Applying Geographic Information Systems to the Study of Honey Bee Diseases and Pests

by

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Submitted in partial fulfilment of the requirements

for the degree of Master of Information

at

Dalhousie University
Halifax, Nova Scotia
April 2020

Table of Contents

List of Tables

List of Figures

Abstract

The western honey bee (*Apis mellifera*) is one of the most valuable pollinators in the global agriculture industry. However, recent years have seen a decrease in the worldwide honey bee population through colony collapse, disease, pests, urban growth, climate change, and the increased use of pesticides. This thesis explores the quality of open data available to researchers interested in understanding the geographic distribution of honey bee diseases and pests in Nova Scotia, Canada, and identifies locations within the province that may be vulnerable for honey bees. Results of a Land Suitability Analysis using geographic information systems (GIS) software show that GIS can be used to identify regions that meet certain conditions related to disease and pest development. However, this research concludes that more credible, relevant, and legitimate information needs to be accessible through data portals and requests for information for GIS to be more useful in this capacity.

List of Abbreviations Used

AFB	American Foulbrood
ATIP	Access to Information and Privacy Request
DEM	Digital Elevation Model
CSV	Comma-Separated Values
ERIC	Enterobacterial Repetitive Intergenic Consensus
FAO	Food and Agriculture Organization of the United Nations
FOI	Freedom of Information
FOIPOP	Freedom of Information and Protection of Privacy
GIS	Geographic Information Systems
HRM	Halifax Regional Municipality
LiDAR	Light Detection and Ranging
MCDA	Multi-Criteria Decision Analysis
MADM	Multi-Attribute Decision Making
USA	United States of America

Acknowledgements

I would like to thank my thesis supervisor, Professor Jennifer Grek Martin – for all the hard work, time, and guidance she has put into my thesis to ensure that it is successful. I would also like to thank my thesis committee – Dr. Bertrum MacDonald and Dr. Chris Greene – who have contributed their knowledge and talents to ensure that this thesis would be successful and without their guidance and support this thesis would not have been possible. A special thank you goes to Jennifer Strang, who was always available to answer my questions about the software used in this research.

Finally, I would also like to thank my friends, co-workers, fellow graduate students, and family for lending me an ear to ramble to and for supporting me through this process. I could have not completed this thesis without everyone.

Thank you.

Chapter 1: Introduction

Imagine yourself strolling along a trail, listening to the chirping of birds, the wind blowing through the leaves, the sounds of squirrels jumping from branch to branch, and the buzzing of bees moving from one flower to the next. For almost 10,000 years, humans and honey bees (*Apis mellifera,* hereafter referred to as "honey bees") have shared a strong relationship (Seeley, 2019); humans provide the honey bees with shelter and nutrition and the honey bees provide us with food through pollination as an ecosystem service – e.g. honey, fruits, and wheat – and resin for pottery. Since the beginning of the development of beekeeping, honey bees have been important pollinators for a wide range of crops, such as berries, apples, beans, nuts, and canola. But, due to increased stressors, the lovely sound of the hard-working honey bee has become threatened (Morris, 2015).

Since 2006, the global honey bee population has seen a decrease in number[1] due to an increase in bee stresses, such as, colony collapse disorder (a phenomenon occurring throughout the United States, that is not yet well-understood causing a colony's worker bees to disappear, leaving the queen bee, nurse bees, and plenty of food behind), urban sprawl, climate change, the use of chemicals on farmland, and diseases and pests (Doublet, Laarussias, de Miranda, Mortize, & Paxton, 2015; Suryanarayana & Kleinman, 2011). Beekeepers were the first to notice the declining population of bees when

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[1] Some regions have seen an increase in honey bee numbers but the overall global honey bee population has been declining (Abejeq, & Zeleke, 2017; Klein, Cabirol, Devaud, Barron, & Lihoreau, 2017; Seeley, 2019)

American beekeepers reported losing 30 to 90 percent of their hives during the 2006 winter, an increase from the minimum 15 percent over the normal winter loss rate (Vanegas, 2017). Since the 2006 outcry from US beekeepers, the health of the global honey bee population has become a prominent topic on social media and news outlets, resulting in numerous studies being conducted to determine the best course of action to ensure the survival of one of the world’s most significant pollinators (Food and Agriculture Organization of the United Nations, 2019; Morris, 2015; Touart, & Maciorowski, 1997; vanEngelsdorp et al., 2017). There have been no confirmed cases of Colony Collapse Disorder in Canada, instead increased mortality of Canadian honey bee colonies has been linked to winter loss and dwindling colony numbers during the early spring (Health Canada, 2014)

