ENHANCING ECOSYSTEM SERVICES MAPPING WITH PRIMARY DATA: OPPORTUNITIES TO EXPAND NOVA SCOTIA'S MANAGED POLLINATION SERVICES CAPACITY

by

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"Science, my lad, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth."

Jules Verne, A Journey to the Center of the Earth

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ABSTRACT

Spatially explicit mapping of ecosystem services is a growing trend that shows potential as a decision-making tool. Using pollination services in Nova Scotia, Canada as a case study, this thesis had two primary goals: to investigate the impacts of incorporating field based primary data into ecosystem services mapping studies and to identify areas of the province best suited for hosting honeybee (*Apis mellifera*) colonies. Results indicate field based data offers important insights that may be overlooked in remotely sensed data, and underscore the importance of matching the scale of data collection to the scale at which underlying biophysical processes driving ecosystem services occur. Building on these insights, the InVEST pollination model was used to identify areas of high quality land for honeybees. These results, when compared to the current distribution of colonies, indicate substantial opportunities for the province to host more colonies exist particularly in Colchester, Pictou and Inverness counties.

LIST OF ABBREVIATIONS USED

ELC: Ecological Land Classification

FEC: Forest Ecosystem Classification

InVEST: Integration Valuation of Ecosystem Services and Tradeoffs

IOA: Index of Abundance

LULC: Land Use Land Cover

MEA: Millennium Ecosystem Assessment

NSBA: Nova Scotia Beekeepers Association

TEEB: The Economics of Ecosystems and Biodiversity

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CHAPTER 1:
INTRODUCTION

1.1 MOTIVATION

Over the past decade, the western honey bees (*Apis mellifera*) (hereafter referred to as honey bee) have garnered a lot of attention in both the academic literature (e.g. Klein et al., 2007; Losey & Vaughn, 2006; Neumann & Carreck, 2010; Potts et al., 2010) and in popular culture (e.g. Atkins, 2014; Infantry, 2016; Suzuki, 2014; Thomson & Ahluwalia, 2013) because of their perceived status as a critical pollinator for food crops around the world and the current trends of colony loss (Neumann & Carreck, 2010; Potts et al., 2010).

The western honey bee is a highly adaptable and generalist species, with a native range reaching from southern Scandinavia to central Asia, as well as throughout Africa (vanEngelsdorp & Meixner, 2010). However, human intervention has resulted in the honey bee becoming a cosmopolitan species, persisting virtually wherever we do (Moritz et al., 2005; vanEngelsdorp & Meixner, 2010). The ancient Egyptians were the first to domesticate the species for the purposes of honey production, a practice that spread to the Greeks, the Romans and eventually Medieval Europe and subsequently to the New World (vanEngelsdorp & Meixner, 2010). Today, honey continues to be an important commodity, but in many parts of the world, beekeepers are increasingly using their colonies to provide commercial pollination services, a task at which honey bees are adept because of their generalist nature (Waser et al., 1996), and our ability to manage and relocate tens of thousands of individuals with relative ease (Javorek et al., 2002; Klein et al., 2007; Rader et al., 2009).

Although many species of bees, including mason bees (*Osmia sp.*) and leaf cutter bees (*Megachile sp.*), are used as managed commercial pollinators, honey bees are the most commonly used. In 2015, there were approximately 3.6 million honey bee colonies in the United States and Canada (Agriculture and Agri-Food Canada, 2016; USDA, 2016). Although it is unknown exactly how many of these colonies are used to provide commercial pollination services across the continent, demand for colonies is high in particular seasons and locales when pollinator-dependent crops are in bloom, from lowbush blueberries (*Vaccinium angustifolium*) on the east coast to almonds (*Prunus dulcis*) on the west coast (VanEngelsdorp & Meixner, 2010).

Despite the prevalence of their use, there is a lot of debate as to whether the honey bee is the best species to use as a large-scale crop pollinator (Buchmann, 1996; Steffan-Dewenter & Tscharntke, 2000). On a bee-to-bee basis, other species such as the buff-tailed bumblebee (*Bombus terrestris*) and plaster bees (*Leioproctus sp.*) can more effective pollinators in terms of efficiency (per visit pollen deposition) and visit rate (the number of flower visits per minute) (Rader et al., 2009). The popularity of honey bees as a commercial pollinator is because of the number of individuals in a colony (10,000 – 40,000) (Javorek et al., 2002; Klein et al., 2007; Rader et al., 2009). The ability to manage large numbers of honey bees in one place, and easily move them around, makes them an appealing choice for providing pollination services on large, industrial scales. Despite the arguments against using honey bees for agricultural pollination, they remain an attractive choice and the demand for honey bees as crop pollinators is not likely to decrease. Across North America, agriculture is intensifying, and farms are, on average, becoming larger in area (Agriculture and Agri-Food Canada, 2012a; USDA, 2014). Intensive agriculture is often coupled with a decrease in the amount of natural or semi-natural habitat surrounding fields, meaning there will be less critical habitat for wild pollinators (Garibaldi et al., 2004; Kremen et al., 20004), and thereby necessitating the expanded use of managed pollinators despite their shortcomings.

1.1.1 General Beekeeping Practices

1.1.1.1 Beekeeping in the Spring

In the spring (late March through May) beekeepers are focused on strengthening their colonies and preparing them for the summer season. At this time of the year, beekeepers will inspect their colonies to ensure the queen is laying eggs and check for signs of disease. During the spring, colonies are also often fed sugar syrup to jumpstart their growth. The number of individuals in colonies will begin to grow and splits may occur, creating new colonies (British Columbia Ministry of Agriculture, 2015).

1.1.1.2 Beekeeping in the Summer

The summer season (May through August) is when honey bee colonies are at their largest. Colonies are often moved from their main yards to agricultural fields to provide pollination services to crops such as apple (*Malus sp.*) and lowbush blueberry. Throughout the season, honey bees are actively foraging for nectar and pollen and are producing honey and beeswax. Towards the end of the summer, beekeepers will begin to extract honey from their colonies. Feeding colonies food supplements in the summer is rare (British Columbia Ministry of Agriculture, 2015).

1.1.1.3 Beekeeping in the Fall

During the fall season (September through November), beekeepers are generally focused on preparing their colonies for winter. At this point of the year, honey production begins to slow and the number of individuals in a colony drops. As fewer sources of forage are available, as well as to strengthen colonies before the winter, beekeepers will feed their colonies sugar syrups (British Columbia Ministry of Agriculture, 2015).

1.1.1.4 Beekeeping in the Winter

During the winter (December through March), colonies are largely left alone. Although some colony death over the winter is normal, colonies are insulated either through natural (snow) or artificial (hay bales, insulation) means to protect against loss British Columbia Ministry of Agriculture, 2015).

1.1.2 Beekeeping in Nova Scotia

The research in this thesis was conducted in Nova Scotia, Canada, where the beekeeping industry is currently composed of about 400 beekeepers who manage approximately 25,300 honey bee colonies (Sproule, 2016). Currently, the beekeeping industry in Nova Scotia has a total annual reported income of approximately $4.6 million (Cdn $) (Darrach & Page, 2015). While honey is an important commodity, most of a beekeeper's income (about $3 million of the sector's total reported income) comes from seasonally renting out their colonies to provide pollination services to pollinator dependent agricultural crops, particularly lowbush blueberry (NSBA, 2015).

Currently, the lowbush blueberry industry in Nova Scotia operates on 15,000 ha (however, only approximately half of this hectarage produces fruit in each year, as fields are managed on a two-year cycle, in which a fruit production year is proceeded by a sprout year (Ismail & Hanson, 1982)), but the industry is growing (seeing a 21% increase between 2001 and 2006), a trend that is slowing, but projected to continue (Agriculture and Agri-Food Canada, 2012b). Accompanying this growth is an increased demand for colonies to provide pollination services (Melathopoulos, 2016). The growth in demand for colonies has already outpaced the number of colonies currently being kept in the province. Based on the coarse recommended stocking rate of four colonies per hectare (Eaton & Nams, 2012), in theory, total demand from Nova Scotia's lowbush blueberry industry would amount to approximately 30,000 colonies to provide pollination services during the blueberry bloom period. In 2014, however, approximately 20,000 colonies from across the province were used for pollinating blueberry fields (NSBA, 2015). Therefore, from the perspective of blueberry producers, there is a deficit of managed pollination services available in the province; one which will only become more pronounced as blueberry hectarage in the province increases. To meet their demands, and make up for the deficit of locally available pollinators, some of the larger blueberry producers in the province have begun to look to colony sources outside of Nova Scotia (primarily the Niagara region of Ontario). In this context, starting in 2014, the blueberry sector has been permitted to temporarily bring 5,000 colonies into the province for a period of two to three weeks while the blueberry fields were in bloom (NSBA, 2015).

Currently, honey bee colonies being brought into Nova Scotia, even temporarily, require special permits as the border has been closed to the free movement of colonies since the early 1990s under the Nova Scotia *Bee Industry Act* c.3 2005. While there is pressure coming from the blueberry producers to lift the restrictions on the cross-border movement of colonies, the Nova Scotia Beekeepers Association (NSBA), want border restrictions to remain in place (NSBA, 2015). While the sector has not made public the basis of their opposition to colony importation, there are at least two bases upon which it could be founded. First, blueberry sector access to abundant, less expensive colonies elsewhere will drive down colony rental prices in the province. As previously mentioned, renting out colonies for pollination purposes can be a substantial component of a beekeeper's income, therefore an open border may have a negative economic effect on the local industry. Secondly, opening the border also poses the risk of pests, specifically small hive beetle (*Aethina tumida*), becoming established in the province, facilitated by the movement of colonies for pollination services (Melathopoulos, 2016). Small hive beetle, which feed on honey, pollen and bee brood, effectively killing the colony (Hood, 2004), is not currently established in Nova Scotia, but it is found in other regions of the country including those that are common sources for temporary colony importation by blueberry producers (i.e. southern Ontario) (Melathopoulos, 2016).

There are clear economic incentives associated with increasing Nova Scotia's managed pollination services capacity by increasing the number of honey bee colonies in the province. However, it is unknown if such an expansion is biologically feasible, which would ultimately determine its economic feasibility. In theory, the province could support an infinite number of colonies by supporting them entirely by artificial food supplements such as sugar syrups. However, this is not a desirable situation from a bee health perspective, as syrup supplements do not provide the same nutritional quality as natural nectar and pollen (Pedersen & Omhlt, 1993), nor an economic one, as maintaining colonies sustained solely on sugar supplements would be expensive. Therefore, it must be determined whether Nova Scotia has sufficient floral resources, in terms of abundance, density and seasonal diversity to effectively support an increase in colonies.

There is a finite amount of floral resources (nectar and pollen, which are critical food sources for honey bees) available in the province (Figure 1). However, not all the resources are effectively available to honey bees. They may not be accessible for morphological reasons, as the flower may be too small or of an inaccessible shape for the honey bee to extract nectar and/or pollen from or because the flowers are too sparsely populated to be a useful resource based on optimal foraging theory (Charnov, 1976) (Figure 1). Of those that are effectively available, honey bees are not the only species utilizing the resource. Thus, the actual amount of floral resources available for honey bees is further reduced through resource overlap (Steffan-Dewenter & Tscharntke, 2000) (Figure 1). Of the resources actually attainable for use by honey bees, it is unclear how much they are actually using (Figure 1). This thesis seeks to better understand the spatial distribution of floral resources across Nova Scotia to identify areas of the province that have high potential to support honey bee colonies, but are currently underutilized.

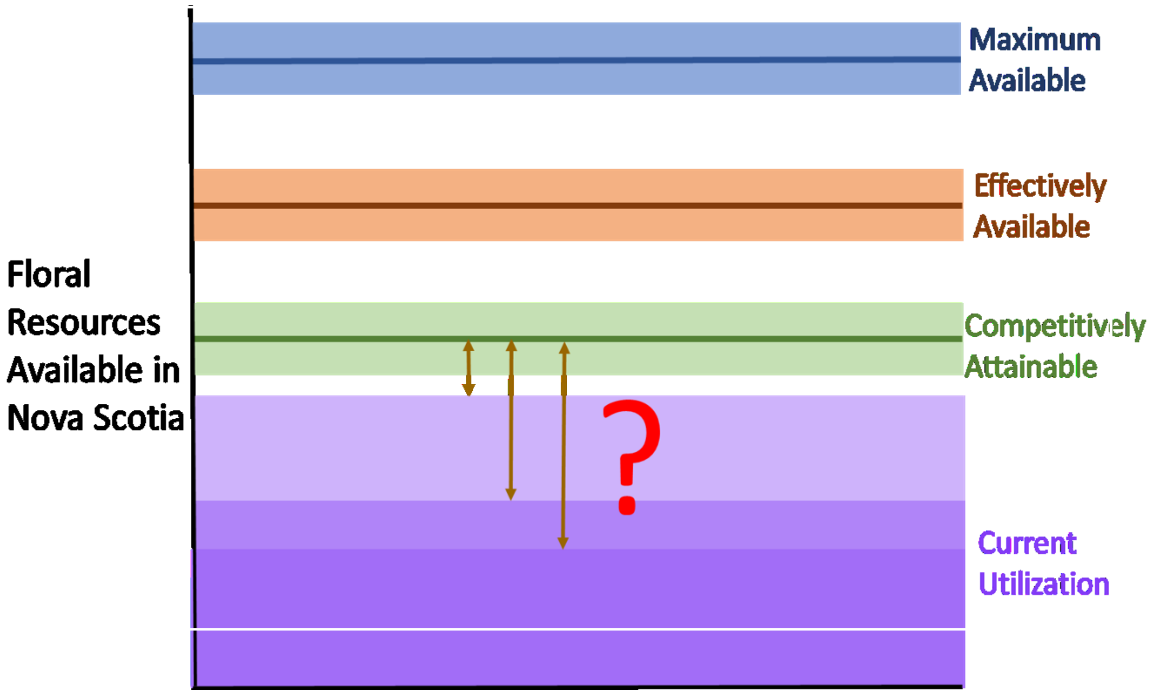

Figure 1. There is a finite amount of floral resources available in Nova Scotia, not all of which are available to honey bees (either through physiological inabilities or competitive exclusion). Of what is attainable by honey bees, it is unclear how much of it they are currently using. This research is seeking to determine how large a gap exists between what is attainable and what is currently being utilized.

Initially, we set out to quantitatively determine the number of honey bee colonies Nova Scotia could support given the province's current landscapes and the floral resources they provide. We partnered with beekeepers in Cumberland and Colchester counties, who collected data on the productivity of their colonies, recording information such as the number of splits, the amount of honey produced and the number of colonies dying over the course of the 2015 growing season. Over the course of that same season, we conducted detailed surveys of the vegetation surrounding these same apiaries. However, we were unable to determine if any relationship existed between the two data sets because of a low response rate. Of the eighteen sites involved in the study, only six had a complete dataset. However, shifting to an ecosystem services mapping approach allowed for us to analyse the differences in the ability of various landscapes to support honey bee populations, and identify regions of the province with high potential to support honey bee colonies. Comparisons of model results to current numbers of honey bee colonies in each county allowed us to identify counties in the province where there is likely opportunity to host more colonies. Details regarding the methods employed and results of the analyses are reported in Chapters 2 and 3.

1.2 CONTEXT

Ecosystems, both natural and human dominated, and the species they comprise, of provide numerous benefits to humans, such as food sources, pollination services, recreation opportunities and nutrient cycling (Daily, 1997). These benefits are known as ecosystem services, and they enrich our lives on many fronts, and in some cases are essential to our existence. The Millennium Ecosystem Assessment (MEA), a report commissioned by the United Nations, classifies ecosystem services into four categories, where three (provisioning, cultural and regulating) categories provide direct benefits to humans, and the fourth (supporting) are required to sustain all other services (MEA, 2005) (Table 1).

Table 1. The four categories of ecosystem services as defined by the Millennium Ecosystem Assessment (MEA, 2005)

Category	Definition	Examples
Provisioning	Products humans obtain from ecosystems	Food, Timber
Regulating	Benefits obtained from a regularly functioning ecosystem	Air Purification, Pollination
Cultural	Non-material benefits from ecosystems	Recreation, Spiritual Values
Supporting	Long term benefits obtained from ecosystems that allow for other services to persist	Soil Formation, Nutrient Cycling

Although the MEA (2005) is often credited with popularizing the term, ecosystem services was not a new concept at the time of its publication. Humans have understood that we have profound linkages to the natural environment, necessary for our survival, for centuries. The concept of how damages to the Earth's ecosystems can affect us dates back to at least Plato (c. 400 BC):

> What now remains of the formerly rich land is like the skeleton of a sick man with all the fat and soft earth having wasted away and only the bare framework remaining. Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only food for bees. Once the land was enriched by yearly rains, which were not lost, as they are now, by flowing from the bare land into the sea. The soil was deep, it absorbed and kept the water ... and the water that soaked into the hills fed springs and running streams everywhere. Now the abandoned shrines at spots where formerly there were springs attest that our description of the land is true. — Plato (Hillel, 1991, p. 104; as cited in Daily, 1997, p. 6)

The term ecosystem services was first introduced into our lexicon in the 1970s as a means of bringing attention to biodiversity and conservation issues and their role in sustaining human societies (Gomez-Baggethun et al., 2010). Tracking the usage of the term ecosystem services in the scientific literature, as recorded by Web of Science, revealed some interesting trends (Figure 2). Following its initial entrance into the literature in 1983 (Ehrlich & Mooney, 1983), it took five years before the term appeared again. The concept did not gain a lot of traction until the 1990s following the passage of the *Clean Air Act 104 s. 2468, P.L 101-549* in the United States which created a market for ecosystem services by granting tradeable permits for the emission of SO_2 (Bayon, 2004). Throughout the early 1990s, a handful of papers each year made reference to the concept of ecosystem services. Records of its use in the literature began to proliferate following the publication of Costanza and colleagues' (1997) landmark paper in which they attempt to quantify the total economic value of ecosystem services globally, a trend that accelerated following the release of the MEA in 2005.

