 2001) may be why bumble bees in our study are supplementing their diet with other pollen types. Our results suggest that bees are modifying their foraging to ensure that they collect high-quality protein. Similar to our results, honey bees in intensively managed farms collected pollen from a diversity of non-crop flowers which was related to the nutritional value of the collected pollen (Requier et al. 2015).

Higher bee fat content in natural areas supports the idea that resource availability may have implications for bee health. Bees on farms may be flying further from their nests to forage compared to bees in natural areas, which may lead to decreased fat content in bees. Decreased fat content of bees on farms may have synergistic effects with stressors, such as the ability for bees to cope with toxins and pathogens (Goulson et al. 2015). We were surprised by our result of smaller bees having relatively higher fat content. Relative fat content increases with body size for the European beewolf, *Philanthus triangulam* (Strohm 2000), and we expected a similar relationship with bumble bees. Although pollination effectiveness increases with bumble bee size (Willmer and Finlayson 2014), our results indicate that size may not be reflective of overall health of the bee. Other metrics of health could be included in future work, including individual haemocyte concentration, or phenoloxidase activity (Alaux et al. 2010) or if possible to measure colony metrics of health such as brood production (Smart et al. 2016).

Other considerations besides protein content in pollen could cumulatively represent foraging choices of bumble bees, including amino acid compositions, lipids, and micronutrients. Foraging choices of pollen and assessment of pollen is a complex task for bees, compared to assessment of sugar content which can be done immediately (Nicholls and Ibarra 2016). There are 10 essential amino acids required for honey bee nutrition (de Groot 1953), and balancing amino acid ratios is important for bee health (Somerville 2005). Besides being low in crude protein content, blueberry pollen is low in the amino acid tryptophan (Somerville and Nicol 2006), which further suggests that blueberry pollen alone is not an adequate resource for bee nutrition. Stoichiometric balancing of elements in pollen can also play a role in pollen selection by bumble bees since limitation of elements may decrease bee growth and development (Filipiak et al. 2017). Our study did not assess the full nutritional profile of bumble bees preferred pollen sources, and future work could investigate different components of nutritional profiles of pollen to understand why bees are selectively foraging for particular pollen sources.

Consideration of the nutritional requirements of wild bees is still a relatively new field, and there are two ways future work could improve on our study. Total crude protein in pollen loads could be measured directly, leading to more accurate estimates than those based on published estimates, but this has only been done in a few cases (Tasei and Aupinel 2008; Somme et al. 2015; Vaudo et al. 2016). Another important consideration for future work is the best proxy for nutritional state. Larvae in colonies of the three species of bumble bees that we collected were presumably fed blueberry pollen. However, the bees that we analyzed for fat content provided an indirect proxy of what is fed to developing larvae, since the pollen that we analyzed would have been fed to the next generation of larvae, not the adult bees we analyzed.

Supplementing floral resources on farms could be beneficial to bees and farmers because bees would forage closer to the farm. This study could be used to provide insight about floral preferences of bees in agricultural landscapes of our region. Wildflower plantings on farms can increase diversity and abundance of beneficial insects, including wild pollinators (Williams et al. 2015) but also insects providing pest control services (Sidhu and Joshi 2016). Our pollen analysis lists numerous preferred pollen sources for bumble bees that if provided on farms, might reduce the distance these bees need fly to forage, potentially leading to more foraging time in the crop. However, although we demonstrate a strong foraging preference for shrub Rosaceae pollen in this study, many species within this family produce fleshy fruits which can serve as an alternative host for the invasive *Drosophila suzukii* in our region. It is therefore recommended by the British Columbia Ministry of Agriculture that these plants be removed from the farm landscape. This highlights a conflict between needs for beneficial insects on farms and the costs that can arise from plants that are alternative hosts for pests. We therefore suggest that on-farm habitat enhancements could benefit from planting non-invasive garden plants that provide high nutritional value for bees but which are not attractive to pests. Since our results provide evidence that higher diversity of plants leads to higher fat content of bees, there is a benefit to a diversity of pollen sources available to bees, whether through wildflower enhancements on farms or through the preservation of natural landscapes adjacent to farm landscapes.