Ensuring that beekeepers, decision-makers, and academics have access to high-quality, credible, relevant (also referred to as salient), and legitimate information (Cash et al., 2003) will allow all stakeholders to undertake more informed discussion about the importance of honey bees and their impact on ecosystems. Open data are data and information produced by the government that are available for anyone to access, modify, and share at no cost, and open access is generally peer-reviewed research that has a limited cost barrier and can be accessed by anyone (Even & Shankaranarayanan, 2009). Both open data and open access need to be of good quality to provide added value to the discussion already occurring between parties and increase the transparency of government bodies and academia (Vetro et al., 2016). However, open data and open access face several issues, not the least of which are datasets or information that are not of good quality. Datasets that require substantial modifying or that do not contain enough information to be useful will reduce the public's usage and opinion of the information provided by the government, as well as increase the cost and time researchers need to complete their studies (Even et al., 2009; Vetro et al., 2016).

The credibility, relevance, and legitimacy of information are key factors that are needed in making effective decisions (Cash et al., 2003). As defined by Cash et al. (2003), credibility is the quality of a piece of information and the authority of the individual presenting the information. Relevance is how useful the information is in making a decision. Finally, legitimacy is the fair incorporation of the values, interests, and beliefs of the stakeholders. Ensuring that stakeholders have access to credible, relevant, and legitimate information, through either open data or open access portals, will allow for better solutions to be discovered and implemented.

Researchers agree that geographic information systems (GIS) are an exceptional tool for understanding spatial data and generating information in a way that reveals spatial patterns and connections as long as the data used is of good quality (Horn, Pitman, & Potter, 2019, Ruikkala et al., 2019). Geographic information systems have been used to study animal boundaries, human movement, climate change, and disease patterns, among many other phenomena, but, has only recently been used to study honey bees (Cunningham, 2017; Galbraith, Vierling, & Bosque-Perez, 2015; Gallant, Euliss,

& Browning, 2014). My research will address how GIS can be integrated with and improve the management of simultaneous honey bee operations from the perspective of honey bee disease and pests and will assess the quality of accessible data to conduct studies on honey bee diseases and pests in Nova Scotia.

1.1 Purpose of this Study

This research aims to determine if adequate open data are available to be applied in the understanding of the spatial patterns of honey bee diseases and pests in Nova Scotia, Canada, and to explore if the open data can be used to determine if there are regions within the province that promote the development of honey bee diseases and pests. Nova Scotia's unique geography as a peninsula and its strict honey bee industry policy allow the province to be nearly isolated from outside forces such as honey bees travelling across the province's border. Nova Scotia only has a narrow isthmus with a 25 kilometre terrestrial, provincial boundary connecting the province to the rest of Canada, and the rest of Nova Scotia is surrounded by water. This unique geography makes Nova Scotia virtually an island and an exceptional region to view as a case study.

Improving macro-level management of apiaries requires access to high-quality datasets about the coordinate location of all honey bee hives within the province and accurate and consistent reporting of honey bee diseases and pests, which would allow us to obtain a better understanding of the geographic distribution pattern of honey bee diseases and pests within Nova Scotia. However, even the best quality datasets have quality problems and are often inaccessible. Instead, researchers often need to use proxy datasets to develop a proof of concept and argue for better access to information (Kostyk, Zhou, & Hyman, 2019). For example, if accurate disease reporting is not available, we could use climatic data as a proxy, since some honey bee diseases and pests rely on damp areas for development.

The first step toward disease reduction is for beekeepers to have access to high-quality data that provides information on the location of hives and confirmed cases of honey bee diseases. This information might allow beekeepers to improve their hive management to reduce the development and spread of honey bee diseases and pests and relieve some of the financial stress beekeepers face. By using open data and GIS to visualize and identify regions within Nova Scotia that tend to be vulnerable to honey bee colony health, this research encourages stakeholders to continue to collect and make available high-quality data for future use in hive placements and disease and pest tracking.