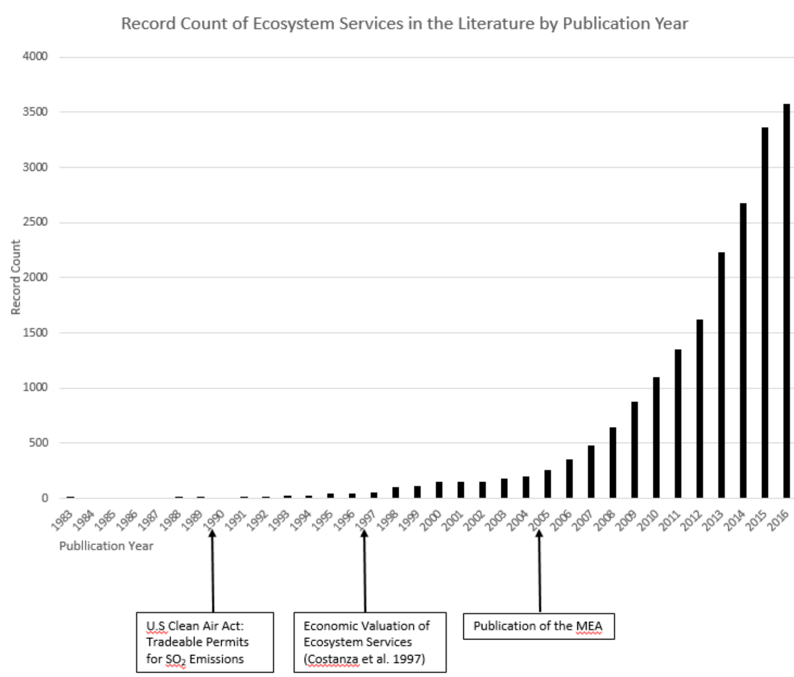

Figure 2. Bibliometric analysis of records of ecosystem services in the literature as captured by Web of Science. Usage of the term became commonplace after the passing of the U.S Clean Air Act in 1990 which created the first market for ecosystem services with tradeable permits for SO_2 emissions. The term caught on, and records of its use began to increase, in 1997 after the publication of Costanza et al.'s landmark paper on the economic valuation of ecosystem services. Usage of the term ecosystem services increased exponentially following the publication of the MEA in 2005.

To date, much of the focus within the realm of ecosystem services has been on attributing monetary value to services (e.g. Costanza et al., 1997; de Groot et al., 2002; Losey & Vaughan, 2006). While economic valuation studies have utility, and are often promoted on the grounds that they are a useful decision making tool for land use planning, there is little evidence to indicate they are actually being used to inform policy making decisions (Laurans et al., 2013; Laurans & Mermet, 2014). It may be the case that the use of ecosystem service valuation in policy making is common practice, but is not well documented in the literature, or there may indeed be a lack of uptake amongst policy makers (Laurans et al., 2013). However, there is a lack of a clear mechanism to incorporate ecosystem services into policy making (Maes et al., 2012; Seppelt et al., 2011). It is possible, that by considering the spatial complexities of ecosystem services, and the differences in services provision that arise from differences in spatial configuration, size and quality of habitat, we can garner a more complete view of the system, and better incorporate ecosystem services into policy making (Maes et al., 2012; Tallis & Polasky, 2009). Specifically, by mapping ecosystem services, areas of high importance for the provision of ecosystem services are identified, which can aid policy makers in their understanding of the impacts of different land use planning regimes on service provision (Martinez-Harms & Balvanera, 2012). Maps of ecosystem service provision across landscapes are a more valuable tool than economic valuation for policy makers because of the ability to visualize areas of high importance for service provision.

Spatially explicit modelling of ecosystem services is a growing trend, as evidenced by the development of several software packages to quantify and map the value of ecosystem services across landscapes. One of these software packages is the

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), a suite of eighteen different spatially explicit models that are designed to be used to map a variety of ecosystem services including pollination, recreation and carbon sequestration across landscapes (Sharp et al., 2016). This thesis utilizes the crop pollination model from the InVEST suite to evaluate the potential for managed honey bee colonies to persist across Nova Scotia.

1.3 PURPOSE OF STUDY

The research presented in this thesis aimed to determine the current spatial distribution of honey bee habitat across Nova Scotia, and whether there are any underutilized regions of the province that could host an increase in colonies. Pollination is dependent on the presence of floral resources that occur on a fine scale, a scale which is not captured in typical remotely sensed data sets. Therefore, this study also offered the opportunity to analyze the effects locally collected field data can have on ecosystem service mapping studies, a practice which is uncommon in the discipline (Martinez-Harms & Balvanera, 2012; Seppelt et al., 2011).

1.4 RESEARCH QUESTIONS

This thesis aimed to answer the following questions:

(1) What are the effects of incorporating locally collected, field based data into the mapping of pollination services which has biophysical underpinnings that operate on a fine scale?

(2) What is the distribution of land suitable for honey bees across Nova Scotia?

(3) Are there any areas of Nova Scotia that are currently being underutilized by beekeepers and could thus host an expansion of the industry?

1.5 SCOPE

The research conducted for this thesis took place in the Canadian province of Nova Scotia. Located in the Maritime region, the province's natural state is largely densely forested (Davis & Browne, 1996). Pre-European contact, there was very little habitat conducive to supporting pollinators, but after European arrival, the forests began to be cleared at rapid rates to make way for agricultural settlements (Davis & Browne, 1996). Such activities created clear cuts and pasture that were much more favourable for pollinators than the natural state of the province. After three centuries of intense landscape modification, Nova Scotia is now a highly heterogenous patchwork of land covers and land uses, many of which are favourable environments for honey bees and other pollinators. The field data used in this thesis were collected in Colchester and Cumberland counties of Nova Scotia. Cumberland and Colchester counties both have a well-established beekeeping industry, with approximately 4,000 of Nova Scotia's 25,300 colonies based across the two counties. The landscapes are characterized by small farms punctuated by tracts of forest of varying densities, making it representative of the rest of the province.

This thesis represents only a snapshot in time. Field data were only collected during the summer of 2015. The results of this work are thus only applicable to the present. Future changes to the landscape, including those brought on by climate change, are beyond the scope of this research.

1.6 THESIS STRUCTURE

The balance of this thesis is composed of three chapters, two of which have been written for submission to the peer reviewed literature. Chapter 2 is essentially a methodological paper that explores the benefits of using primary data in ecosystem services mapping. Using the case study of potential honey bee abundance in Cumberland and Colchester counties, the benefits of using locally collected field based data to inform ecosystem services mapping models are highlighted. The manuscript based on Chapter 2 will be prepared for submission to *Ecosystem Services* and will include Peter Tyedmers and Kate Sherren as co-authors. Chapter 3 is an application paper that applies the methodology described in Chapter 2 to all of Nova Scotia to identify areas of the province that are currently underutilized by the beekeeping industry. The manuscript based on Chapter 3 will be prepared for submission to *International Journal of Biodiversity Science, Ecosystem Services and Management* and will include Peter Tyedmers and Kate Sherren as co-authors. The final and concluding chapter summarizes the work presented in the thesis, making general recommendations and outlines the needs for future research.

CHAPTER 2: ENHANCING ECOSYSTEM SERVICES MAPPING THROUGH PRIMARY DATA: A CASE STUDY OF POTENTIAL HONEY BEE (*Apis Mellifera*) ABUNDANCE IN CUMBERLAND AND COLCHESTER COUNTIES, NOVA SCOTIA, CANADA

ABSTRACT

Spatially explicit ecosystem services modelling is on the rise, and one of the most common aspects in the field is the reliance on secondary data. To date, few studies involving ecosystem services mapping have integrated primary data into the modelling process. This study utilized the InVEST pollination model to investigate the impacts of primary data on ecosystem services mapping studies by using potential pollination services in Cumberland and Colchester counties in Nova Scotia, Canada as a case study. The model was run using two different sources of data to inform the floral resource component of the model. First, the model was run driven by proxies and approximate values gathered from the literature. The second iteration of the model utilized field based primary data to generate floral resource values. Results indicated that in no land uses or land cover classes did the value of floral resources drop with the addition of field based data. In all cases, the values either remained the same or increased, resulting in a 9.5% increase in the amount of land designated as high quality when the model was informed by field based primary data. Such discrepancies are important when considering the potential implications of ecosystem services mapping studies on policy. As a tool, ecosystem services mapping provides the opportunity to spatially evaluate the impact that different land use planning regimes could have on the supply and provision of various ecosystem services. However, as its popularity rises it is important to keep in mind the accuracy and resolution of the data used to inform the modelling process. Locally collected field based data enhances ecosystem services mapping and allows for more informed decision making.

2.1 INTRODUCTION

Ecosystem services are defined as the “conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life” (Daily 1997, p.3). The concept was first introduced as a mechanism for increasing public interest in biodiversity conservation in the late 1970s (Gomez-Baggethun et al., 2010), and became mainstreamed in the academic literature in the 1990s (Costanza & Daily, 1992; Daily, 1997; Gomez-Baggethun et al., 2010). As they became more mainstream, interest focused on attributing economic value to ecosystem services (e.g. Costanza et al., 1997; de Groot et al., 2002; Losey & Vaughan, 2006), a trend that intensified with the publication of the Millennium Ecosystem Assessment (MEA) in 2005. The MEA encouraged the integration of ecosystem services into policy making surrounding natural resource management (MEA, 2005), which led to the creation of markets and payment schemes for ecosystem services, for example, corporations paying for the planting of trees to offset their carbon emissions (Wunder, 2005). Although the valuation of ecosystem services is often promoted on the grounds that it is a decision-making tool, there is little evidence to indicate they are actually used to form policy making decisions (Laurans et al., 2013; Laurans & Mermet, 2014). It may be the case that the use of ecosystem service valuation in policy making is common practice, but is not well documented in the literature, or there may be a lack of interest or uptake amongst policy makers (Laurans et al., 2013).

Another approach to better incorporate ecosystem services into decision making is to be cognizant of the spatial aspects of service provision and delivery. Accounting for the spatial complexities of ecosystem services allows for the production of maps, which can be utilized by policy makers to identify key areas of ecosystem service supply and assess potential trade-offs in land use planning (Martinez-Harms et al., 2016; Martinez-Harms & Balvanera, 2012; Seppelt et al., 2011; Tallis & Polasky, 2009).

Although spatial modelling and mapping of ecosystem goods, such as timber and food, has a long history, the mapping of ecosystem *services* is a relatively new discipline. Despite this novelty, some common patterns and approaches have emerged. In particular, the use of proxies such as land cover to represent complex ecosystem processes, and the reliance on data from remote sensing sources (Martinez-Harms & Balvanera, 2012; Seppelt et al., 2011). The use of primary data is relatively uncommon in ecosystem services mapping. A review of 153 studies by Seppelt and colleagues (2011) found that less than 40% of studies involving ecosystem services utilize primary data sources, and only approximately 10% of the studies in the review incorporated locally collected field based data. Martinez-Harms and Balvanera's (2012) review of 41 studies mapping ecosystem services yielded similar results. Of those that utilized field data, most were focused on a single service over a relatively small and specific area, such as carbon storage in the soils of southeast Queensland, Australia (Collard & Zammit, 2006), the cultural services of deer hunting on farmlands in Michigan (Knoche & Lupi, 2007), or crop pollination services on Californian watermelon crops (Kremen et al., 2004).

Pollination is one of the most well studied ecosystem services, likely because of its perceived importance in food production (Breeze et al., 2011; Hanley et al., 2015; Klein et al., 2007; Potts et al., 2010; Ricketts et al., 2008). Although a variety of insects provide pollination services, such as beetles, flies and butterflies (Cutler et al., 2012), bees are the most familiar and most studied (Rader et al., 2016). Numerous studies have evaluated the potential of different landscapes to support bee pollinator populations, based on elements such as the influence of natural, semi-natural and anthropogenic landscapes (Garibaldi et al., 2004; Hines & Hendrix, 2005), nest site availability (Potts et al., 2003; Potts et al., 2005) and floral communities (Lazaro et al., 2008; Potts et al., 2003). Most of these studies have focused on the floral resources necessary to sustain populations of wild bees in agroecosystems (reviewed by Ricketts et al., 2008 and Kennedy et al., 2013).

The spatial process of pollination is quite well understood. Kremen and colleagues (2007) developed a conceptual model to describe the delivery of pollination services across agricultural landscapes. In the model, land management and disturbance regimes determined landscape patterns and structure, which in turn influence the pollinator and plant communities used to calculate the value of pollination services (Kremen et al., 2007). A simplified version of this model, based on landscape structure, pollinator communities, plant communities and the linkages between them was developed by Lonsdorf and colleagues (2009) to quantify and map relative pollinator abundances across agroecosystems (Figure 3). The model, which eventually became part of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software series of models, begins by locating appropriate nesting substrates and floral resources for the wild pollinators present in a system based on a land cover map. The amount and location of these resources is then used to generate a map of pollinator abundance (Lonsdorf et al., 2009).

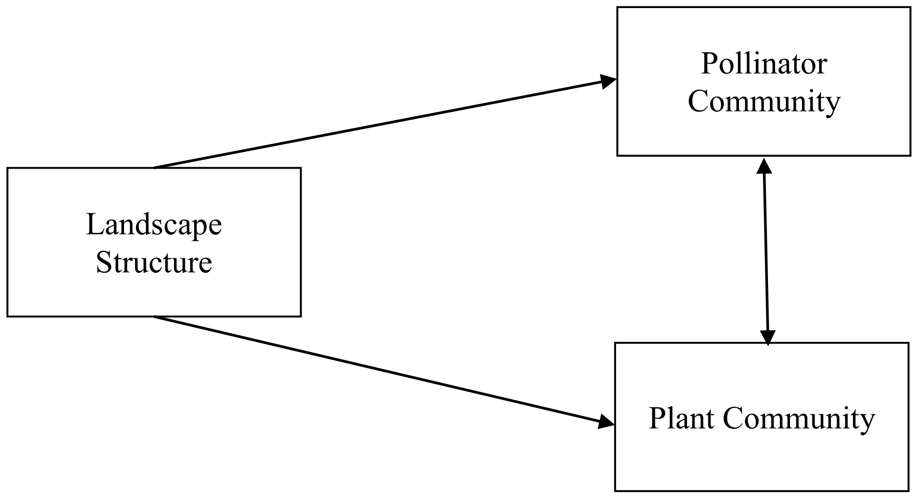

Figure 3. Simplied version of the Kremen et al. (2007) model which forms the basis of the model used by Lonsdorf et al. (2009) and subquently in the InVEST model. The spatial arrangement and quality of habitat patches produced by landscape structure influences both plant and pollinator communities (Adapted from Kremen et al. 2007).

In comparison to wild pollinators, relatively few studies have looked at the relationship between managed western honey bee (*Apis mellifera*) (hereafter referred to as honey bee) colonies and the landscapes that sustain them. Early work analyzed the spatial information encoded within the dance language of honey bees to better understand their foraging patterns (Haldane & Spurway, 1954; Schürch & Ratnieks, 2015). More recent studies have aimed to better understand the relationship between different land uses and land covers and their ability to support honey bees. For example, to assess the effects that various future land use scenarios in North Dakota will have on the ability of honey bee populations to be supported, Gallant and colleagues (2014) used land use and land cover data to identify potential apiaries sites across the state. Visual comparison between the model generated and the North Dakota Department of Agriculture apiary registry indicated that the model was broadly successful at identifying good apiary sites (Gallant et al. 2014). Although managed pollinator populations require some human intervention to persist, particularly in colder climates, the availability of floral resources is generally used to determine whether a landscape can support managed pollinators.

Using the potential supply of forage for managed honey bees in Cumberland and Colchester counties as a case study, here we aim to investigate the influence of primary data on ecosystem service mapping studies. Using the InVEST pollination model, we examined the differences in model output that occur when estimating floral resource values using proxies and approximate values found in the literature alone as compared to using locally collected primary data for a set of key model inputs. The discrepancies between the two outputs highlights the importance of calibrating models to local conditions using field based data. This is of importance when the model results will be used as a decision support tool in policy making.

2.2 METHODS

2.2.1 Study Area

This study was conducted in Cumberland and Colchester counties in the province of Nova Scotia, Canada (Figure 4). As is the case in much of the province, the landscape of Cumberland and Colchester is highly heterogeneous, a result of a long history of human modification. Pre-settlement, the region was densely forested, and is presently characterized by small farms separated by tracts of forests of varying density – a heterogeneous and complex landscape. The history of forest clearing has created an ideal landscape for blueberry production, and the two counties are responsible for the majority of Nova Scotia's lowbush blueberry (*Vaccinium angustifolium*) production, which, provincially, had a total farm gate value of $20.6 million (Cdn $) in 2010 (Agriculture and Agri-Food Canada 2012b). Lowbush blueberry is pollinator dependent, meaning that without pollinators, there will be no fruit. There therefore exists a deep connection between the blueberry and beekeeping industries (Eaton & Nams, 2012), and it is no surprise that beekeeping is well established in Cumberland and Colchester, with approximately 4,000 honey bee colonies being managed across the two counties.