Figures

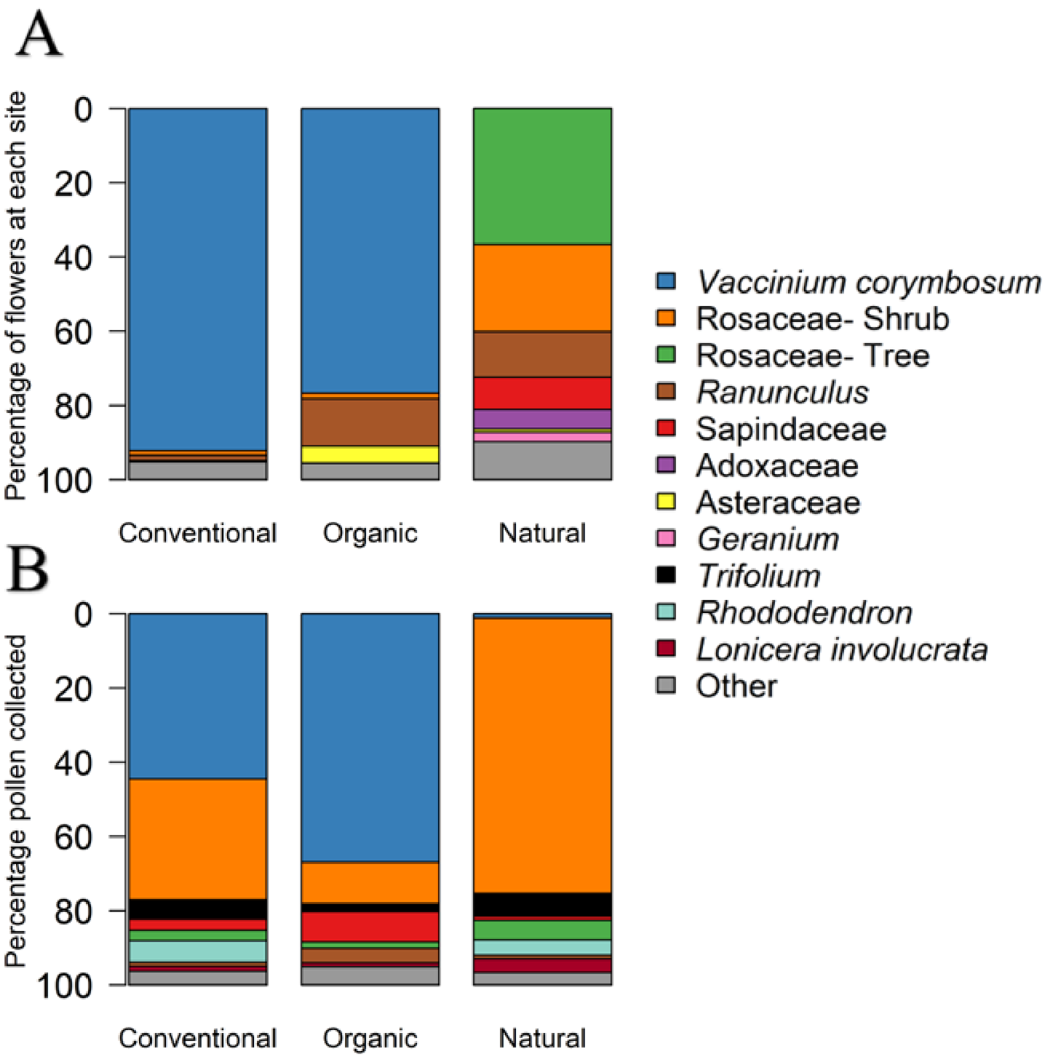

Figure 3.1. **A.** Floral resources present at three site types collected by bumble bees at 6 conventional blueberry farms, 6 organic farms and 6 natural areas in the Fraser River valley, British Columbia. **B.** Pollen collected by bumble bees differs significantly from the resources availabel within each site type (Chi-squared tests: conventional: $\chi2 = 1321.4$, $P < 0.0001$; organic: $\chi2 = 1204.7$, $P < 0.0001$; natural: $\chi2 = 825.2$, $P < 0.0001$). “Other” pollen types comprise less than 5% of total pollen collected by site type and are listed in Table 3.2.