1.3 Research Questions

This research addressed the following question: given the current state of publicly available data, and using Nova Scotia as a case study, to what degree can GIS be integrated with and improve the management of contemporary honey bee operations from the perspective of understanding honey bee disease and pests? To aid in answering this question, the research was guided by four sub-questions:

1) How can GIS be used to study the distribution patterns of honey bee diseases and pests in Nova Scotia?

2) How effective is GIS in studying the relationship between environmental conditions and honey bee diseases and pests?
3) How can GIS be used to assess environments that promote honey bee diseases or predict where diseases may occur?
4) What data sources would make for a better analysis of the distribution of disease-prone environments and how can these data sources become more accessible?

Chapter 2: Literature Review

This chapter presents an in-depth literature review and exploration of data quality and the importance of access to data of high quality. It then briefly discusses geographic information systems (GIS) and how it has been applied to the study of honey bees. Afterwards, the next section explores the history of honey bees in North America including the introduction and migration of honey bee subspecies throughout the continent and their impact on the ecosystems. Then, this chapter discusses common honey bee behaviours, such as pollen and nectar collection. Finally, the chapter closes by discussing a few of the most common and impactful honey bee diseases and pests found in Nova Scotia.

2.1 Understanding the Quality of Data

During the 1950s, researchers began to study data quality variability from source to source, which prompted debate about what characterizes data quality (Cai & Zhu, 2015). This debate highlighted three interconnected aspects of data quality. The first aspect is an understanding that quality is based on the number of requirements fulfilled by the dataset outlined by the researchers and their needs (Cai & Zhu, 2015). A dataset that meets and fulfills a large number of outlined requirements is deemed to be of high quality while a dataset that fulfills a small number of requirements is of low quality. The second aspect focuses on the data's "fitness for use" by the researcher (Deming, 1986). Wang and Strong (1996) created four subcategories to help better classify the meaning of "fitness for use": intrinsic, contextual, representational, and accessible. Data are considered to be of high quality should be "intrinsically good, contextually appropriate for the task, clearly represented, and accessible to the data consumer" (Wang & Strong, 1996, p. 22). The third aspect is about the data's conformance to what is required of it (Crosby, 1988); in other words, how easy is it for the researcher to use and work with the data.

The level of quality given to a dataset is determined by a combination of these three aspects and by the researcher carefully evaulating the dataset (Cai & Zhu, 2015; Vetro et al., 2016). If researchers cannot apply a dataset for use in their study – because the dataset either contains no relevant information, or is missing important data – the dataset is assigned a low-quality level. However, different researchers could evaluate the same dataset and assign it a high-quality level because it fits into the research topic or provides enough data to be useful. But, in order for a researcher to determine a dataset's quality level the researcher needs to be able to access the data.

Open data portals have emerged as an increasingly important source of data and provide researchers with a wide range of topics. Researchers can find and combine large datasets from multiple disciplines at no cost. However, the quality of data distributed through open data portals is often lower than the data collected by a private organization (Cutler & Scott-Dupree, 2016; Vetro et al., 2016). Responding to pressure to make data funded by tax revenue available to the public, many open data portals in Canada are operated by the government, either at the federal, provincial, or municipality level. Though most government agencies strive to release good quality data this is not always the case; many government agencies are not provided with detailed guidelines on how to release data that are usable by the public and may release incomplete or unusable datasets (Gasco-Hernandez, Martin, Reggi, Pyo, Luna-Reyes, 2018; Harrison, Pardo, & Cook, 2012). Some of the biggest issues with data quality are related to the accuracy, format, aggregation, integration, and precision of the data (Tauberer, 2014; Vetro et al., 2016).

A study conducted by Martin, Law, Ran, Helbig, and Birkhead (2017) conducted an in-depth search on the quality of data released on three government open data portals in the United States. The authors concluded that most of the data and datasets available to the public lacked enough demographic variables to be used or aggregated to overly broad demographic categories which may limit the usefulness of the data. The study also noted that most of the datasets did not supply the same metadata fields, which could make it difficult to find high quality “fit for use” data. Another study conducted by Moudry and Devillers (2020) examined three global biodiversity open data portals. The study argued that the three portals provide data that can be used by some researchers but not others. The study reported that the three data portals provided good, up to date, and accurate datasets with a few datasets containing incorrect data. However, the three data portals contained multiple duplicates of datasets. These two studies provide an example of how both government and non-government open data portals have problems with managing data quality.