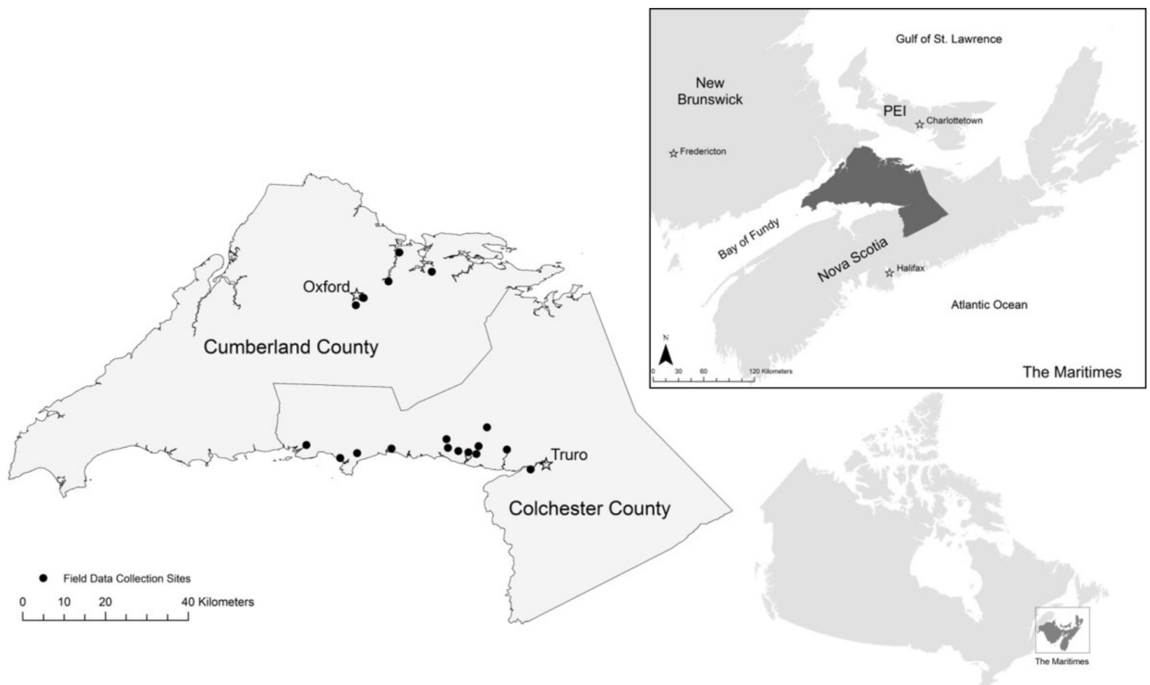

Figure 4. The study area, Cumberland and Colchester counties of Nova Scotia, Canada, including the sites where field data was collected in the summer of 2015.

Beekeeping in Cumberland and Colchester is typically done on smaller scales (beekeepers typically have fewer than one hundred colonies across multiple apiaries) in comparison to other regions of Nova Scotia, such as the Annapolis Valley where individual beekeepers may maintain hundreds of colonies. The smaller scale of operation made beekeepers in Cumberland and Colchester ideal participants for this study, as beekeepers were asked to identify apiary sites for field data collection, and collect data on colony productivity to be compared to landscape data, a process that could not be completed because of a low response rate. Beekeepers participated voluntarily, and were identified through the Nova Scotia Beekeepers Association (NSBA), a presentation at the NSBA Annual General Meeting in 2015 and through the social networks of participating beekeepers (snowball sampling).

2.2.2 InVEST Modelling

The InVEST suite of models was developed by the Natural Capital Project (http://www.naturalcapial project.org) as a tool to quantify, map and where possible, assign monetary value to ecosystem services to better incorporate values associated with natural capital into decision making (Sharp et al., 2016). The primary aim of the software is to provide information concerning how changes in ecosystems are likely to lead to changes in the flow of ecosystem services to people (Sharp et al., 2016). Currently, there are eighteen spatially explicit models in the InVEST suite used to map a variety of ecosystem services in terrestrial, freshwater and marine systems (Sharp et al., 2016). Among the suite of models is a crop pollination model, designed to model and map relative patterns of pollinator abundance and potential pollination service values across landscapes (Sharp et al., 2016).

The InVEST pollination model which was used in this study is GIS based and spatially explicit. It uses information concerning the potential availability of nesting sites and floral resources in combination with the flight range of the species in question to map an index of potential bee abundance across a given landscape (Sharp et al., 2016). The final output of the model is based on Equation 1, where N_j is the suitability for nesting of land use/land cover (LULC) type j, F_j is the relative amount of floral resources LULC type j produces, D_{mx} is the Euclidean distance between cells m and x and $\alpha\beta$ is the expected foraging distance of pollinator species β (Sharp et al., 2016).

$$P_{x\beta} = N_j \frac{\sum_{m=1}^{M} F_{jm} e^{\frac{-D_{mx}}{\propto\beta}}}{\sum_{m=1}^{M} e^{\frac{-D_{mx}}{\alpha\beta}}}$$

Equation 1. The equation the InVEST pollination model utilizes to produce the final index of potential pollinator abundance.

The crop pollination model focuses on wild bees as key pollinators, however there is nothing inherent in the model that means it cannot be used for managed honey bees. For honey bees to persist on the landscape, two things are necessary: a suitable spot to place hives and sufficient food proximal to their nesting site, both of which are accounted for in the InVEST pollination model (Kremen et al., 2007; Lonsdorf et al., 2009; Sharp et al., 2016).

2.2.3 Data Inputs

There are three primary inputs needed to run the InVEST pollination model: a table of pollinator species, a digital LULC map in raster format and a table of land cover attributes.

2.2.3.1 Table of Pollinator Species

In the InVEST pollination model, the table of pollinator species is used to inform the model of the nesting and foraging preferences of each species to be modelled (Sharp et al., 2016). Since only one species (honey bees) was modelled in this study, the table is fairly simple (Appendix I, Table S1.1).

2.2.3.2 LULC Raster

The LULC raster was generated using the Nova Scotia Forest Ecosystem Classification (FEC) (Nova Scotia Department of Natural Resources, 2007) and data provided in the Nova Scotia Topographic Geodatabase (Service Nova Scotia and Municipal Relations, 2009). Two alterations to the FEC were made. First, a sub-class was extracted from the forested classes based on their canopy cover; polygons with less than forty percent cover were separated from those that are more densely covered. There were two reasons for doing so. First, conversations with participating beekeepers indicated they prefer areas with some, but not a lot of tree cover as apiary sites. Secondly, a less dense canopy allows for more growth in the understory, including many shrubs and herbaceous species that provide a good source of pollen and/or nectar for honey bees (Cho et al., 2017; Latif & Blackburn, 2010; Lefrancois et al., 2008). The urban class in the FEC was also further sub-classified because it encapsulated a multitude of urban elements with varying potentials to host and support honey bee populations, such as buildings, parking lots, parks and backyards. Data concerning buildings, parking lots and parks, among other classes provided in the Nova Scotia Topographic Geodatabase were used to delineate urban areas into two new classes: one that has the potential to host honey bee colonies and provide floral resources (e.g. cemeteries, parks) and one incapable of doing so (e.g. buildings, parking lots). The altered FEC was then used to create a 10 x 10 m raster of the study area representing LULC.

2.2.3.3 Table of Land Cover Attributes

A table of honey bee-specific land cover attributes had to be constructed that characterized each LULC class in terms of nest site suitability and floral resource availability in the early and late summer. For this study, two tables of land cover attributes were used, one which populated the floral resource availability based on data found in the literature on the spatial analysis of bee floral resources (e.g. Lonsdorf et al., 2009) (Appendix I, Table S1.2), and one populated using primary data collected through the fieldwork process described in section 2.2.4 (Appendix I, Table S1.3). The nesting site potential values are the same in both tables and are based on identifying LULC classes with potential vehicle access, minimal tree cover and a likelihood to harbour a wide variety of herbaceous plants.

2.2.4 Primary Data Collection

Throughout the summer of 2015, detailed surveys were conducted of flowering vegetation within a one kilometer radius of the apiaries identified by participating beekeepers (Figure 4). A one kilometer radius was chosen because although honey bees are generally accepted to forage at distances greater than one kilometer (Beekman & Ratnieks, 2000; Visscher & Seeley, 1982), typical foraging distances are known to be shorter in complex landscapes (Steffan-Dewenter & Kuhn, 2003), as is the case in Cumberland and Colchester counties. The high degree of landscape heterogeneity found throughout the study area prompted us to reduce the assumed foraging distance and thus the area over which data were collected.

At each apiary site identified by beekeepers, four radial, one kilometre transects were laid out beginning at the honey bee colonies, using satellite imagery obtained from Google Earth. Transects were laid out to target open areas, but forested areas within sites were alsovisited to get a sense of the species present (Figure 5). Along each transect, up to twenty 3m x 3m vegetation plots were established. Transects were sometimes terminated before one kilometer because of impassable bodies of water (see the white transect in Figure 5).

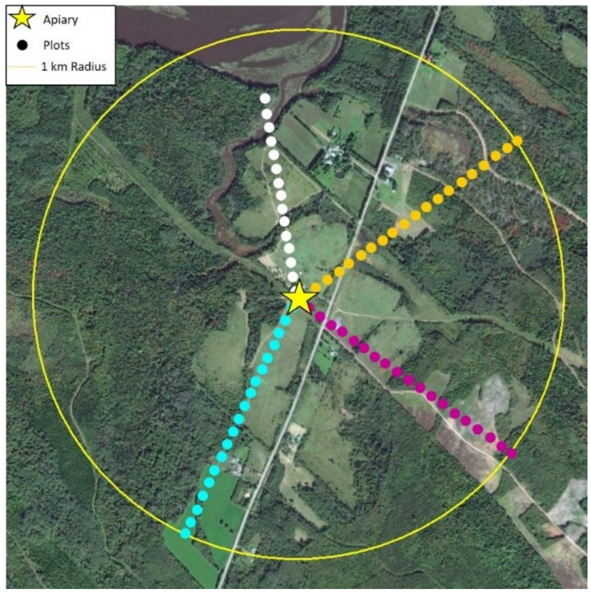

Figure 5. The layout of plots (circles) along transects surrounding an apiary within a 1 km radius.

In each plot, all species of flowering plants were identified and their percentage cover recorded, using a modified Daubenmire (1959) method with ten classes (Table 2). Two observers carried out the vegetation surveys for this study. To ensure consistency between observers, identical training was provided, and the two conducted ‘calibrating transects’, in which both observers evaluated the same plots, every ten transects. Geotagged photographs were taken using a Garmin Oregon 750™ of every plot which were reviewed at random to ensure consistency between observers in their cover class determinations. Each site was surveyed twice over the growing season, once in the early summer (June 5 to July 10) to capture early blooming species, such as willow (*Salix sp.*) and dandelion (*Taraxacum officinale*), and again later in the season (July 30 to August 25) to capture late flowering species such as clover (*Melilotus officinalis*) and goldenrod

(*Solidago sp.*). When unfamiliar plants were encountered, a sample and photograph were taken and the species was identified in the lab.

Table 2. Modified Daubenmire method for evaluating vegetation percentage cover. The cover class codes are shown with their corresponding percentage cover ranges.

Cover Class	Percentage Cover
0	0%
1	0-5%
2	5-10%
3	10-25%
4	25-33%
5	33-50%
6	50-66%
7	66-75%
8	75-90%
9	90-95%
10	95-100%

After field work, the data were converted to digital format in Excel and used to generate landscape forage quality scores for each plot in the study. The scores were based on the quality and quantity of forage available for honey bees over a given area and were calculated through a two-stage process. Initially, each species present in each plot was assigned two scores, one based on its percentage cover within a plot (as recorded in the field), and one based on the species' utility to honey bees. The utility scores were derived from the Canadian Pollination Initiative's electronic floral calendar (NSERC-CANPOLIN, 2013). The products of the percent cover and utility scores for each species in a plot were then summed to arrive at an overall forage quality score for each plot. A more detailed description of how these scores were calculated is found in Appendix II.

For each LULC class, an average of forage quality from each visit to that LULC class was calculated. InVEST is based on relative values, therefore each average was calculated as a percentage of the highest score and entered into the table of land cover attributes. Classes in which no field data were collected (e.g. plantation, beach) were either given a value of 0 or a value of a justifiably similar class (e.g. the various classes of wetlands were all assigned the same value) (Appendix I Table S1.3).

2.2.5 Running the Model

The InVEST pollination model was run to generate a relative index of pollinator abundance (IOA) on a scale of 0 to 1 for each 10 x 10 m cell of the LULC raster. The model was run twice, once with the table of land cover attributes informed by the values found in the literature (Appendix I, Table S1.2), and once informed by the data collected through fieldwork (Appendix I, Table S1.3).

2.2.6 Analyzing Model Results

Results of both the secondary and primary data driven InVEST models were grouped based on index of abundance to determine the amount of land designated as high, medium and low quality. The two resulting rasters were also subtracted to quantify the difference between the two models.

2.3 RESULTS

Recruitment efforts described in section 2.2.1 resulted in eighteen apiaries being included in this study (Figure 4). Two parallel analytic processes were conducted. Both utilized the InVEST model, but the floral resource availability in one iteration was based on values found in the literature, and in the other the field based data were used. This process and the results are illustrated for both the secondary and primary data driven iterations of the model (Figure 6).

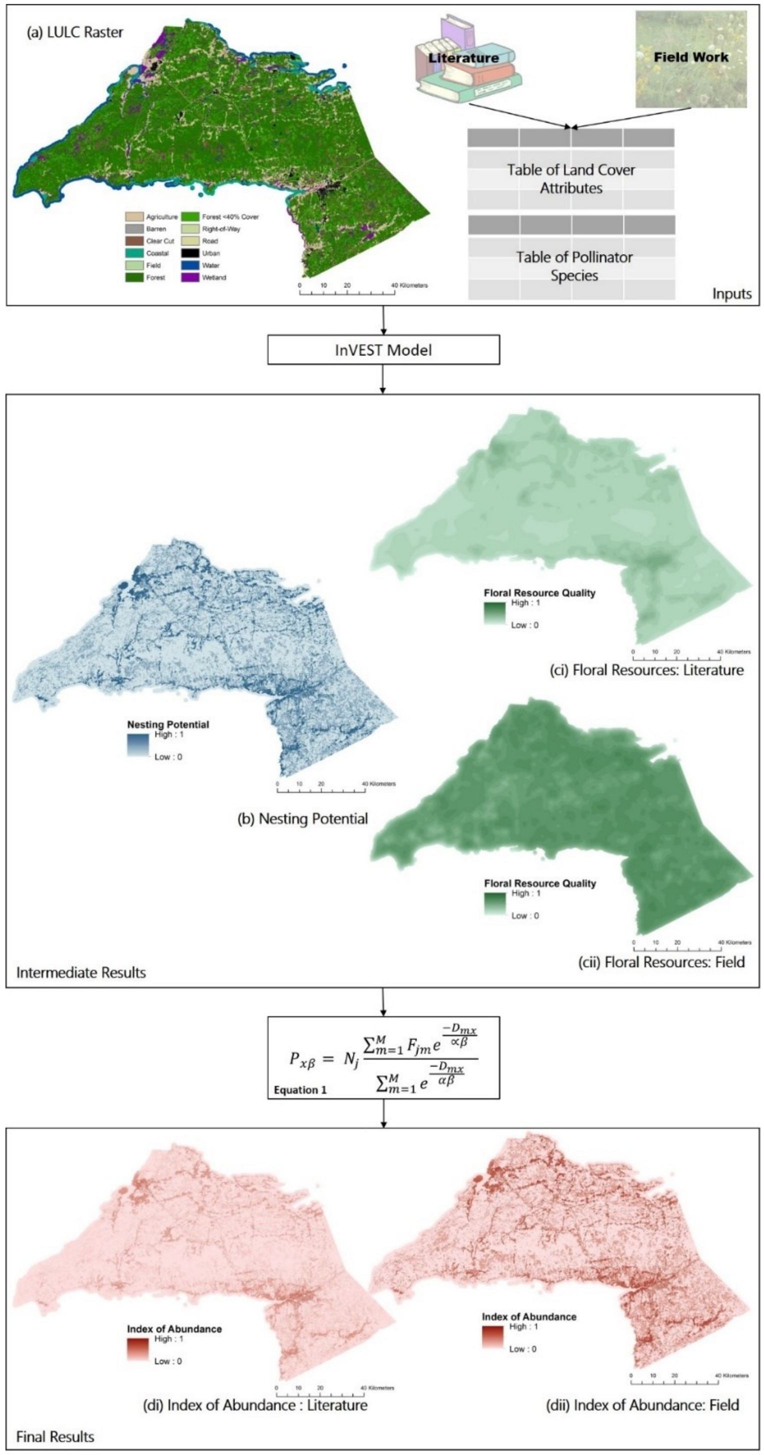

Figure 6. Results of the InVEST modelling for the potential abundance of honey bees in Cumberland and Colchester counties of Nova Scotia. The model uses an LULC raster (a), a table of land cover attributes (one iteration was informed by the literature and one was informed by field work) and a table of pollinator species as inputs to derive maps of nesting suitability (b) and floral resources (c). Combining (b) and (c) using Equation 1 generates an index of potential pollinator abundance on the landscape (d). Two iterations of the model were run, one informed by proxies and approximate values from the literature (i) and the other by field work (ii).

Visual inspection of Figure 6 indicates higher levels of floral resource availability, and therefore higher IOA when the model is informed by primary data (Figure 6cii and 6dii) compared to secondary data (Figure 6ci and 6di). Of particular note are the differences in floral resource values recorded for the forested classes, both with more than 40% cover and less than 40% cover, wetland classes and agricultural classes (Appendix I, Tables S1.2 and S1.3). Not surprisingly given the heterogeneity of the landscape, the areas of high potential abundance are fragmented and distributed across both Cumberland and Colchester counties. This visual inspection was further confirmed through a raster subtraction which indicated that in every landscape across the study area the field data driven model produced an equal or higher index of abundance than the literature driven model (Figure 7).