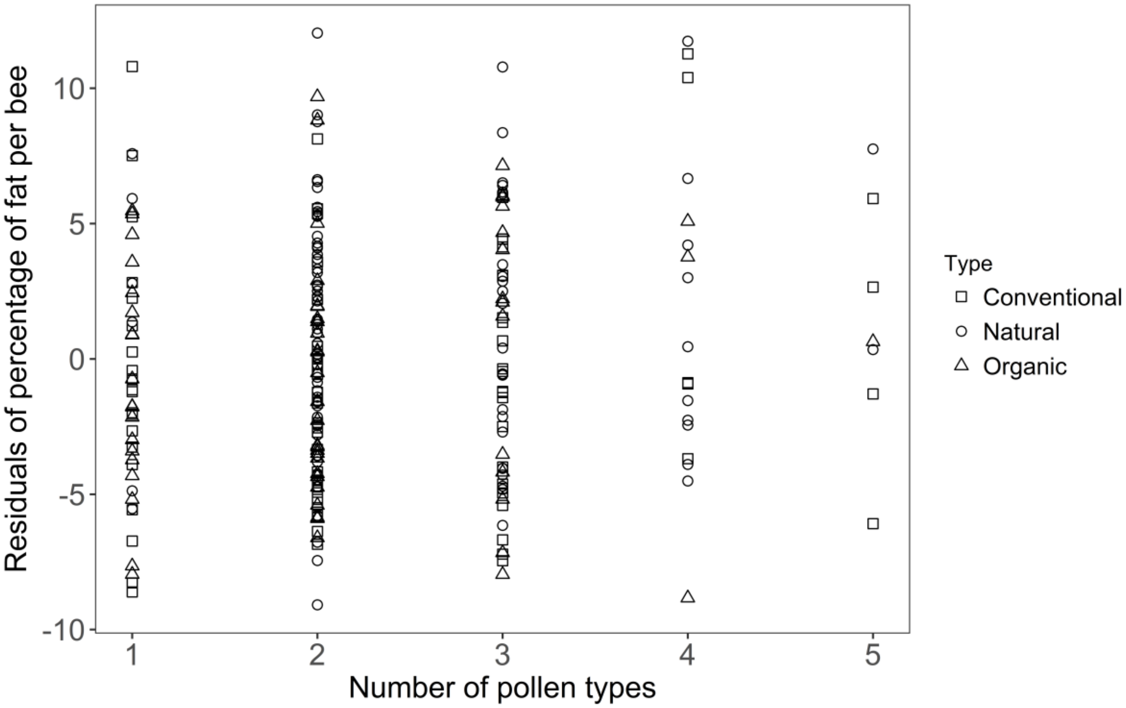

Figure 3.2. The number of pollen types collected does not predict the fat content of bees when bee size (IT-spab) is included in the model (F = 2.46, *P* = 0.12). The sample size is 244 worker bumble bees from three site types in the lower Fraser River valley in British Columbia (n = 6 sites per site type).