To help manage and promote high-quality datasets, several schemes have been created to assess the quality of publicly released data sets and promote the importance of the release of high quality, standardized datasets. For example, Berners-Lee (2006) created a five-star rating scheme that assesses the file format and how the data was released. Viscusi, Spahiu, Maurino, and Batini (2014) created a scheme that analyzed the completeness, accuracy, and timeliness of the datasets available on open data portals. Even though each scheme analyzes open datasets slightly differently, they are looking for the same key elements: completeness, accuracy, traceability, currentness, expiration, compliance, and understandability (Berners-lee, 2006; Scannapieco & Catarci, 2002; Spahiu et al., 2014; Vetro et al., 2016; Ubaldi, 2013). Datasets that aim to meet the majority, if not all, of the elements listed could be used successfully in multiple fields of study but to use the data in a GIS means some spatially-specific types of data – such as longitude and latitude coordinates – need to be present (Bowman, 2020).

2.2 Geographic Information Systems

Geographic information systems (GIS) were introduced in the 1960s as a way to handle and visualize large volumes of spatial data that would be too difficult to handle and draw by hand and could be used in a wide variety of disciplines (Goodchild, 2004). The systems were introduced as a database management system to manage and tie in large amounts of census data to the street level and have since developed to include the added benefits of processing and manipulating aspatial data variables attached to spatial (coordinate) data through functions such as queries, overlays, buffers, map algebra, and the calculation of surface derivatives (Unwin, 1996). In particular, the work done by Roger Tomlinson on land inventory and environmental impact assessments through the ability to store, analyze, and manipulate geospatial data layers (Albrecht et al. 2020), relates to the land suitability analysis that was used in this thesis.

GIS experienced a shift during the late 1980s and early 1990s when discussions surrounding the relationship between GIS and spatial analysis began to arise. GIS users began to question the reliability of the results determined through interpolation and overlay and asked how statistics can be applied to the practice (Goodchild, 1987; Unwin, 1995). Since then, GISystems have become extremely powerful tools used to statistically describe spatial phenomena, infer and predict spatial patterns, and to represent geographic information on computer-generated maps, allowing researchers to process data and provide answers to questions that were thought impossible to answer because of the complexity of geographic data.

Since its introduction, GIScience and GISystems have been used in a range of fields and disciplines to understand patterns over space and time. More specifically, the software has been used to study animal behaviour (Douglas, Hunt, Abery, & Allen, 2009; Hooge, Eichenlaub, & Solomon, 2001; Norstrom, 2001), human behaviour (Lawrence, Stevenson, Oxley, & Logan, 2015; Meyer, 2017), and climate (Clark, Rose, Levine, & Hargrove, 2001: Swetnam et al., 2011). The application of GIS becomes even more powerful when it is used to study the spatial trends of variables and phenomena within an area, which allows researchers the ability to view changes over a period of time and to hypothesize and conduct research into why those changes occurred.

However, one of the biggest drawbacks to GIScience and GISystems is that the quality of the produced maps are only as high as the data used to create the maps (Medeiros & Holanda, 2019; Prokudin, Levit, & Hossfeld, 2019), especially if the researcher is integrating data obtained from open data portals (Antoniou & Skopeliti, 2015). As mentioned previously, open data portals contain many free-to-use datasets, most of which contain some sort of geographic information, but not all datasets have the same level of data quality.

Geographic information is made up of three main aspects which makes this type of information uniquely special. The first aspect of geographic information is the use of discrete and continuous data to describe geographic features (Longley, Goodchild, Maguire, & Rhind, 2015). Discrete features are objects that are easy to locate, count, measure, identify, and have a clear boundary. For example, buildings, roads, trails, and parks would all be considered discrete features. Continuous features are less defined, harder to count, and exist across a wider space. Examples of continuous features used in the analysis in this thesis are elevation and temperatures that tend to change over large areas.

The second aspect is the types of levels of measurements used in GIScience. There are four types of levels of measurements used in statistics – nominal, ordinal, interval, and ratio (Longley et al., 2015). Each level of measurement acts differently than the next. Nominal level data are the names feature and in the case of this thesis, the nominal level data are the names of honey bee disease and pest names. The ordinal level of measurement ranks geographic features but not based on numerical value, instead features are placed in order of importance. Interval data are numeric with no fixed beginning or end numbers and zero if arbitrary (zero degrees Celsius is different than zero degrees Fahrenheit). Temperature is an excellent example of interval data. The final type of level of measurement is a ratio but zero is not arbitrary (zero metres is the same as zero feet). Data types are important: if an analysis requires data with different levels of measurement, it may be necessary to standardize the data across the various datasets.