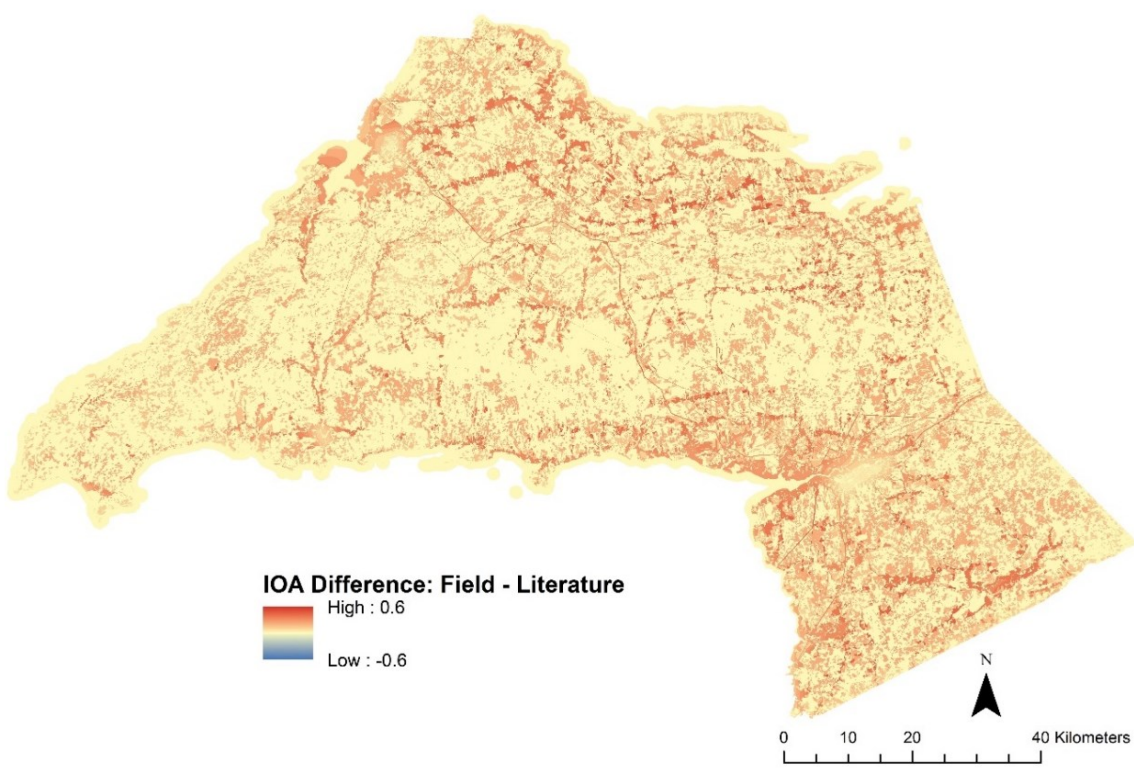

Figure 7. Results of a subtraction between the results of the field based InVEST model and the results of the literature driven iteration

To better understand the scale of increase in pollinator abundance between the secondary and primary data driven models, we compared the amount of land that falls into different levels of IOA generated by the analysis informed by primary and secondary data (Figure 8). Results of the primary data driven iteration of the model indicate there is an increased potential for the study area to support honey bees than when the model is informed by established values in the literature. The field data driven model produces a 9.5% increase in the amount of the study area that could be considered to have high potential to support honey bees (IOA >0.5). It should be noted that the amount of land falling into the lowest category (IOA 0 – 0.05), with no potential to support honey bees is almost the same in both iterations of the model (in both cases 63.0% of the study area). Therefore, the increase in area with a high IOA is because the floral resource quality of marginal lands (especially in forested, wetland and agricultural classes) in the literature based iteration are improved based on the data derived from field work.

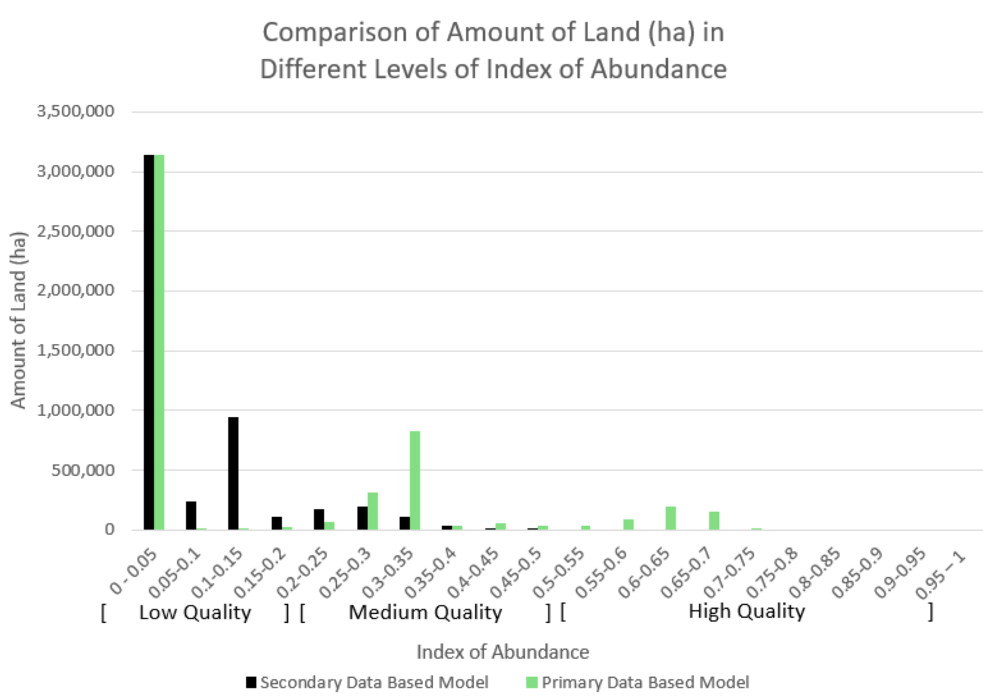

Figure 8. Comparison of the amount of land in different levels of the Index of Abundance generated by the analysis informed by secondary (literature) and primary (field) data.

2.4 DISCUSSION

2.4.1 Source of Difference in the Models

Since both the primary and secondary data driven models had the same values for nesting site potential, any difference in output are entirely attributable to the floral resource values. The largest changes in floral resource potential were found in the forested classes. Floral resource values for forested classes with more than 40% cover increased from 0.4/0.0 (early summer/late summer) in the literature based iteration of the model to 0.42/0.85 in the primary data iteration (Appendix I, Tables S1.2 and S1.3). Forested classes with less than 40% cover increased from 0.4/0 to 0.64/1 (Appendix I, Tables S1.2 and S1.3). This difference is likely because the literature driven values focus solely on the floral resource potential of the trees present. Trees provide floral resources for honey bees only in the spring and early summer (NSERC-CANPOLIN, 2013). However, this neglects the understory of the forest, which despite comprising less than one percent of the total biomass of forest ecosystems, accounts for upwards of ninety percent of the floristic diversity of the system, including many species that provide good forage for honey bees throughout the growing season, such as raspberry (*Rubus idaeus*), wild rose (*Rosa accicularis*), and aster (*Aster sp.*) (Cho et al., 2017; Gilliam, 2007; Proctor et al., 2012). The presence of a forest understory is limited by the amount of light that reaches the forest floor, and therefore forests with less dense canopies will be more likely to support an understory with the rich floristic diversity conducive to supporting honey bee populations (Cho et al., 2017; Latif & Blackburn, 2010; Lefrancois et al., 2008). As such, the increase of floral resources in the forested classes is likely to be at the lower densities of canopy closure.

The potential of wetlands to provide floral resources also appears to have been underestimated in the literature driven model. The early/late season floral resource value of wetlands in the literature driven model was 0.2/0.2 and in the field driven model the values were 0.38/0.6 (Appendix I, Table S1.2 and S1.3). There is a lack of literature on the value of wetlands as forage for honey bees, but studies that have looked at the relationship between bees and the landscapes on which they depend have consistently attributed low value to wetlands (e.g. Lonsdorf et al., 2009; Sponsler & Johnson, 2015). In the case of this study, the value of wetlands in the field data appears to be attributed to the presence of dense patches of goldenrod, common vetch (*Vicia sativa*) and aster on lands designated as wetlands in the FEC, but were not noted as wetland during the field data collection process. This disparity may be caused by issues within the FEC when it comes to identification of wetlands. Numerous authors have noted the difficulties in identifying wetlands through image classification, and thus it is reasonable to assume there are accuracy issues with the wetland classification classes in this dataset (Hogg & Todd, 2007; Sader et al., 1995). The data in the FEC is also nearly ten years old, meaning it is also possible that some of the parcels designated as wetland may have undergone some form of land cover/land use change, either through natural or anthropogenic means, resulting in an LULC class change on the ground which is not recorded in the dataset. This source of error in the model may have resulted in an overestimation of the value of wetlands. However, it should be noted that wetlands constitute only a small portion of the study area (5.2%), so the impacts of this overestimation on the results should be minimal.

The early/late season value of agricultural land as a source of floral resource for honey bees was also noticeably higher in the primary data driven model compared to the secondary data based iteration (0.68/0.85 compared to 0.5/0.5 respectively; Appendix I, Table S1.3 and S1.2). This may be attributed to the age of the data used (2007) and the ongoing trend of land abandonment of some historically cultivated agricultural land in the study area (Devanney & Reinhardt, 2011). During the field data collection component of the study it was observed that numerous plots of land designated as agriculture in the FEC were in fact no longer in production. Vegetation succession patterns on abandoned farmland follows a general pattern of colonization by spontaneous vegetation, beginning with an herbaceous phase, moving to a shrub dominated phase and culminating in a forested phase (Benjamin et al., 2005; Cramer et al., 2007; Smith et al., 1993). The abandoned parcels of agricultural land of concern in this study have likely been out of cultivation for less than ten years, meaning they are characterized by herbaceous species, particularly weedy, often exotic species, and a few small trees (Benjamin et al., 2005; Cramer et al., 2007; Drinkwater, 1957). The increase in floral diversity, particularly that of weedy species, has a positive impact on the ability of a parcel of land to support honey bees (Alaux et al., 2010; Di Pasquale et al., 2013; Requier et al., 2015). Thus, explaining the increase in floral resource quality of agricultural classes.

2.4.2 Fine Scale Ecological Conditions Lead to the Provision of Ecosystem Services

Broad scale, landscape level processes are important for the provision and management of ecosystem services (Daily, 2000; Steffan-Dewenter et al., 2002). However, it is important to understand and account for what is occurring on the finer scale to fully understand the biophysical conditions required for ecosystem service provision. Field based approaches to mapping ecosystem services at a scale reflective of the biophysical underpinnings of the service provides a finer scale understanding of how the processes responsible for the delivery of services operate across landscapes (Kremen, 2005; Kremen & Ostfeld, 2005; Martinez-Harms et al., 2016; Schroter et al., 2014).

In the case of pollination, a small-scale approach is of value because the provision of pollination services is reliant on the distribution of floral resources at fine resolutions not captured in typical remotely sensed imagery. Moreover, temporal granularity matters. Many bees, including honey bees, are active for the entire growing season, thus temporal diversity in floral resources spanning across the entire growing season is required (Requier et al., 2015), a factor which may be difficult to capture with remotely sensed data. The fine scale nature of the biophysical underpinnings of pollination, make it an ideal ecosystem service to study using boots-on-the-ground primary data collection. Results of this study indicate it is important to match the scale of data used to inform the modelling process with the scale at which key biophysical processes occur to provide the service. Therefore, it is unlikely that pollination is the only ecosystem service in which the incorporation of fine resolution data is important. To map any ecosystem service which occurs at small scales, such as soil nutrient cycling and crop production, the use of fine resolution data is likely critical.

Evaluating the species and seasonal diversity of the floral resources required to sustain pollinator populations is difficult to do using remotely sensed data. While estimates can be made as to the floral resource potential of different land classes, these relationships are not well documented in the literature, and have only been established for a handful of ecosystems around the world (e.g. coffee farms in Costa Rica, the agricultural regions of central California and the agricultural regions of New Jersey and

Pennsylvania used in Lonsdorf et al., 2009). The use of locally collected primary data, as presented in this study, highlights the shortfalls of using an entirely literature based approach and the disparities between such estimates and what is on the ground. Basing ecosystem service mapping studies on estimates of service levels from other regions is insufficient, and it is therefore important to collect data locally for use in model building (Martinez-Harms et al, 2016).

2.4.3 Better Data for Better Policy Making

The publication of the MEA in 2005 resulted in a lot of attention being placed on the integration of ecosystem services into policy making surrounding natural resource management (MEA, 2005). However, a clear framework as to how policy makers can incorporate ecosystem services into their decision making is lacking (de Groot et al., 2010). There are numerous challenges that must be addressed before a clear way forward emerges, such as clarifying the relationship between landscapes and the services they provide, how the dynamic nature of landscapes and land use influences ecosystem service provision and how to spatially define ecosystem services (de Groot et al., 2010). The rise of ecosystem services mapping has allowed for a better understanding of the relationship between landscapes and how different land use planning regimes could affect the supply and provision of ecosystem services (Martinez-Harms et al., 2016; Martinez-Harms & Balvanera, 2012; Seppelt et al., 2011).

For the use of ecosystem services maps to become more common place as a decision support tool, it is important to consider the source of the data used to inform the modelling process. As was demonstrated in this study, the incorporation of locally collected primary data can have significant influence on the output of the modelling process. Whenever possible it is essential to collect data at the local scale for use in ecosystem services mapping as this will allow for more informed decision making.

2.5 CONCLUSION

This study used both a primary and secondary data driven approach to model the potential for managed honey bees to persist on landscapes in Cumberland and Colchester counties as a result of floristic resources that provide forage. Results indicate that the ability to understand the system and predict potential abundance of honey bees across the study area was enhanced using primary data. The disparities between the two models indicates the importance of the inclusion of primary data in ecosystem services mapping studies, and matching the scale of data collection to the scale of the biophysical processes driving the service.

CHAPTER 3:
OPPORTUNITIES FOR EXPANDING NOVA SCOTIA'S MANAGED POLLINATION SERVICES CAPACITY

ABSTRACT

The beekeeping industry in Nova Scotia, Canada is currently at a crossroads. It is under immense pressure to provide more colonies to the province's blueberry producers, who require tens of thousands of honey bee (*Apis mellifera*) colonies to pollinate their fields. Currently, there are not enough colonies in the province to meet their demand, but access to colonies from elsewhere is restricted through the Nova Scotia *Bee Industry Act*, which prohibits the importation of colonies. Permission for temporary importation has been granted over the past three growing seasons, but blueberry producers want the government to eliminate the ban completely. This, however, has been met with resistance from local beekeepers who raise concerns over cheap colonies and diseases. Building on Chapter 2, in this study we apply the InVEST pollination model to all of Nova Scotia to identify areas of the province with high potential to support honey bee colonies. Comparing the results of the InVEST modelling to the current distribution of colonies at the county level, we identify underutilized areas of the province. Results indicate that there are likely significant amounts of underutilized honey bee habitat in Colchester, Pictou and Inverness counties. Therefore, the pollination demands of the blueberry producers can likely be met domestically, and thus the beekeeping industry in Nova Scotia should be given support to grow.

3.1 INTRODUCTION

Western honey bees (*Apis mellifera*) have garnered a lot of attention over the last decade because of their perceived status as a critical pollinator for crops, and recent patterns of increased rates of colony loss around the world (Neumann & Carreck, 2010; Potts et al., 2010). In the Canadian province of Nova Scotia, about 400 beekeepers collectively manage approximately 25,300 honey bee colonies (Sproule, 2016). The majority of these colonies are based for most of the year in Kings and Hants counties, but a substantial portion of the sector is based in adjacent Annapolis, Digby, Cumberland and Colchester counties (Figure 9). In 2014, the beekeeping industry in Nova Scotia had a total reported sector-wide income of approximately $4.6 million (Cdn $) (Darrach &

Page, 2015). While honey is an important commodity, it only accounts for approximately one quarter of the industry's total value in Nova Scotia (Darrach & Page, 2015). The majority of the sector's income ($3 million) comes from renting out colonies to provide pollination services to agricultural crops, such as lowbush blueberry (*Vaccinium angustifolium*) and apple (*Malus sp.*). Importantly, demand for colonies to provide pollination services is increasing from the agricultural sector, particularly from the province's commercial blueberry industry, the fifth most valuable agricultural sector in the province in 2014 (Thibodeau, 2014) and one that has been expanding. Between 2006 and 2011, the total hectarage in blueberry production in Nova Scotia grew 16.7% (Agriculture and Agri-Food Canada, 2012b), while farm-gate value decreased from just over $43 million to just over $22 million (Cdn $) over the same time period (Statistics Canada, 2017).