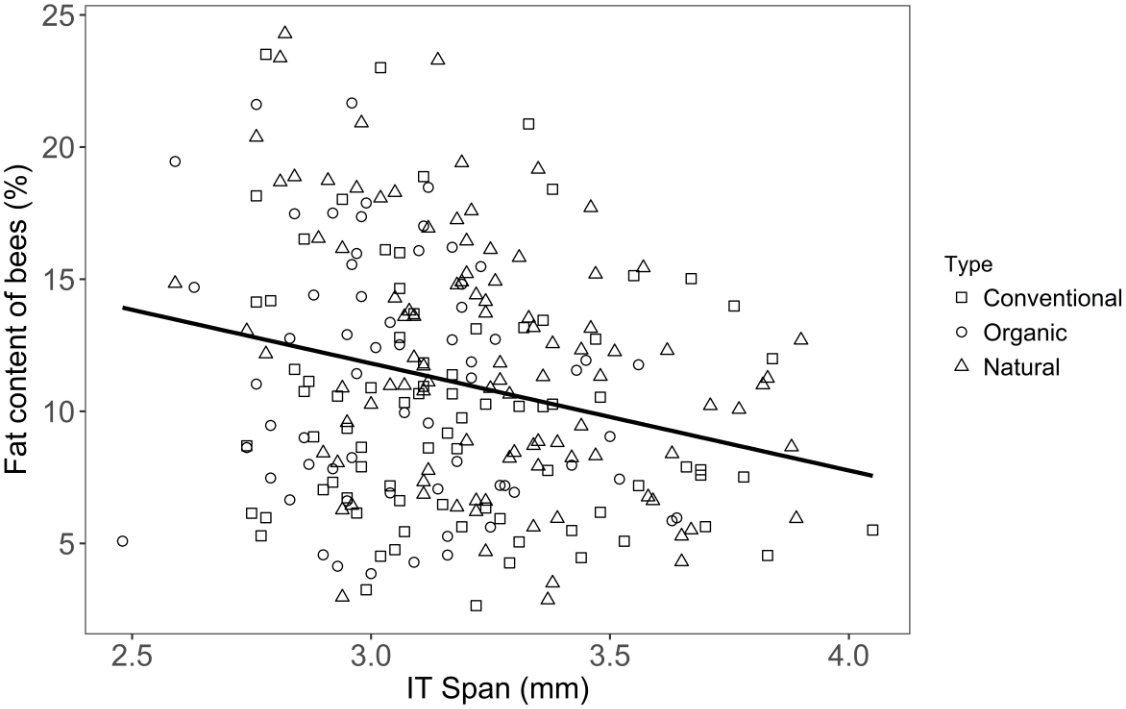

Figure 3.3. For every mean increase in IT-span there is a decrease in mean fat content by 3.9 % (SE: 1.07; *P* = 0.004). The analysis was performed on 244 worker bumble bees on conventional farms, organic farms, and natural areas in the lower Fraser River valley, British Columbia (n = 6 sites per site type).

Tables

Table 3.1. Mean and standard error of pollen richness, pollen protein content (% crude protein) and fat content (%) of bumble bees from conventional blueberry farms, organic blueberry farms and natural areas (n = 6 for each site type) in the lower Fraser River valley, British Columbia.

Variable	*Conventional*		*Organic*		*Natural*	
	Mean	SE	Mean	SE	Mean	SE
Pollen richness	2.30	0.12	2.06	0.10	2.44	0.09
Pollen protein	17.8	0.42	17.1	0.47	20.9	0.34
Bee fat content	10.1	0.51	11.1	0.52	11.9	0.53

Table 3.2. Protein content (% crude protein) for the pollen types identified in this study, as compiled from published estimates. If it was not possible to find a protein value for that particular pollen type or for the species we knew to be present in our study region, we used a representative species from the same genus or family as our identified pollen sample. Types listed under "other" comprised less than 5% of total pollen collected by bumble bees in each of three site types: conventional blueberry farms, organic blueberry farms, and natural areas in the lower Fraser River valley, British Columbia.

Pollen type	Family	Representative spp.	Protein	Reference
Common pollen types:				
Lonicera involucrata	Caprifoliaceae	*Diervilla lonicera*	14.9	Pernal and Currie 2001
Ranunculus spp.	Ranunculaceae	*Ranunculus* spp.	16.3	Szczêsna 2006, Liolios et al. 2015
Rhododendron spp.	*Ericaceae*	*Calluna vulgaris, Vaccinium angustifolium, V. corymbosum*	15.4	Hanley et al. 2009, Pernal and Currie 2001, Somerville 2005
Rosaceae- Shrub	Rosaceae	*Rubus discolor, R. ideus, R. fruticosis*	20.3	Somerville 2005, Pernal and Currie 2001 Szczêsna 2006, Hanley et al. 2008
Rosaceae- Tree	Rosaceae	*Rosa canina, R. acicularis, Prunus spp.*	21.1	Hanley et al. 2009, Pernal and Currie 2001, Liolios et al. 2015
Sapindaceae	Sapindaceae	Aesculus hippocastanum	29.1	Liolios et al. 2016
Trifolium pratense	Fabaceae	*Trifolium pratense*	40.8	Hanley et al. 2009
Trifolium repens	Fabaceae	*Trifolium repens*	30.3	Hanley et al. 2008, Pernal and Currie 2001
Vaccinium corymbosum	Ericaceae	*Vaccinium corymbosum*	13.9	Somerville 2005
Other, including:				
Acer spp.	Aceraceae	*Acer* spp.	21.0	Liolios et al. 2016
Asteraceae	Asteraceae	Asteraceae spp.	18.7	Pernal and Currie 2001, Liolios et al. 2015, Baum et al. 2004, Rouslton et al. 2000
Brassicaceae	Brassicaceae	*Sisymbrium irio*	22.3	Liolios et al. 2016
Cerastium spp.	Caprifoliaceae	*Diervilla lonicera*	14.9	Pernal and Currie 2002