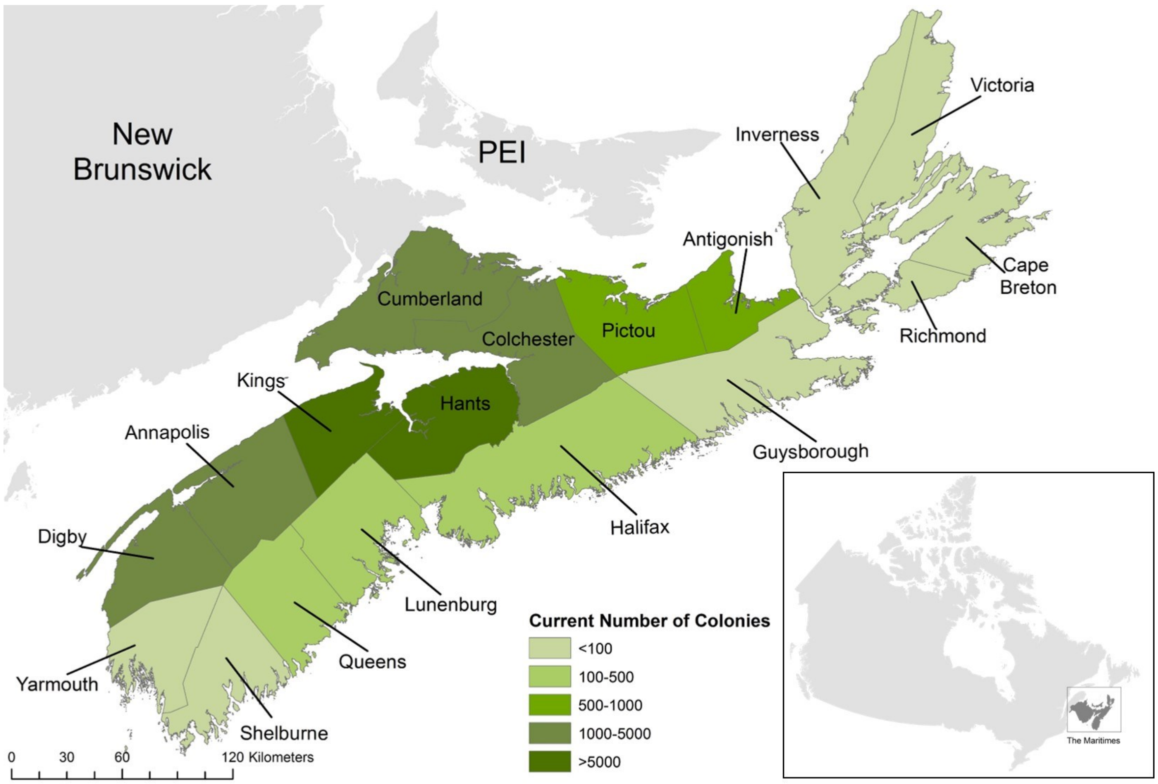

Figure 9. Number of honey bee colonies currently managed by county in Nova Scotia, Canada

The increase in blueberry hectarage is coupled with an increase in demand for pollination services from managed honey bee colonies, a practice, which although common, may not be as effective as many producers believe. Although the morphology of lowbush blueberry flowers is well adapted for pollination by bees (Buchmann, 1983; Javorek et al., 2002; Jesson et al., 2014), there is debate as to whether managed or wild pollinators are best suited to provide pollination services at commercial scales (Buchmann, 1996; Steffan-Dewenter & Tscharntke, 2000). On a bee-to-bee basis many wild pollinators, including common eastern bumble bees (*Bombus impatiens*), are better pollinators than honey bees in terms of efficiency (per visit pollen deposition) and visit rate (the number of flower visits per minute) (Rader et al., 2009). In the case of lowbush blueberry, it has been estimated that honey bees need to visit a flower four times to deposit the same amount of pollen that a bumble bee can in a single visit (Javorek et al., 2002). Despite this disadvantage, the sheer number of honey bees in a single colony (10,000 – 40,000) makes them an attractive choice for large scale, commercial pollination (Javorek et al., 2002; Klein et al., 2007; Rader et al., 2009). The ability to manage large numbers of individuals in a single place has resulted in the majority of Nova Scotia's blueberry producers stocking their fields with commercial honey bee colonies for a period of two to three weeks at the height of the bloom period (Eaton & Nams, 2012; Javorek et al., 2002), and it is reasonable to assume that in the near future this demand will not subside.

In 2014, approximately 20,000 of Nova Scotia's 25,300 colonies were hired by the blueberry sector for pollination purposes (NSBA, 2015). However, based on the coarse recommended stocking rate of four colonies per hectare (Eaton & Nams, 2012), 20,000 colonies are not enough for the province's ~7,500 hectares of commercial blueberry fields (in total there are about twice this hectarage of blueberry fields in Nova Scotia, but each field is managed on a two-year cycle in which a fruit production year, requiring pollination services, is proceeded by a sprout year (Ismail & Hanson, 1982)). There is thus a deficit of managed pollination service capacity in the province, which has increased the cost of hive rentals to ~$150 (Cdn $) per colony (NSBA, 2015). Given the shortage of managed pollinator colonies in the province, blueberry producers have looked to rent colonies from outside Nova Scotia (primarily from the Niagara region of Ontario) to meet their demand since 2014 (Melathopoulos, 2016). However, bringing honey bee colonies into Nova Scotia requires special permits from the provincial government, as the border has been closed to the free movement of colonies since the early 1990s under the Nova Scotia *Bee Industry Act* c.3 2005. Despite the historic constraints on the movement of colonies into the province, in each of the 2014 – 2016 seasons, 5,000 colonies were temporarily brought into Nova Scotia under special permits for use during the blueberry bloom season (Melathopoulos, 2016).

The deficit of managed pollination services in the province, coupled with the projected growth of the blueberry industry, has initiated a conversation about whether or not to open the provincial border to the free movement of colonies. There is concern, however, that opening the border would be detrimental to Nova Scotia's beekeeping industry. Concerns have been raised that an open border would drive down the price of colony rentals for pollination services, negatively impacting the $3 million (Cdn $) portion of beekeeping revenues derived from renting out colonies. Opening the border also risks introducing pests to Nova Scotia's colonies. Specifically, there are concerns that the highly invasive small hive beetle (*Aethina tumida*) could become established in the province, facilitated by the movement of hives for pollination services from other parts of Canada where the pest is already established (e.g. southern Ontario) (Melathopoulos, 2016).

Those concerned with an open border would prefer to see the local beekeeping industry grow to meet the pollination demands of the blueberry industry. Although the economic incentives for the local honey bee industry to grow are clear, it is less clear if such growth is biologically feasible based on current floral resource availability in the province. It is impractical to encourage the industry to expand if it will increase the reliance of colonies on syrup and other food supplements. Such supplements can aid in colony productivity, but they do not provide the same nutritional quality as natural pollen and nectar (Pedersen & Omhlt, 1993), nor are they free, and can be expensive. Thus, it is imperative to know if the province's floral resources can support more colonies year-round in terms of their abundance, density and seasonal diversity.

The intent of this study is to identify areas of Nova Scotia where an increase in colonies could be supported. Applying the methodology of Chapter 2 to all of Nova Scotia, we determined the spatial distribution of lands suitable for honey bees across the province. Comparing the distribution of attainable floral resources with the current distribution of colonies at a county level allowed for the identification of areas of the province currently being underutilized by the beekeeping sector.

3.2 METHODS

Following broadly similar work undertaken by Gallant and colleagues in North Dakota (2014) and Sponsler and Johnson in Ohio (2015), we tackled the identification of potentially underutilized honey bee floral resources across Nova Scotia using geospatial techniques. In contrast to the analyses undertaken by Gallant and colleagues (2014) and Sponsler and Johnson (2015), who in both cases relied exclusively on secondary data sources throughout their analyses, here we combine secondary sources with the insight derived from field based, primary data regarding the abundance, diversity and quality of floral resources in Nova Scotia landscapes.

We began by first identifying and quantitatively characterizing the floral resources surrounding eighteen active apiary sites in Nova Scotia in the early and late summer (Chapter 2). Data from these sites were compiled to attribute floral resource quality scores for different land use and land cover (LULC) classes across Nova Scotia, a process described in full in Chapter 2. As indicated by the comparative analysis in Chapter 2, it is preferable to take a locally collected, field data driven approach to spatially model ecosystem services, particularly when the phenomenon of interest (here, flowering plants) occurs at scales far finer than are readily assessed using standard remote-sensing techniques. Therefore, this study applied the primary data approach of the analysis performed in Chapter 2 to the entire province of Nova Scotia.

3.2.1 Study Area

This study was conducted in the Atlantic Canadian province of Nova Scotia (Figure 9). Nova Scotia's landscape pre-European contact was largely composed of dense forested communities dominated by white spruce (*Picea glauca*), balsam fir (*Abies balamea*), and red pine (*Pinus resinosa*) (Davis & Browne, 1996, p. 186). Such communities were not likely to be conducive to supporting honey bees (though we recognize there were no honey bees in Nova Scotia until after European arrival) or other pollinators, except in areas subject to seasonal or occasional disruption through natural processes (e.g. forest fires) or disturbance by First Nations Peoples. These sources and intensity of forest cover disruption were amplified substantially following European arrival in Nova Scotia. Forests began to be heavily cleared, coastal wetlands drained and agricultural settlements were developed (Davis & Browne, 1996 p. 311-313). Such activities resulted in open areas, such as clear cuts and pasture, that were much more favourable for pollinators, including honey bees. Three centuries of intense landscape modification by humans has resulted in a patchwork of land covers and land uses across much of the province. This long term modification coupled with the more recent trend of farmland abandonment and subsequent infill with early successional plants (Davis & Browne, 1996, p.190; Devanney, 2010), has resulted in Nova Scotia becoming a much more favourable environment for honey bees and other pollinators.

The field data used to inform the model were collected in four of Nova Scotia's nine ecoregions (Northumberland and Bras D'Or, Nova Scotia Uplands and Valley, Fundy Shore and Central Lowlands) (Figure 10). Though primary field data used to inform this analysis are drawn from only four ecoregions in central Nova Scotia, we are confident that insight from our eighteen sites are more broadly applicable given the relatively small size of the province and that the LULC classes used have similar vegetation structures across the province.

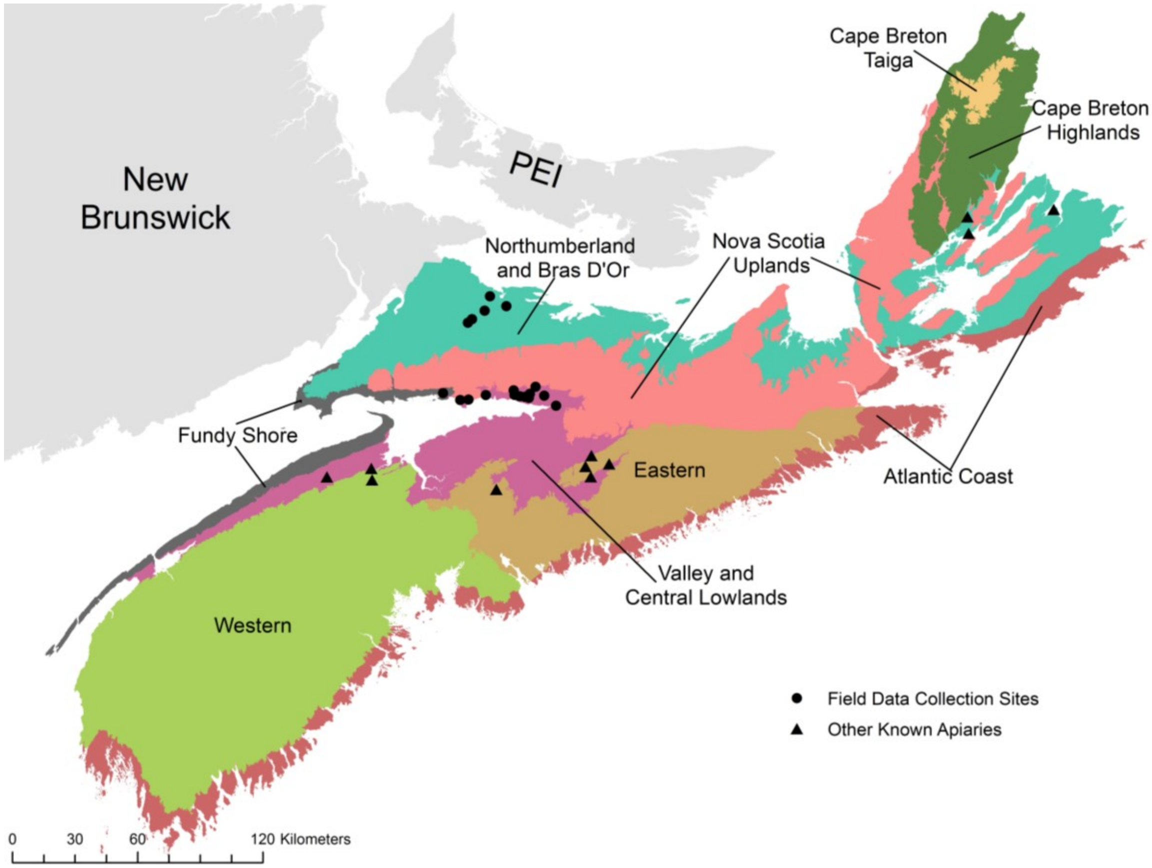

Figure 10. Ecoregions of Nova Scotia. Field data collected to inform the analysis of floral resources surrounding apiary sites for this study were collected at the 19 indicated sites in the Northumberland/Bras D'Or, Nova Scotia Uplands and Valley, Fundy Shore and Central Lowlands ecoregions and applied to the entire province. Other known apiary sites, which were used in the model validation process are also indicated.

3.2.2 InVEST Modelling

This study utilized the pollination model from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of models, a set of models designed to quantify, map, and where desired and supportable by data, assign monetary value to ecosystem services to better incorporate values associated with natural capital into decision making (Sharp et al., 2016). The InVEST pollination model is GIS based and spatially explicit, using information concerning the availability of nesting sites and floral resources in combination with the flight range of the species of interest to map an index of potential bee abundance across a given landscape (Sharp et al., 2016). The cell-based output of the model is driven by Equation 1, where N_j is the suitability for nesting of LULC type *j*, F_j is the relative amount of floral resources LULC type *j* produces, D_{mx} is the Euclidean distance between cells *m* and *x* and αβ is the expected foraging distance of pollinator species β (Sharp et al., 2016). Although the model was designed to focus on wild bees, there is nothing inherent to the model that means it cannot be used for assessing habitat suitability of managed honey bees. Although some human intervention occurs for honey bees to persist on the landscape their primary requirements for survival are a suitable spot to nest (place hives) and sufficient food sources in proximity to the nesting sites, both of which are accounted for in the InVEST model (Kremen et al., 2007; Lonsdorf et al., 2009; Sharp et al., 2016).

$$P_{x\beta} = N_j \frac{\sum_{m=1}^{M} F_{jm} e^{\frac{-D_{mx}}{\propto\beta}}}{\sum_{m=1}^{M} e^{\frac{-D_{mx}}{\alpha\beta}}}$$

Equation 1. The equation the InVEST pollination model utilizes to produce the final index of potential pollinator abundance.

3.2.3 Data Inputs

The InVEST pollination model requires three primary inputs: a table of pollinator species, a digital LULC map in raster format and a table of land cover attributes, which contains information on the ability of each LULC class to host colonies and the relative quality of their floral resources at different points of the growing season.

3.2.3.1 Table of Pollinator Species

The table of pollinator species informs the model of the nesting and foraging preferences of each species to be modelled (Sharp et al., 2016). In this study, there is only one species (honey bee) involved, so the table is fairly simple (Appendix III, Table S 3.1).

3.2.3.2 LULC Raster and Table of Land Cover Attributes

Unlike the prior analysis presented in Chapter 2, which sought only to assess the value of incorporating field-level data into landscape scale ecological modelling, here we are interested in understanding not only the extent of suitable habitat available, but the extent of suitable habitat that is practically accessible. Therefore, this study began with the LULC raster and table of land cover attributes used in Chapter 2, but then altered the nesting site potential scores in two key ways (described below) to account for whether or not a site is accessible to beekeepers and thus suitable to host honey bee colonies. The floral resource values used were derived from the primary data driven model in Chapter 2. The altered land classification was then used to create a 25 x 25 m raster of the study area (the entire province of Nova Scotia), representing LULC.

The first issue of accessibility is road access. Unlike wild pollinators, managed honey bees require human intervention to persist on the landscape with the cool climate and long winter conditions that exist in Nova Scotia. The necessity of human access to apiary sites makes distance to roads a useful proxy for determining nest site suitability. Through consultation with beekeepers in the study area, it was determined that beekeepers generally do not place their apiaries more than 100 m from a road. Therefore, a 100 m buffer was placed around all of the roads in the province, as defined by the Nova Scotia roads database. All land beyond 100 m of a road was given a nesting site potential score of 0. Lands lying within 100 m were given the original nesting site potential scores as assessed in Chapter 2 (Appendix III, Table S 3.2).

The second issue of accessibility is human population density. Conversations with participating beekeepers indicated that beekeepers do not typically place apiary sites in areas with a high population density, though rural suburban settings are often utilized for beekeeping. Based on this, parcels of land with a population density of more than 100 people per square kilometer (as indicated by Statistics Canada's 2006 Census data), a density that eliminates urban centres such as Halifax and Truro from consideration as apiary sites, but still allows for rural suburban areas to remain within the model, were given a nesting potential score of 0. Those lands with fewer than 100 people per square kilometer were given the same nesting site potential scores, based on minimal tree cover, as presented in Chapter 2 (Appendix III, Table S 3.2).

3.2.4 Running the Model

The InVEST pollination model was run to generate a relative index of pollinator abundance (IOA) on a scale of 0 to 1 for each 25 x 25 m cell of the LULC raster. The model was run informed by locally collected field data because, as indicated in Chapter 2, such methods offer important insight that literature based data driven models are often at too coarse of a scale to capture.

3.2.5 Model Validation

Based on the assumption that beekeepers place their colonies on sites well suited for honey bees, the model was validated using the location of twenty-nine known apiaries (the eighteen used in the original mapping of landscape attributes plus eleven more whose locations were revealed to us through subsequent interaction with beekeepers; Figure 10). The location of apiaries was provided voluntarily by beekeepers because, unlike in other jurisdictions, beekeepers in Nova Scotia are not required to register the location of their apiaries. Those apiaries that were involved in the field data collection process (see Chapter 2) were visited and the co-ordinates of the location recorded. The other eleven apiaries used to validate the model were not visited, but located through communications with beekeepers, and thereby making the co-ordinates approximations.

3.2.6 Identifying Opportunities for Expansion in the Nova Scotia Beekeeping Sector

The most detailed distribution data on honey bee colonies across Nova Scotia is at the county level. Therefore, we can only identify opportunities for expansion at the same scale. Upon completion of the modelling process, we compared the amount of land designated as low quality (IOA < 0.25), medium quality (IOA 0.25 – 0.5) and high quality (IOA > 0.5) in each county of Nova Scotia to the number of colonies currently being kept there. This comparison allowed for counties with significant amounts of underutilized high quality land to be identified.

3.3 RESULTS

3.3.1 Modeling Results

The process and results generated by the InVEST modelling are illustrated in Figure 11.

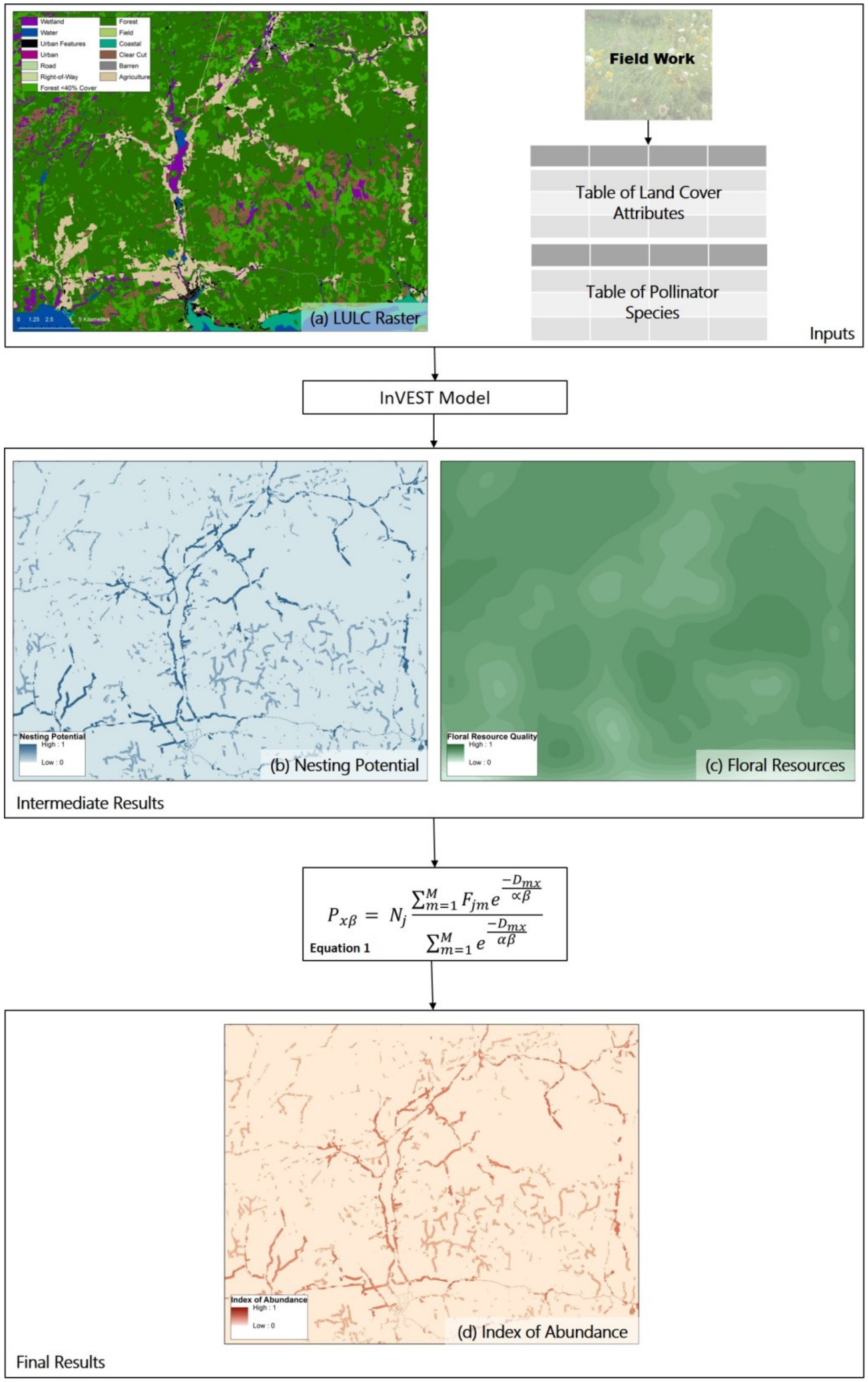

Figure 11. Sample results of InVEST modelling for the potential abundance of honey bees. The model uses a land use/land cover raster (a), a table of land cover attributes and a table of pollinator species as inputs to derive maps of nesting suitability (b) and floral resources (c). Combining (b) and (c) using equation 1 generates the final output, an index of pollinator abundance across the landscape (d).

3.3.2 Model Validation

Validation of the model using known apiary locations indicated that seventeen of the twenty-nine were on land designated as high quality (IOA > 0.5) by the model. Of the twelve that were not, most were found to be on lands designated as agriculture (five). The others were on urban features (three), forested land (two), barren land (one), and a clear-cut (one) (Table 3).

Table 3. Modelled index of abundance quality of the apiaries involved in this study and their LULC class

		LULC Class							
Apiaries	IOA Class	Agriculture	Urban	Urban Features	Barren	Forest (More than 40% Cover)	Forest (Less than 40% Cover)	Clear-cut	Total
Apiaries Where Field Data were Collected	High	12	1	0	0	0	0	0	13
	Medium	1	0	0	0	0	0	0	1
	Low	2	0	0	1	1	0	0	4
Other Known Apiaries	High	2	2	0	0	0	0	0	4
	Medium	0	0	1	0	0	0	0	1
	Low	2	0	2	0	0	1	1	6

* Note: Urban refers to the subclass of lands designated by the FEC as urban that can support and host honey bee colonies (i.e parks, cemeteries). Urban Features is the subclass of urban lands incapable of supporting and hosting honey bee colonies (i.e. buildings, parking lots)

3.3.3 Identifying Opportunities for Expansion in the Nova Scotia Beekeeping Sector

The amount of land classified as low (IOA <0.25), medium (IOA 0.25 – 0.5) and high (IOA >0.5) quality in each county was calculated in hectares and as a percentage of the county's total area (Table 4). Comparing by county the current numbers of colonies with the modelled area with high potential for honey bees (an IOA > 0.5), there appears to be substantial opportunities for expansion in Colchester and Pictou counties (Table 4). Both counties have similar amounts of modelled high quality land for honey bees as

Kings and Hants counties, but they have about a quarter of the number of colonies. Both Kings and Hants currently support over 5,000 colonies on 10,205 and 7,341 ha of high quality land, respectively. Given that Colchester and Pictou counties currently support 1,000 – 5,000 and 500 – 1,000 colonies on 10,342 and 7,098 ha, respectively, there appears to be room for an expansion in both parts of the province. There is also likely an opportunity for an expansion in Inverness county, as there are currently fewer than 100 colonies being supported on 3,207 ha of high quality land, a similar amount of high quality land as Halifax county which currently hosts 100 – 500 colonies.

Table 4. Comparison of the amount of land in different levels of the index of abundance generated by the analysis informed by the field data and the literature and the current number of honey bee colonies by NS county. Data arranged in descending order of total area of each County found to have high potential to support honey bees (i.e. an IOA of >0.5)

		Area in hectares (and % of total) of each county identified as Low (IOA: <0.25), Medium (IOA: 0.25-0.5) and High (>0.5) quality for honey bees			
County	Total(ha)	Low	Medium	High	# of Colonies
Colchester	27,267	14,059 (51%)	2,866 (11%)	10,342 (38%)	1000 - 5000
Kings	20,455	7,814 (38%)	2,436 (12%)	10,205 (50%)	>5000
Hants	22,308	11,415 (52%)	3,553 (16%)	7,341 (33%)	>5000
Pictou	22,674	11,925 (53%)	3,650 (16%)	7,098 (31%)	500 – 1000
Cumberland	30,863	15,823 (51%)	9,086 (29%)	5,954 (19%)	1000 – 5000
Annapolis	25,056	16,116 (64%)	3,864 (15%)	5,076 (20%)	1000 – 5000
Antigonish	12,066	5,859 (49%)	2,341 (19%)	3,866 (32%)	500 – 1000
Halifax	30,046	23,386 (78%)	3,225 (11%)	3,435 (11%)	100 – 500
Inverness	16,422	9,962 (61%)	3,253 (20%)	3,207 (20%)	<100
Lunenburg	17,902	12,133 (68%)	2,907 (16%)	2,862 (16%)	100 – 500
Guysborough	19,153	15,841 (83%)	1,576 (8%)	1,737 (9%)	<100
Digby	15,971	11,735 (73%)	2,588 (16%)	1,648 (10%)	1000 – 5000
Queens	12,020	10,094 (84%)	937 (8%)	989 (8%)	100 – 500
Victoria	8,901	6,584 (74%)	1,582 (18%)	736 (8%)	<100
Cape Breton	11,298	7,164 (63%)	3,399 (30%)	734 (7%)	<100
Richmond	6,604	4,931 (75%)	1,183 (18%)	490 (7%)	<100
Shelburne	7,827	6,392 (82%)	1,053 (14%)	382 (5%)	<100
Yarmouth	9,179	6,377 (70%)	2,464 (27%)	337 (4%)	<100
Nova Scotia	**316,012**	**197,610 (62.5%)**	**51,963 (16.4%)**	**66,439 (21.0%)**	**~25, 300**

Based on the data presented in Table 4, we created a map showing the relative amounts of land designated as high quality by the model (Figure 12). Contrasting this map to the current distribution of colonies (Figure 9) highlights the counties in which there are likely opportunities to host additional colonies. Most notably, the analysis indicates that Colchester county has the most potential to support honey bee colonies, as opposed to Kings and Hants counties which currently host the most colonies.

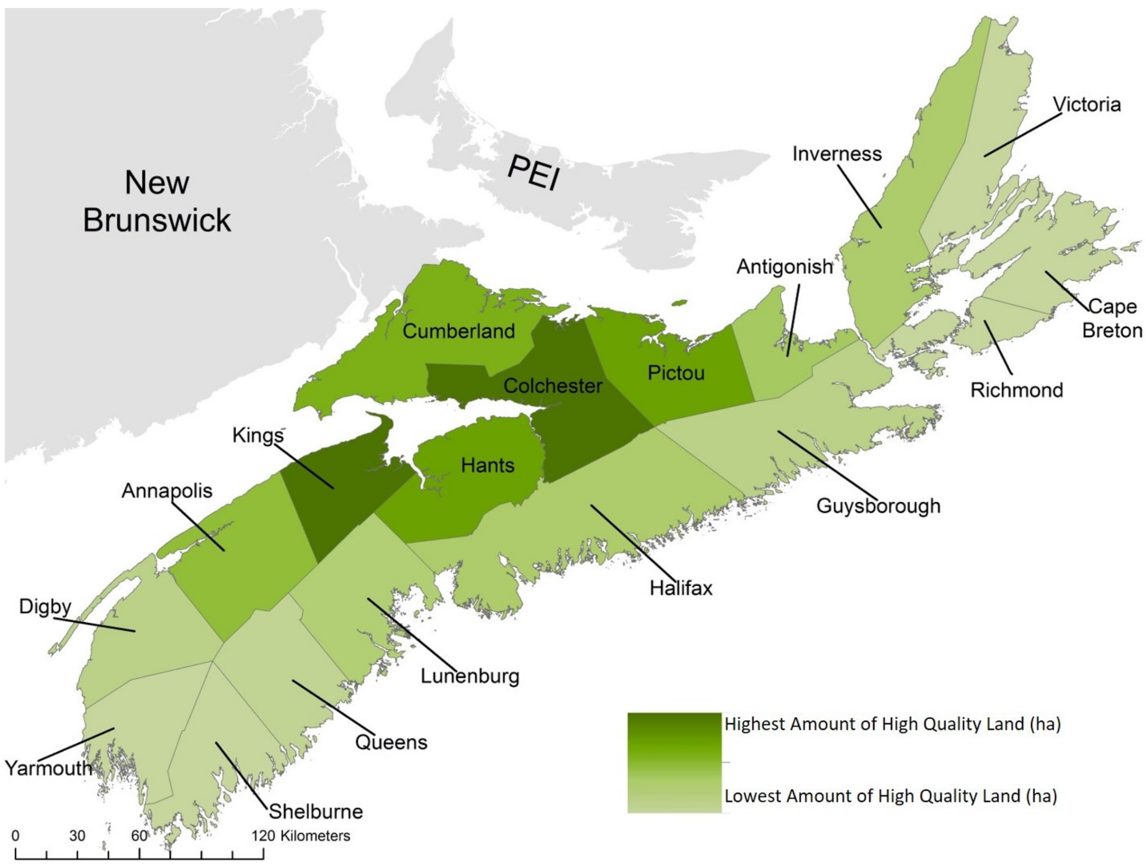

Figure 12. Potential relative distribution of honey bee colonies across Nova Scotia.

3.4 DISCUSSION

3.4.1 Model Validation

There are possible sources of error in this validation stemming from both the location of the apiaries and the LULC data. Some apiaries were visited and co-ordinates recorded (those at which field data were collected, see Chapter 2). In contrast, the locations of others (identified by triangles in Figure 10) were determined through communications with beekeepers, often relying on civic addresses, and thus only roughly located. There are also inaccuracies associated with the LULC data. First, the data is from 2007, and therefore the LULC classes may have changed since then. For example, agricultural land abandonment has been a growing trend in the province, resulting in mismatches between what is in the database and what is actually on the ground (Chapter 2). Secondly, the raster used in the model is at a 25 x 25 m resolution. Therefore, there are again potential issues with accuracy, as some of the features of importance in the landscape are smaller than this resolution. This is of particular issue for the urban features class which are primarily buildings that are actually smaller than the size of a single pixel. It is very likely that apiaries found to be on urban features are actually beside buildings or in people's backyards. A visual analysis of the apiary sites in Google Earth indicates that this is the case for all three of the apiaries found on urban features.

As was noted in Chapter 2, there are inaccuracies associated with wetland identification in the Forest Ecosystem Classification (FEC) used to generate the LULC raster for this study. These inaccuracies likely resulted in an overestimation of the value of the floral resources of wetland classes throughout the study area. However, the impacts of such overestimation on the overall identification of high quality land for honey bees is likely minimal as wetlands only constitute 5.3% of the total study area.

The fact that the majority of the medium/low IOA sites were located on agricultural land raises another shortfall of the model. Many agricultural fields have access roads running through them that are not captured in the Nova Scotia roads database, but could still be used by beekeepers to deploy and regularly access colonies.

Had such roads been included in the analysis, it is likely that the amount of land suitable for honey bees would have increased, particularly in those counties that have a larger proportion of their land base in agriculture (e.g. Cumberland, Colchester and Kings counties). A visual analysis of the apiaries in Google Earth indicates that at least three of the five apiaries on agricultural land deemed medium/low quality in the model were within 100 m of an informal agricultural access road, meaning they would have likely been deemed high quality if said roads were included in the Nova Scotia roads database.

The validation process of the model indicates that there is likely more suitable land for honey bees than indicated in the model because of the resolution of the LULC raster used and the absence of some classes of roads in the Nova Scotia roads database. Consequently, our results are likely to be conservative, as there is likely more high quality land available for honey bees in the province than is being captured by the model.

3.4.2 Opportunities for Expansion in the Nova Scotia Beekeeping Sector

The results of this study indicate an expansion of the Nova Scotia beekeeping sector is possible in certain parts of the province even given our likely conservative estimate of suitable habitat that results from underestimating road access to habitat on agricultural land. In particular, Colchester, Inverness and Pictou counties (Figure 12) appear to contain considerable high quality habitat relative to the current number of colonies that they host (Table 4).

Fuelling this potential for expansion is the recent land cover change driven by human activity, such as forestry and agriculture. In addition to these forest clearing activities, there has been a growing trend of land abandonment over the past seventy years across the province (Davis & Browne, 1996, p. 190). Once a parcel of land is abandoned, it follows a general pattern of vegetation succession beginning with an herbaceous phase, followed by a shrub phase and culminating in a forested phase (Benjamin et al., 2005; Cramer et al., 2007; Smith et al., 1993). For pollinators, the first ten years following abandonment are the most desirable, as they are characterized by an increase in floral diversity, generally by herbaceous species, particularly weedy, often exotic species, and a few small trees (Alaux et al., 2010; Benjamin et al., 2005; Cramer et al., 2007; Di Pasquale et al., 2013; Drinkwater, 1957; Requier et al., 2015). However, it should be noted that this increase in suitability for honey bees is temporary, and is likely only occurring in a small fraction of the province (note that only 21% of the province was deemed to be high quality in the model; Table 4). The natural state of the majority of Nova Scotia is not ideal for supporting honey bees, as evidenced by the fact that even today, the majority of the province (62.5%) has virtually no ability to support honey bee populations (Table 4). Counties with the lowest amounts of land designated with a high IOA (Yarmouth, Shelburne, Richmond, Cape Breton, Victoria, Queens; Figure 12) are all highly forested. They also have large tracts of land in protected areas (i.e. Kejimkujik and Cape Breton Highlands National Parks; Figure 13). These protected areas closely resemble the natural state of what is now Nova Scotia pre-European colonization and thus are not conducive to supporting honey bee populations.