Pollen type	Family	Representative spp.	Protein	Reference
Convulvus sepium	Convolvulaceae	*Bonamia sp., Ipomoea squamosa , I. tiliacea, Merremia umbellata*	32.3	Roulston et al. 2000
Fabaceae	Fabaceae		29.9	Somerville 2005, Hanely et al. 2008, Pernal and Currie 2001, Liolios et al. 2016, Andrada et al. 2005, Somerville 2006
Geranium spp.	Geraniaceae	Unknown		
Liliaceae	Liliaceae	*Allium* spp.	23.7	Liolios et al. 2016
Mahonia aquifolium	Berberidaceae	*Berberis microphylla*	16.8	Forcone et al. 2011
Medicago lupulina	Fabaceae	*Medicago minima, M. sativa, M. trunculata*	18.7	Andrada et al. 2005, Somerville 2005, Somerville 2006
Phalaris arundinacea	Poaceae	*Phalaris arundinacea*	10.4	Somerville 2005
Rhamnus purshiana	Rhamnaceae	*Ceanothus crassifolius, C. integerrimus*	40.4	T'ai and Roulson 2000
Salix spp.	Salicaceae	*Salix* spp.	20.2	Somerville 2005 , Genissel et al. 2002
Unknown conifer	Pinaceae	*Pinus* spp.	3.5	Feas et al. 2012

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Chapter 4.

General Conclusions

Agricultural expansion and intensification is inevitable (Tilman et al. 2001a). Ecosystem functions, such as pollination and pest control, are dependent on maintaining species diversity (Tilman et al. 1996; Balvanera et al. 2006) yet globally biodiversity is declining at an unprecedented rate (Thomas et al. 2004). Biodiversity loss can increase the vulnerability of ecosystems to secondary extinctions and run-away extinction cascades (Sanders et al. 2018). Insects in particular may be vulnerable to decline, as a biomass decline of 78% of insects was shown over a 24-year period in Germany (Vogel 2017). My research provides an understanding of how modern agricultural practices and landscape composition affect pollinator abundance as well as bird abundance and richness.

I assessed whether farming practice (organic vs. conventional) had an effect on abundance and diversity of pollinators and birds. The majority of highbush blueberry in British Columbia is grown conventionally, yet organic farms are increasing throughout the lower Fraser River valley. My research is the first to my knowledge that compares how organic and conventional practices on blueberry farms affect pollinators and birds in this region. Organic blueberry farming practices did not increase wild pollinator or bird abundance and richness (Chapter 2). Organic farming of blueberries in British Columbia can be agriculturally intensive, including the use of pesticides. Although my results are limited to this farming system in our region, they are consistent with other research that states the effects of organic farming on biodiversity can vary considerably, based on the surrounding landscape and cropping system (Bengtsson et al. 2005). Organic agriculture may be beneficial in some systems, especially in highly agriculturally intense areas (Kremen et al. 2002; Tuck et al. 2014) where the surrounding landscape provides few resources.

Forest in the adjacent landscape was the main predictor of both wild pollinator and bird abundance and richness (Chapter 2). My results fit into a growing body of literature that supports the preservation of natural areas for the conservation of biodiversity in agricultural landscapes (Kremen et al. 2002; Kennedy et al. 2013; Park et al. 2015; Cusser et al. 2016). Although blueberry agriculture dominates some parts of the Fraser River valley in British Columbia, this region has vast forested regions surrounding the valley, some of which are protected as Provincial parks. My research supports the continued preservation of these landscapes for the benefit of wildlife biodiversity.