The land designated as high quality by the model is also highly fragmented, a product of the highly modified nature of long settled Nova Scotia landscapes (Figure 13). The highly fragmented nature of the land suitable to host honey bees means apiaries in Nova Scotia will not be able to host large numbers of colonies as is commonplace in other regions of North America, such as the prairies. In homogenous, open grassland or agricultural landscapes, it is common for a single apiary to be home to over one hundred colonies (Gallant et al., 2014). However, the fragmented nature of the landscapes in Nova Scotia results in apiaries generally having fewer than twenty colonies, as noted through conversations with participating beekeepers. Therefore, any expansion of the beekeeping industry in Nova Scotia will likely take place through an increase in the number of small apiaries, distributed in places where underutilized high quality forage exists. The large apiaries that are commonplace in other regions, though economically more desirable, are not possible in Nova Scotia. This is an important factor to keep in mind when considering how the industry will look in the future. While it would be more desirable from the perspective of blueberry producers to keep vast numbers of colonies in one place because it would be easier to facilitate transport of colonies, such an arrangement may not be possible given current landscape patterns.

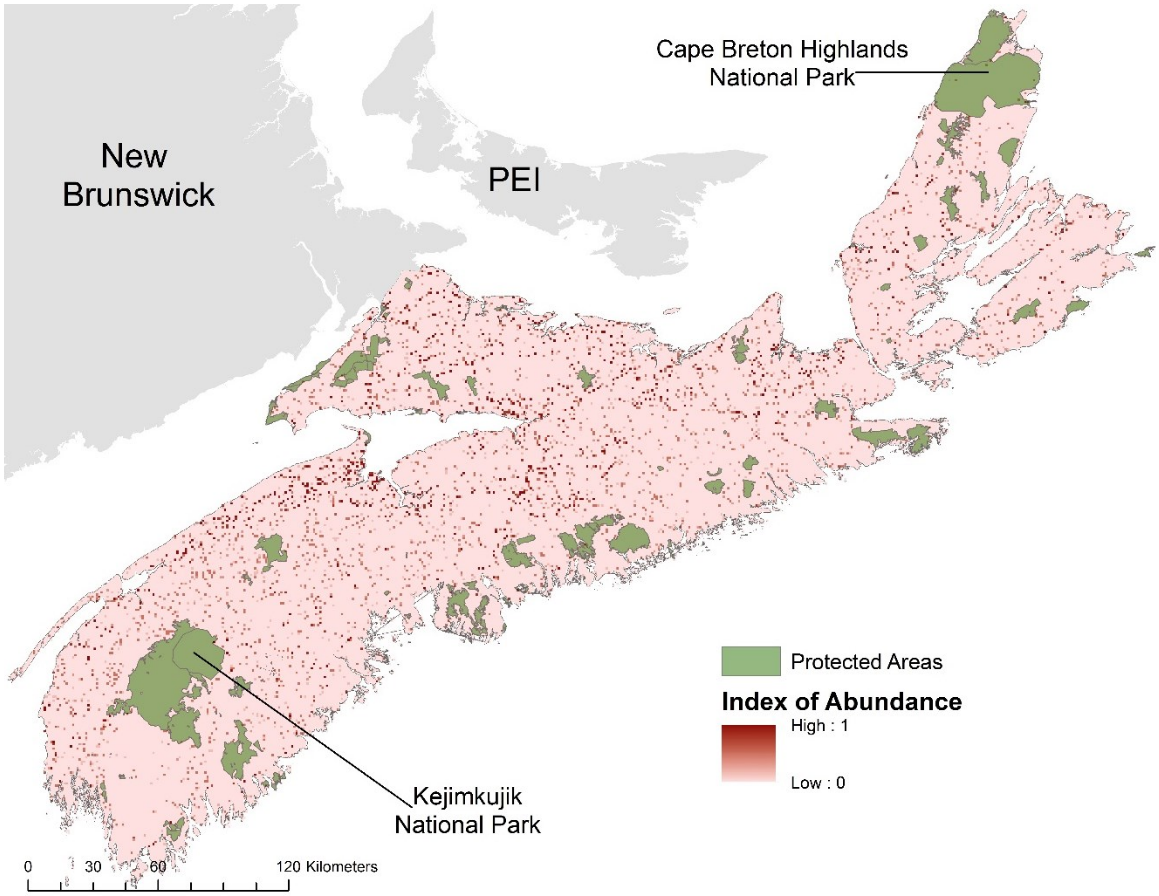

Figure 13. IOA of the entire province of Nova Scotia at a 1 km resolution to highlight the fragmented nature of the lands designated as high quality for honey bees by the model.

Overall, these results should offer a positive outlook for both the beekeepers and blueberry producers of Nova Scotia. Although we are unable to definitively say how many honey bee colonies the province could support, the results indicate a substantial expansion of the beekeeping industry is biologically supportable based on current land use and land covers. Therefore, it is possible that the pollination service demands of blueberry producers could be met domestically, reducing the need to temporarily import colonies from outside the province, a process that can be damaging to both the colonies themselves and the local industry (Ahn et al., 2012). Of course, the demand of the blueberry sector for additional colonies is immediate, but any expansion of the beekeeping sector, either based on new entrants to the industry or the expansion of colony numbers managed by existing participants, will take time. Based on our analysis, however, it appears clear that such an expansion can easily be supported by the floral resources of Nova Scotia.

3.5 CONCLUSION

This study demonstrated a practical application of the methodology presented in Chapter 2 by using the InVEST crop pollination model to identify areas of opportunity for Nova Scotia's beekeeping sector. Results indicate that the province could host more colonies than it currently does, and that Colchester and Pictou Counties on the mainland and Inverness County on Cape Breton Island, are all well suited to support such an expansion. This expansion is largely possible due to the intense human modification of the landscapes in the province which are primarily driven by forestry and agricultural pursuits. An expansion would have positive effects on the province's blueberry producers, as they could meet their pollination services demand domestically rather than temporarily importing colonies, a solution that would benefit local beekeepers economically and reduce their colonies' exposure to unintended introductions of parasites and diseases.

CHAPTER 4:
CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Following the publication of the Millennium Ecosystem Assessment (MEA) (2005), the topic of ecosystem services has received considerable attention. The MEA emphasized incorporating ecosystem services and their economic value into policy making. However, there is little evidence that this is happening in practice (Laurans et al., 2013; Laurans & Mermet, 2014). It may be that the use of ecosystem service valuation in policy making is common practice, but is not well documented in the literature, or there may be a profound lack of utility amongst policy makers (Laurans et al., 2013). However, it may just as easily be a function of the underdeveloped state of practice and knowledge related to the characterization and valuation of ecosystem services. While the economic valuation of ecosystem services may be the ultimate objective by the MEA and others such as the Economics of Ecosystems and Biodiversity (TEEB) (Sukhdev et al., 2010), to help motivate policy making towards increased conservation, such efforts must be better complemented by a deeper understanding of the biophysical underpinnings of services (Daily et al., 2009; Kremen, 2005; Tallis & Polasky, 2009). Put another way, to increase the integration of ecosystem services in land use, or other resource, planning, a focus on the spatial complexities of ecosystem services and the creation of robust maps showing the provision of services across landscapes is needed.

The mapping of ecosystem services is a relatively new discipline, but there are already trends and common practices emerging. Specifically, proxies such as land cover to represent ecosystem processes and the use of remotely sensed imagery is common (Martinez-Harms & Balvanera, 2012; Seppelt et al., 2011). Notably, to date, the use of primary data is relatively uncommon in ecosystem service mapping studies, with only about 10% of the studies involved in reviews by Martinez-Harms and Balvanera (2012) and Seppelt and colleagues (2011) incorporating locally collected, field based data. Those that did incorporate field data were generally focused on a single service over a relatively small and specific area, such as carbon storage in the soils of southeast Queensland, Australia (Collard & Zammit, 2006), the cultural services of deer hunting on farmlands in Michigan (Knoche & Lupi, 2007), or crop pollination services on Californian watermelon crops (Kremen et al., 2004).

Chapter 2 of this thesis explored the potential benefits of incorporating locally collected field based data into the mapping of pollination service potential across Cumberland and Colchester counties in Nova Scotia, Canada. Results indicate that field based data can offer important insights not captured when the mapping of services is based on large scale data sets, such as coarse landscape classifications and remotely sensed imagery that are typically available to resource managers. This is consistent with others who have noted that biophysical models, particularly those incorporating detailed biodiversity data, provide more robust methods for evaluating ecosystem services than solely using land cover attributes and other proxies (La Notte et al., 2012; Vihervaara et al., 2012). In this thesis, the ecosystem service in question, pollination, is dependent on the distribution of floral resources at fine spatial and temporal scales not typically captured in remotely sensed imagery. The fine scale nature of the biophysical elements necessary for pollination makes it an ideal ecosystem service to study through the incorporation of boots-on-the-ground primary data collection.

For the mapping of ecosystem services to become more commonplace, it will be important to consider any potential mismatches in the scale of service provision and the scale of data used to inform modeling processes. The scale at which data is collected and the model is run influences the accuracy of mapping ecosystem services, and thus their ability to be used as a decision making tool (Crossman et al., 2012; Kandziora et al., 2013; Lautenbach et al., 2012). For example, the provisioning service of maple syrup is dependent on the presence of maple trees (*Acer sp.*). In this case, using remotely sensed imagery as the basis of the modelling process may be appropriate, provided it is at a fine enough resolution to identify stands of maple. On the other hand, the regulating service of soil formation and regeneration is dependent on processes that occur within soils and at extremely small scales. Therefore, the use of remotely sensed imagery may be ineffective on its own, and the modelling process would likely benefit from the incorporation of field data collection.

From a policy making perspective, the potential disparity between model outputs produced by literature derived and field data informed models is important. While maps of ecosystem service provision may be a useful tool for making land use planning decisions, they may not convey a completely accurate depiction of provision across the landscape if they were generated solely using secondary data. Locally collected field data calibrates a model to the specific conditions of the study area, thus making the results more applicable for inclusion in policy making. In the case of the study presented in Chapter 2, this need was highlighted in the forested land use land cover (LULC) classes, where the quality of the floral resources available for honey bees increased with the inclusion of field based data. In the case of the forested classes, the underestimation of floral resources using secondary data sources was likely because of the neglect of the forest understory, which is often highly diverse and composed of many species that provide good forage for honey bees such as raspberry (*Rubus idaeus*), wild rose (*Rosa accicularis*), and aster (*Aster sp.*) (Cho et al., 2017; Gilliam, 2007; Proctor et al., 2012). Forest understories are difficult to characterize with remote sensing techniques (Tuanmu et al., 2010), thus collecting boots-on-the-ground data aid in our understanding of the understory, and as shown in Chapter 2, our ability to understand the ability of landscapes to support honey bee populations. There is a need to understand the ecosystem services provided by a given piece of land to better understand the potential implications of landscape changes on ecosystem service provision (Crossman et al., 2013; de Groot et al., 2010). Informing models with primary data is one way to garner a better understanding of the ecosystem services provided by a study area.

Chapter 3 of this thesis provided a practical application of the methodology presented in Chapter 2. By taking an ecosystem services mapping approach to answering the question of whether Nova Scotia can support an increase of honey bee colonies, we were able to account for the spatial complexities of pollination service provision. In doing so, we identified, at the county level, underutilized lands suitable to host honey bee colonies. This builds on the work conducted by Gallant and colleagues (2014) by operating at a smaller spatial scale, and identifying potential apiaries of any size, rather than focusing exclusively on large apiaries (the methodology of Gallant et al. (2014) was used to identify apiaries that could host a minimum of one hundred colonies).

4.2 RECOMMENDATIONS

4.2.1 Ecosystem Services Mapping

As the field of ecosystem services mapping continues to grow, it will be important to match the scale of data collection to the scale of the biophysical underpinnings of the service being mapped. In some cases, remotely sensed data may be sufficient, but in many other cases it will not, as was demonstrated in this thesis. When the biophysical elements which give rise to ecosystem services occur at a smaller spatial scale than what can captured in remotely sensed imagery or land cover datasets, the incorporation of boots-on-the-ground primary data will likely benefit the modelling process. In addition to pollination, such ecosystem services include biological pest regulation (reliant on small insects that in turn are reliant on the fine scale distribution of plants that act as a food source) and nitrogen fixation (dependent on small plants, such as alders (*Alnus sp.*)). As was shown in this thesis, primary data can enhance ecosystem services mapping studies, and contributes to our knowledge as to the ability of different landscapes to provide ecosystem services. It is thus recommended that practitioners collect data at an appropriate scale for the service being mapped. In some cases, remotely sensed data will suffice (e.g. maple syrup, as discussed above), but in others, the collection of local field based data is essential.

The study presented in this thesis represents a snapshot in time. Field data were collected over one growing season (2015) and the LULC data were based on 2007 conditions. There was no inclusion of the temporal dynamics of service provision that occur time due to changes in land cover and use. As land use and land cover patterns change, so do ecosystem service provision patterns (Foley et al., 2005; Metzger et al., 2006; Schroter et al., 2005). Such changes in ecosystem service provision over time will become particularly important as the effects of climate change continue to progress, resulting in large scale landscape changes. Therefore, to better incorporate ecosystem services into land use policy making, it will be important to understand how service provision changes over time, and how said changes may affect potential tradeoffs of land management decisions (Rodriguez et al, 2006). Thus, it is important to repeat analyses such as the one presented in Chapter 3 regularly as new LULC data becomes available. It is thus recommended that the methodology of this thesis be repeated whenever the Nova Scotia Forest Ecosystem Classification (FEC) is updated, or after the completion of a new classification based on remotely sensed imagery. Alternatively, the methods could be applied to a projected LULC raster to assess how climate change may affect Nova Scotia's ability to support honey bee populations.

This work, like so many other studies, focused solely on the supply of ecosystem service provision; the capacity of a particular area to provide a specific ecosystem service(s) over a given time period (Burkhard et al., 2012). In the future, also mapping ecosystem service demand, the ecosystem service(s) used in a particular area over a given time period (Burkhard et al., 2012), would provide valuable information to policy makers interested in the phenomena of concern. Such work would be particularly useful in identifying mismatches in the supply and demand of ecosystem services across landscapes, such as the work done by Schulp and colleagues(2014) in the European Union on the supply and demand of pollination services. This would allow policy makers to further evaluate potential consequences of different land use planning scenarios, as they would not only be able to evaluate potential threats to the supply of ecosystem services but also potential disruptions to their consumption.

4.2.2 Opportunities for Expanding Nova Scotia's Beekeeping Industry

The results of the research presented in this thesis do not allow us to say quantitatively how many honey bee colonies could be supported in the province, or even in each county, but the results indicate that an expansion of the sector is possible, from its current level of around 25,300 colonies. Based on comparisons of the amount of high quality land available for honey bees in each county, and the number of colonies currently in each county (Chapter 3), the best opportunities for expansion are likely to occur in Colchester, Pictou and Inverness counties (Figure 14). It is thus recommended that the Nova Scotia Beekeepers Association (NSBA) focus their efforts toward a colony expansion in these counties.

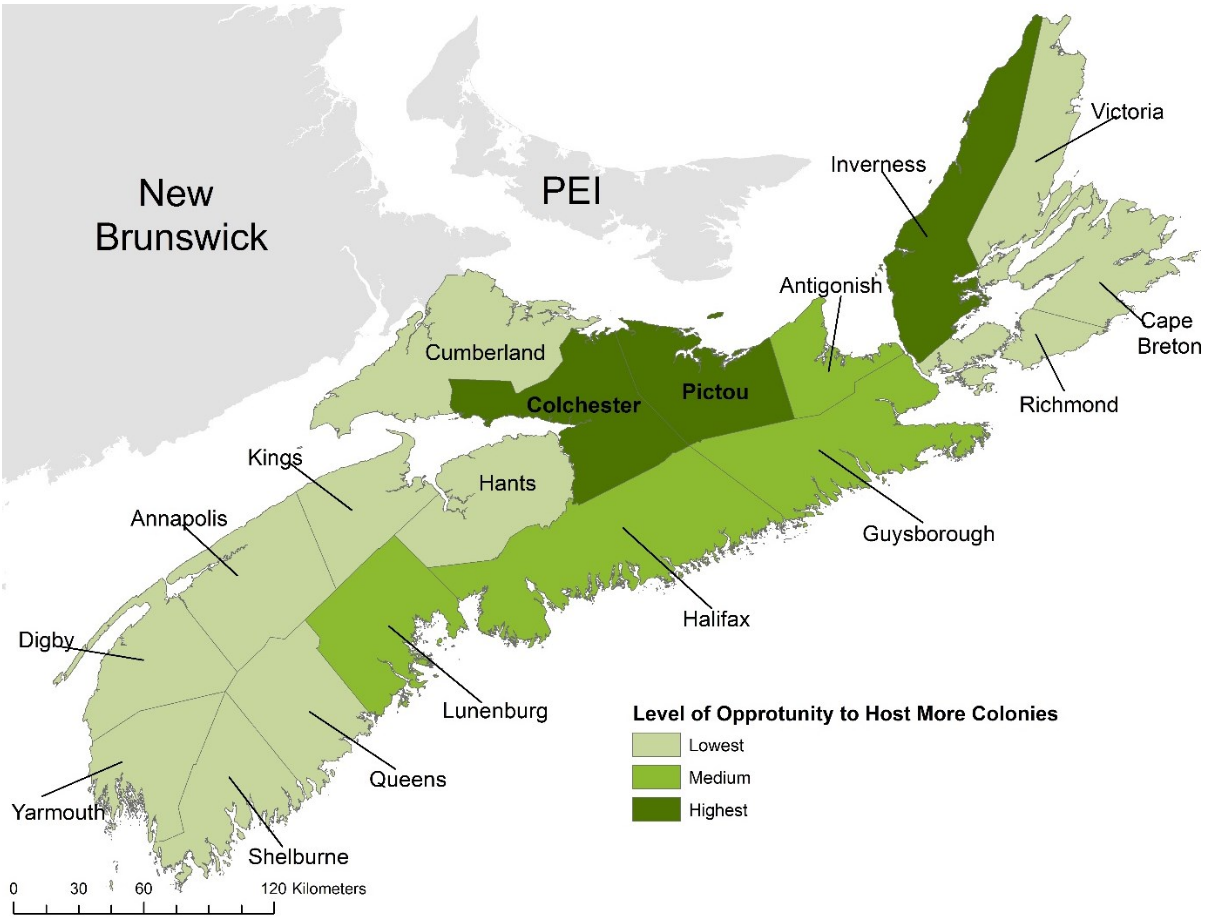

Figure 14. Level of opportunity for each county in Nova Scotia to host more colonies based on the results of this thesis

To better understand how the Nova Scotia beekeeping industry could expand, it will be important to understand the relationship between landscape structure and colony productivity. Through a better understanding of this relationship it would be possible to determine how many colonies could be supported by different landscapes. It is thus recommended that the field work component of this thesis be repeated at more apiaries (preferably across a broader range of the province) and colony productivity data be collected at the same sites. Specifically, information on the number of colonies, amount of honey produced, number of splits, amount of food supplements fed, the number of colony deaths and any diseases present at each apiary should be collected to establish a metric of colony productivity. Comparing said information to landscape metrics such as floral resource quality and the percentage of surrounding land in various land classes (e.g. forest, agriculture, urban) would yield better insight as to the relationship between honey bees and their landscapes than is currently available. Establishing such a relationship would ground truth the results of this thesis and give insight as to the validity of the model.

4.2.3 Nova Scotia Honey Bee Importation Ban

The results of this research indicate Nova Scotia can host more honey bee colonies than it currently does. While we were unable to definitively say how many more colonies the province could support, the results indicate that the beekeeping industry can grow to meet the pollination demands of the blueberry production industry domestically. Therefore, the province should continue to support the Pollination Expansion Program to support, and perhaps fast track, growth within the Nova Scotia beekeeping sector. As this expansion is possible, the honey bee importation ban should remain in place to protect the economic well-being and colony health of Nova Scotia's beekeeping industry.

4.2.4 General Recommendations

Overall, the results of this thesis highlight the importance of being cognizant of the scale at which the various biophysical underpinnings of ecosystem services operate, and matching the scale of data collection in mapping studies to the scale of service provision. The importance of this relationship was emphasized here in the disparities between the literature and field data driven models in Chapter 2. Building on what was learned in our comparison of the two models, we took a field based approach to determining whether an increase in the number of honey bee colonies kept in Nova Scotia is possible in Chapter 3. Results indicate that an expansion of the province’s beekeeping industry is possible, although we are not able to say how exactly many colonies could be supported given current conditions.

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APPENDIX I: CHAPTER 2 INVEST INPUTS

SPECIES GUILDS

Table S 1.1. Species guilds table used in the InVEST modelling

Species	NS_boxes	FS_earlysummer	FS_latesummer	Alpha (m)	Species_Weight
Apis mellifera	1	0.5	0.5	1000	1

LAND COVER ATTRIBUTES TABLE

Table S 1.2. Land cover attributes table where the floral resource values are populated based on the literature

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	0	Natural Stand	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	1	Treated	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	2	Burn	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	3	Christmas	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	4	Sugar Bush	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	5	Old Field	1	Open Area, Some Trees for Shelter	0.5	1	Many Weedy Species, Diverse
	6	Wind Throw	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	7	Dead <25% Live Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	8	Dead 26-50% Live Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	9	Dead 51-100% Live Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	10	Research	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	11	Seed Orchard	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	12	Treated	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	13	Dead 26-50% Dead Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	14	Dead 51-75% Dead Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	15	Dead >75% Dead Crown Closure	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	17	Forest <40% Cover	0.5	Some Cover for Shelter	0.4	0	(Lonsdorf et al., 2009)
	20	Plantation	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	33	Brush	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	38	Alders <75%	0	Canopy Cover too dense	0.6	0	Alders an Important Species in the Spring
	39	Alders >75%	0	Canopy Cover too dense	0.6	0	Alders an Important Species in the Spring
	60	Clear Cut	0.5	Some Open Area, Some Cover	0.4	0	(Lonsdorf et al., 2009)
	61	Partial Depletion Verified	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	62	Partial Depletion Non-Verified	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	70	Wetland	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)
	71	Beaver Flow	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)
	72	Open Bog	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)
	73	Tree Bog	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)
	74	Coastal	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	75	Lake Wetland	0	Wetland Unsuitable for Access	0.2	0.2	(Lonsdorf et al., 2009)
	76	Cliffs	0	Unsheltered from the Elements; Difficult Access	0	0	Not Vegetated
	77	Inland Water	0	Can't put Colonies in Water	0	0	Not Vegetated
	78	Ocean	0	Can't put Colonies in Water	0	0	Not Vegetated
	80	Urban Features	0	Buildings and Parking lots Unsuitable	0	0	Not Vegetated
	83	Brush	0	Canopy Cover too dense	0.4	0	(Lonsdorf et al., 2009)
	84	Rock Barren	0.3	May be Uneven Terrain, but a Mix of Open and Sheltered	0	0.2	Few Plants but those there tend to be Ericacae
	85	Barren	0.3	May be Uneven Terrain, but a Mix of Open and Sheltered	0	0.2	Few Plants but those there tend to be Ericacae

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	86	Agriculture	1	Ideal Area, Open with Hedgerows for Shelter	0.5	0.5	(Lonsdorf et al., 2009)*
	87	Urban	0.7	Could put Colonies in Gardens Particularly in Rural Areas	0.8	0.8	(Lonsdorf et al., 2009)
	88	Alders <75%	0	Canopy Cover too dense	0.6	0	Alders an Important Species in the Spring
	89	Alders >75%	0	Canopy Cover too dense	0.6	0	Alders an Important Species in the Spring
	90	Unknown	0	Unknown	0	0	Unknown
	91	Blueberry	1	Ideal Area, Open with Hedgerows for Shelter	0	0.5	(Lonsdorf et al., 2009)*
	92	Miscellaneous**	0	Majority of Landuses Unsuitable for Access	0.2	0.2	Likely some suitable vegetation but not much
	93	Landfill	0	Unsuitable for Access	0	0	Not Vegetated

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	94	Beach	0.5	Open, Likely Some Shelter but also Exposure to the Elements	0	0	Not Vegetated
	95	Gravel Pit	0	Unsuitable for Access	0	0	Not Vegetated
	96	Pipeline	0.5	Suitable Area but Issues with Access a Likelihood	0.8	1	Disturbance Corridor, Open and Suitable to Host a Wide Diversity of Species
	97	Powerline	0.7	Suitable Area but Issues with Access a Likelihood	0.8	1	Disturbance Corridor, Open and Suitable to Host a Wide Diversity of Species; (Russell et al., 2005)
	98	Road	1	Easy Access and Suitable Area (Lonsdorf et al., 2009)	1	1	Disturbance Corridor, Open and Suitable to Host a Wide Diversity of Species

Legend	LULC	Description	N_ boxes	Nesting Score Logic	F_ early summer	F_ late summer	Floral Resource Score Source/ Logic
	99	Rail	0.5	Suitable Area but Issues with Access a Likelihood	0.8	1	Disturbance Corridor, Open and Suitable to Host a Wide Diversity of Species

* Agriculture would be influenced by whether or not it is organic. Organic agriculture fields would likely have more weeds, therefore producing a more diverse floral palette. In Nova Scotia, there is no data as to whether an agricultural field is organic or not. Therefore, these scores are halfway between the organic and non-organic categories of agricultural in Lonsdorf et al. (2009). Some weeds are assumed to be present, but for the most part the scores are the result of a single bloom of a single species.

** Miscellaneous includes rifle range, quarry, mining sites, wharf, pier and airstrips among others.

Table S 1.3. Land cover attributes table where the floral resource values are populated using field based data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	0	Natural Stand	0	0.42	0.85	Field Data
	1	Treated	0	0	0	No Data
	2	Burn	0	0	0	No Data
	3	Christmas	0	0	0	No Data
	4	Sugar Bush	0	0	0	No Data
	5	Old Field	1	0.89	1	Field Data
	6	Wind Throw	0	0	0	No Data
	7	Dead <25% Live Crown Closure	0	0	0	No Data
	8	Dead 26-50% Live Crown Closure	0	0	0	No Data
	9	Dead 51-100% Live Crown Closure	0	0	0	No Data
	10	Research	0	0	0	No Data
	11	Seed Orchard	0	0	0	No Data
	12	Treated	0	0	0	No Data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	13	Dead 26-50% Dead Crown Closure	0	0	0	No Data
	14	Dead 51-75% Dead Crown Closure	0	0	0	No Data
	15	Dead >75% Dead Crown Closure	0	0	0	No Data
	17	Forest <40% Cover	0.5	0.64	1	Field Data
	20	Plantation	0	0	0	No Data
	33	Brush	0	0.11	0	Field Data
	38	Alders <75%	0	1	0	Field Data
	39	Alders >75%	0	0.6	0	Field Data
	60	Clear Cut	0.5	0.64	1	Field Data
	61	Partial Depletion Verified	0	0	0	No Data
	62	Partial depletion Non-Verified	0	0	0	No Data
	70	Wetland	0	0.38	0.6	Field Data
	71	Beaver Flow	0	0.38	0.6	Type of Wetland
	72	Open Bog	0	0.38	0.6	Type of Wetland
	73	Tree Bog	0	0.38	0.6	Type of Wetland
	74	Coastal	0	0.38	0.6	Type of Wetland
	75	Lake Wetland	0	0.38	0.6	Type of Wetland
	76	Cliffs	0	0	0	No Data
	77	Inland Water	0	0	0	No Vegetation
	78	Ocean	0	0	0	No Vegetation
	80	Urban Features	0	0	0	No Vegetation
	83	Brush	0	0.11	0	Field Data
	84	Rock Barren	0.3	0	0	No Data
	85	Barren	0.3	0	0	No Data
	86	Agriculture	1	0.68	0.85	Field Data
	87	Urban	0.7	0.68	0.48	Field Data
	88	Alders <75%	0	1	0	Field Data
	89	Alders >75%	0	0.6	0	Field Data
	90	Unknown	0	0	0	No Data
	91	Blueberry	1	0.69	0.84	Type of Agriculture
	92	Miscellaneous	0	0	0	No Data
	93	Landfill	0	0	0	No Data
	94	Beach	0.5	0	0	No Data
	95	Gravel Pit	0	0.68	0	Field Data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	96	Pipeline	0.5	0.89	1	Disturbance Corridor, Similar to Road
	97	Powerline	0.7	0.89	1	Disturbance Corridor, Similar to Road
	98	Road	1	0.89	1	Field Data
	99	Rail	0.5	0.89	1	Disturbance Corridor, Similar to Road

APPENDIX II: LANDSCAPE QUALITY SCORES

ORIGINAL DATA COLLECTED AT EACH PLOT

Table S 2.1. Example of data collected in the field at one plot

Species	Cover Class	Utility to Honey Bees
Dandelion (*Taraxacum officinale*)	2	1
Raspberry (*Rubus idaeus*)	1	1
Wild Rose (*Rosa acicularis*)	2	4
Sweet Clover (*Melilotis officinalis*)	2	1
Non-Flowering Grass	3	6

Table S 2.2. Cover class codes and their corresponding percentage covers

Cover Class	Percentage Cover
0	0%
1	1-5%
2	5-10%
3	10-25%
4	25-33%
5	33-50%
6	50-66%
7	66-75%
8	75-90%
9	90-95%
10	95-100%

Table S 2.3. Utility to honey bees codes and their corresponding definitions

Utility to Honey Bees	Definition
1	Nectar and Pollen Utilized; Identified as Important by Beekeepers
2	Nectar and Pollen Utilized
3	Only Nectar Utilized
4	Only Pollen Utilized
5	May be Used if Honeydew Being Produced
6	Not Important
7	Unknown

CALCULATING LANDSCAPE QUALITY SCORES

Table S 2.4. Weighting applied to the cover class component of the data

Cover Class	Percentage Cover	Weighting
0	0%	0
1	1-5%	0.1
2	5-10%	0.2
3	10-25%	0.3
4	25-33%	0.4
5	33-50%	0.5
6	50-66%	0.6
7	66-75%	0.7
8	75-90%	0.8
9	90-95%	0.9
10	95-100%	1

Table S 2.5. Weighting applied to the utility component of the data

Utility to Honey Bees	Definition	Weighting
1	Nectar and Pollen Utilized; Identified as Important by Beekeepers	1
2	Nectar and Pollen Utilized	0.8
3	Only Nectar Utilized	0.6
4	Only Pollen Utilized	0.4
5	May be Used if Honeydew Being Produced	0.2
6	Not Important	0
7	Unknown	0

EXAMPLE OF CALCULATING PLOT SCORE

Table S 2.6. Calculating the Plot Score. For each species in the plot the weight of the cover class score was multiplied by the weight of the utility class. The product of these scores for each species were then summed to determine the overall landscape quality score of the plot.

Species	Cover Class	Utility to Honey Bees	Cover Class Weighting	Utility Class Weighting	Cover Class*Utility Class
Dandelion (*Taraxacum officinale*)	2	1	0.2	1	0.2
Raspberry (*Rubus idaeus*)	1	1	0.1	1	0.1
Wild Rose (*Rosa acicularis*)	2	4	0.2	0.4	0.08
Sweet Clover (*Melilotis officinalis*)	2	1	0.2	1	0.2
Non-Flowering Grass	3	6	0.3	0	0
				Sum (Plot Score)	0.58

APPENDIX III: CHAPTER 3: INVEST INPUTS

SPECIES GUILDS

Table S 3.1. Species guilds table used in the InVEST modelling

Species	NS_boxes	FS_earlysummer	FS_latesummer	Alpha (m)	Species_Weight
Apis mellifera	1	0.5	0.5	1000	1

LAND COVER ATTRIBUTES TABLE

Table S 3.2. Land cover attributes table used in the InVEST modelling

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	0, 100, 200	Natural Stand	0	0.42	0.85	Field Data
	1, 101, 201	Treated	0	0	0	No Data
	2, 102, 202	Burn	0	0	0	No Data
	3, 103, 203	Christmas	0	0	0	No Data
	4, 104, 204	Sugar Bush	0	0	0	No Data
	5, 105, 205	Old Field	1	0.89	1	Field Data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	6, 106, 206	Wind Throw	0	0	0	No Data
	7, 107, 207	Dead <25% Live Crown Closure	0	0	0	No Data
	8, 108, 208	Dead 26-50% Live Crown Closure	0	0	0	No Data
	9, 109, 209	Dead 51-100% Live Crown Closure	0	0	0	No Data
	10, 110, 210	Research	0	0	0	No Data
	11, 111, 211	Seed Orchard	0	0	0	No Data
	12, 112, 212	Treated	0	0	0	No Data
	13, 113, 213	Dead 26-50% Dead Crown Closure	0	0	0	No Data
	14, 114, 214	Dead 51-75% Dead Crown Closure	0	0	0	No Data
	15, 115, 215	Dead >75% Dead Crown Closure	0	0	0	No Data
	16, 116, 216	Moose Meadow	0	0	0	No Data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	17, 117, 217	Forest <40% Cover	0.5	0.64	1	Field Data
	20, 120, 220	Plantation	0	0	0	No Data
	33, 133, 233	Brush	0	0.11	0	Field Data
	38, 138, 238	Alders <75%	0	1	0	Field Data
	39, 139, 239	Alders >75%	0	0.6	0	Field Data
	60, 160, 260	Clear Cut	0.5	0.64	1	Field Data
	61, 161, 261	Partial Depletion Verified	0	0	0	No Data
	62, 162, 163	Partial depletion Non-Verified	0	0	0	No Data
	70, 170, 170	Wetland	0	0.38	0.6	Field Data
	71, 171, 171	Beaver Flow	0	0.38	0.6	Type of Wetland
	72, 172, 272	Open Bog	0	0.38	0.6	Type of Wetland

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	73, 173, 273	Tree Bog	0	0.38	0.6	Type of Wetland
	74, 174, 274	Coastal	0	0.38	0.6	Type of Wetland
	75, 175, 275	Lake Wetland	0	0.38	0.6	Type of Wetland
	76, 176, 276	Cliffs	0	0	0	No Data
	77, 177, 277	Inland Water	0	0	0	No Vegetation
	78, 178, 278	Ocean	0	0	0	No Vegetation
	80, 180, 280	Urban Features	0	0	0	No Vegetation
	83, 183, 283	Brush	0	0.11	0	Field Data
	84, 184, 284	Rock Barren	0.3	0	0	No Data
	85, 185, 285	Barren	0.3	0	0	No Data
	86, 186, 286	Agriculture	1	0.68	0.85	Field Data

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	87, 187, 287	Urban	0.7	0.68	0.48	Field Data
	88, 188, 288	Alders <75%	0	1	0	Field Data
	89, 189, 289	Alders >75%	0	0.6	0	Field Data
	90, 190, 290	Unknown	0	0	0	No Data
	91, 191, 291	Blueberry	1	0.69	0.84	Type of Agriculture
	92, 192, 292	Miscellaneous*	0	0	0	No Data
	93, 193, 293	Landfill	0	0	0	No Data
	94, 194, 294	Beach	0.5	0	0	No Data
	95, 195, 295	Gravel Pit	0	0.68	0	Field Data
	96, 196, 296	Pipeline	0.5	0.89	1	Disturbance Corridor, Similar to Road
	97, 197, 297	Powerline	0.7	0.89	1	Disturbance Corridor, Similar to Road

Legend	LULC	Description	N_boxes	F_early summer	F_late summer	Source
	98, 198, 298	Road	1	0.89	1	Field Data
	99, 199, 299	Rail	0.5	0.89	1	Disturbance Corridor, Similar to Road

* Miscellaneous includes rifle range, quarry, mining sites, wharf, pier and airstrips among others.