Natural and semi-natural landscapes adjacent to farms provide diverse resources for wildlife (Kennedy et al. 2013). I found that bumble bees supplemented their diet with pollen that was not in proportion to flowers available at field sites (Chapter 3). Little is known about bumble bee foraging choices and how these choices impact their health, and future work could continue to assess whether protein content, amino acid ratios and/or lipid composition shape foraging choices. Laboratory studies have identified that foraging choices are based on more than crude protein content alone (Vaudo et al. 2016), but little is known about field choices. In addition, other metrics besides fat content could be explored as the best way to measure health in bumble bees. I interpret my results with caution since bees measured in this study were likely fed different resources as developing larvae than the resources (pollen) they collected. That is, I assessed scopal pollen and fat of foraging bees, but the pollen fed to those bees over their development is unknown.

My research emphasizes the importance of conserving forest landscape surrounding farmland and encouraging beneficial on-farm management practices for the abundance, diversity and health of wildlife that inhabit agro-ecosystems Land managers can utilize these data for understanding pollen preferences of bumblebees in addition to using them to support the maintenance of forested landscape adjacent to agricultural fields.

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Appendix A.

Species list of invertebrate pollinators and birds

Table A1. Compilation of species list and total species of wild invertebrate pollinators at three study types (n=6 sites per site type) in 2015, including butterflies which were not caught but included in analysis and listed below. Managed pollinators such as *Apis mellifera and Bombus huntii* were caught but not included in analysis and not listed below.

Group	Family/ Order	Species	Conventional	Organic	Natural
Bees (Apoidea)	Andrenidae	*Andrena angustitarsata*			X
		Andrena barbilabris			X
		Andrena hemileuca	X	X	X
		Andrena miserabilis			X
		Andrena nivalis			X
		Andrena saccata			X
		Andrena salicifloris			X
		Andrena sola			X
		Andrena sp. 5			X
		Andrena w-scripta			X
	Apidae	*Bombus californicus*	X	X	
		Bombus flavifrons	X	X	X
		Bombus impatiens	X	X	
		Bombus melanopygus	X	X	X
		Bombus mixtus	X	X	X
		Bombus vosnesenskii	X	X	X
		Ceratina acantha	X	X	X
	Colletidae	*Hylaeus modestus*			X
	Halictidae	*Halictus confusus*	X	X	
		Halictus rubicundus	X	X	X
		Lasioglossum (Dialictus) cressonii	X	X	X
		Lasioglossum (Evylaeus) sp. 1			X
		Lasioglossum (Evylaeus) sp. 4		X	
		*Lasioglossum (Evylaeus)*sp. 6	X		
		Lasioglossum planatum	X	X	X
		Lasioglossum zonulum	X	X	X
		Sphecodes sp. 4			X
	Megachildae	*Anthidium manicatum*		X	
		Heriades carinatus			X
		Hoplitis grinnelli	X		
		Megachile frigida			X
		Osmia caerulescens			X
		Osmia coloradensis	X		
		Osmia dolerosa	X	X	X
		Osmia lignaria	X		
		Osmia pusilla	X		

Group	Family/ Order	Species	Conventional	Organic	Natural
(Apoidea)		*Osmia simillima*			X
		Osmia tristella	X		X
Flies (Diptera)	Calliphoridae	*Phormia regina*	X		
	Muscoidea	Anthomyiidae	X	X	X
		Sarcophagidae		X	
		Scathophagidae			X
		Tachinidae		X	X
	Syrphidae	*Chrysogaster* sp. 1		X	
		Eristalinus aeneus		X	
		Eristalis anthophorinus	X	X	X
		Eristalis arbustorum	X	X	X
		Eristalis brousii			X
		Eristalis dimidiatus			X
		Eristalis tenax	X	X	X
		Eupeodes curtus			X
		Eupeodes latifasciatus	X	X	X
		Eupeodes volucris		X	
		Helophilus sp. 9		X	X
		Helophilus intentus			X
		Lejota sp. 1			X
		Melanostoma mellinum	X	X	X
		Merodon equestris	X		
		Parhelophilus sp. 1	X		
		Platycheirus obscurus		X	X
		Platycheirus sp. 4			X
		Platycheirus stegnus	X	X	
		Scaeva pyrastri	X	X	X
		Sphaerophoria weemsi	X	X	X
		Sphegina sp. 1		X	X
		Syritta pipiens		X	
		Syrphus opinator	X	X	X
		Toxomerus occidentalis	X	X	
		Volucella bombylans		X	X
		Xylota sp. 1			X
Others (Beetles, Butterflies and Wasps)	Crabronidae	*Bembix occidentalis*			X
		Philanthus sp. 1			X
		Trypoxylon sp. 1			X
	Coleoptera	Buprestidae			X
		Cortodera spp.		X	X
		Elateridae			X
	Ichneumonidae	Ichneumonidae			X
	Lepidoptera	*Carterocephalus palaemon*			X
		Thymelicus lineola			X
		Vanessa atalanta			X
	Siricidae	*Urocerus albicornis*		X	
	Sphecidae	Sphecidae			X
	Symphyta	Symphyta	X		
		Tenthredinidae spp.		X	X

Group	Family/ Order	Species	Conventional	Organic	Natural
Others	Vespidae	*Ancistrocerus* sp. 1	X	X	X
		Dolichoves pulamaculata	X		
		Polistes dominula	X	X	X
			39	42	64

Table A2. Compilation of species list and total species of birds, including common names and guilds of birds at 18 field sites in the lower Fraser River Valley, British Columbia (n = 6 sites per site type).

Guild	Common name	Conventional	Organic	Natural
Carnivore	Bald eagle	X		
	Great blue heron	X		X
	Northern harrier	X	X	X
Frugivore	American robin	X	X	X
	Cedar waxwing	X	X	X
	House finch	X	X	X
Granivore	American goldfinch	X	X	X
	Golden-crowned sparrow	X	X	X
	Purple finch	X		X
	Red-breasted nuthatch	X		X
	Red-winged blackbird	X		X
	Song sparrow	X	X	X
	Warbling vireo			X
Insectivore	Barn swallow		X	
	Bewick's wren	X	X	X
	Black-capped chickadee	X	X	X
	Black-headed grosbeak	X	X	X
	Brewer’s blackbird		X	
	Brown creeper		X	X
	Brown-headed cowbird	X	X	X
	Bushtit	X	X	X
	Common yellowthroat	X	X	X
	Golden-crowned kinglet	X		
	Killdeer	X	X	
	Marsh wren	X	X	X
	Northern flicker	X	X	X
	Orange-crowned warbler	X	X	X
	Pacific slope flycatcher	X		X
	Pacific wren	X		X
	Pileated woodpecker	X		
	Ruby-crowned kinglet	X	X	
	Tree swallow	X	X	X
	Unknown gull			X
	Varied thrush		X	X
	Western wood peewee			X
	White-crowned sparrow	X	X	X
	Willow flycatcher	X	X	X
	Wilson’s warbler			X
	Yellow warbler			X

Guild	Common name	Conventional	Organic	Natural
Nectarivore	Anna's hummingbird	X	X	X
	Rufus hummingbird	X		X
	Yellow-rumped warbler	X		X
Omnivore	Bullock’s oriole			X
	Dark-eyed junco	X	X	X
	European starling	X	X	X
	Lazuli bunting		X	X
	Northwestern crow	X	X	X
	Pine siskin	X	X	X
	Ring-necked pheasant	X		
	Savannah sparrow	X	X	X
	Spotted towhee	X	X	X
	Swainson's thrush	X	X	X
Total		41	34	44

Appendix B.

EIQ values for all pesticides applied in 2015

Table B1. Characteristics of all pesticides, including herbicides, fungicides, and insecticides, applied to conventional and organic bluberry farms. Products with an * denote those used on organic farms. EIQ values listed for bees and birds from Pesticide Active Ingredient EIQ values database (Eschenaur et al. 2010).

Class	Product	Active Ingredient	A.I. Concentration	EIQ value for bees	EIQ value for birds
Fungicide	Bravo	Chlorothalonil	50.0%	15	12
	Bumper	Propiconazole	41.8%	9	12
	Captan	Captan	80.0%	9	6
	Cantus	Boscalid	70.0%	9.3	12.15
	Copper*	copper oxychloride	50.0%	9	12
	Echo 720	Chlorothalonil	72.0%	15	12
	Elevate	Fenhexamid	50.0%	3	3
	Funginex	Triforine	19.0%	9.3	12.2
	Maestro	Captan	80.0%	9	6
	Mission	Propiconazole	41.8%	9	12
	Pristine	Boscalid	25.2%	9.3	12.15
	Pristine	Pyraclostrobin	12.8%	9.3	9.15
	Switch	Cyprodinil	37.5%	9.3	9.15
	Switch	Fludioxonil	25.0%	9.3	6.15
	Topas	Propiconazole	25.0%	9	12
	Quilt	Azoxystrobin	0.8%	9.3	9.15
	Quilt	Propiconazole	12.5%	9	12
Herbicide	Chateau	Flumioxazin	51.1%	9	6
	Dual II Magnum	S-Metolachlor	91.5%	3	6
	Maestro	dimethylamine salt	75.0%	9	6
	Mission	Flazasulfuron	25.0%	9	6
	Sandea	Halosulfuron	72.6%	9	6
	Sinbar	Terbacil	80.0%	3	9
	Touchdown	Glyphosate	50.0%	9	9
	Vantage	Glyphosate	48.0%	9	9
	Roundup	Glyphosate	49.0%	9	9
Insecticide	Actara	Thiamethoxam	24.0%	28.5	7.35
	Assail	Acetamiprid	70.0%	17.1	4.35
	Admire	Imidacloprid	24.0%	28.5	22.05
	Capture	Bifenthrin	24.0%	28.5	10.35
	Decis	Deltamethrin	0.5%	15	3
	Delegate	spinetoram	25.0%	18.81	4.35

Class	Product	Active Ingredient	A.I. Concentration	EIQ value for bees	EIQ value for birds
Insecticide	Entrust*	Spinosad	24.0%	15	3
	Exirel				
		Cyantraniliprole	10.0%	18.81	10.35
	Fulfill	Pymetrozine	50.0%	3	9
	Malathion	Malathion	85.0%	15	3
	Pyganic*	Pyrethrins	1.4%	28.5	4.35
	Sevin	Carbaryl	42.8%	15	9

Appendix C.

Example of spray record

Table C1. Record of all pesticides applied to a conventional blueberry farm in the Lower Fraser River Valley, British Columbia. These values were used to calculate a toxicity index for pollinators and birds for each site. Concentration is the % of active ingredient found in a pesticide, and application rate is grams per acre.

Date	Name	Type	Active ingredient	Concentration	Application Rate
7-Mar	Bravo	Fungicide	Chlorothalonil	50	1000
7-Mar	Mission	Fungicide	Propiconazole	42	200
18-Mar	Mission	Fungicide	Propiconazole	42	200
9-Apr	Cantus	Fungicide	Boscalid	70	236.588
9-Apr	Captan	Fungicide	Captan	80	946.36
22-Apr	Switch	Fungicide	Cyprodinil	38	390
22-Apr	Switch	Fungicide	Fludioxonil	25	390
30-Apr	Pristine	Fungicide	Boscalid	25	640
30-Apr	Pristine	Fungicide	Pyraclostrobin	13	640
6-May	Captan	Fungicide	Captan	80	946.36
26-Mar	Sinbar	Herbicide	Terbacil	80	177.441
27-Mar	Sandea	Herbicide	Halosulfuron	73	21
2-Apr	Chateau	Herbicide	Flumioxazin	51	75
18-Mar	Decis	Insecticide	Deltamethrin	1	50
5-Jun	Actara	Insecticide	Thiamethoxam	24	112
15-Jun	Capture	Insecticide	Bifenthrin	24	180
15-Jun	Pristine	Insecticide	Imidacloprid	24	70
22-Jun	Delegate	Insecticide	Spinetoram	25	110
29-Jun	Capture	Insecticide	Bifenthrin	24	180
9-Jul	Delegate	Insecticide	Spinetoram	25	110
16-Jul	Capture	Insecticide	Bifenthrin	24	178
25-Jul	Malathion	Insecticide	Malathion	85	300
30-Jul	Malathion	Insecticide	Malathion	85	300