One method used by GIScience and GISystems to combat data quality issues is the multi-criteria decision analysis (MCDA) – also referred to as multi-attribute decision making (MADM) - which allows researchers to incorporate and test relationships across multiple disciplines and datasets and can be applied to multiple problems (Medeiros et al., 2019). The use of MCDA allows researchers to draw upon and combine knowledge from multiple disciplines to answer a specific question; in a GIS-based MCDA, each criterion contains some geographic elements that can be visualized and analyzed within a GIS setting (Fang, 2015). Multi-criteria decision analysis can allow researchers, decision-makers, or stakeholders to rank factors relating to a problem and present them in the same geographical space (Fang, 2015). However, if four low-quality datasets are used in an MCDA, the produced map will be of low-quality. To avoid the creation of low-quality maps, GIS allows researchers to use proxy datasets to aid in proving their concept (Prokudin et al., 2020).

One of the most useful MCDA techniques is suitability analysis (Malczewski, 2004). Suitability maps, or series of maps, highlight how suitable an area is for a specific variable based on a series of ratings. Suitability maps combine the derivatives of several individual inputs, each representing a different factor that could potentially affect the variable or phenomenon of interest (Hopkins, 1977). This method can be applied to a wide range of research, such as land suitability for animals and plants, agriculture activities, landscape evaluation, impact assessment, and regional planning (Malczewski, 2004). The method has been used to understand and predict diseases, such as the spread of Lyme disease in the north-central United States and Eastern Ontario (Chen et al., 2015; Guerra et al., 2002).

Studies by Makori et al. (2017), Maris et al. (2008), Von Buren et al. (2019), and Zoccali et al. (2017) have shown that GIS, and more specifically MCDA, can be used to help beekeepers better manage their beehives and reduce the spread and development of honey bee diseases and pests. Maris et al. (2008) were able to use MCDA to identify regions in Selangor, Malaysia, which meet the needs of honey bees but are currently underutilized by beekeepers. Makori et al. (2017) and von Buren et al. (2019) used GIS to identify and predict disease and pest clusters by using known disease and pest locations as well as geographic and bioclimatic variables to identify the conditions needed for the development of the diseases and pests. These studies employ a wide range of variables – including the length of the season, population growth in honey bee colonies, slope, temperatures, evapotranspiration, rainfall, and moisture indexes – to determine the best locations for beehives or to predict the spatial distribution of honey bee diseases and pests. Von Buren, Oehen, Kuhn, and Erler (2019) studied the spatial distribution of honey bee brood diseases in Switzerland by mapping the density of apiaries and the density of reported brood diseases.

Other studies have shown that aerial photographs and satellite imagery can be used to determine and map bee friendly locations by analyzing landscape characteristics, bee foraging ranges, and migratory pollination variables (Galbraith et al., 2015; Gallant et al., 2014; Zoccali et al., 2017); harmonic radar and LiDAR – data gathered from an airplane or helicopter using pulse lasers to measure ranges of the Earth – have been used to tag and track small-scale honey bee density and spatial variation (Galbraith et al., 2015; Jarnevich et al., 2013). Researchers using GIS have been able to establish that native wild bees are more efficient as crop pollinators when their hive has access to forested areas (Arthur, Li, Henry, & Cunningham, 2010), to identify a population relationship between climate and native bee populations (Giannini et al., 2012), and to map potential apiary locations for a region to promote the growth of the honey bee industry (Cunningham, 2017; Gallant et al., 2014). A 2017 article showed that suitability analysis could be used to predict the spatial distribution of Varroa mites in Kenya by using remote sensing and bioclimatic variables data – such as mean annual temperature, maximum yearly temperature, evapotranspiration, mean annual rainfall, and moisture index – to map out potential areas in Kenya that promote the growth of Varroa mites (Makori et al., 2017).

In an ideal world with high-quality data available for the use of research, we would have access to the following high-quality datasets:

1) Coordinate, (e.g., simple longitude / latitude, or UTM), locations of every honey bee hive in Nova Scotia which will allow researchers to visualize the distribution of hives within the province which would provide a better understanding of the Nova Scotia bee industry and which parts of the province are housing hives.
2) Coordinate locations of all reported suspected cases of honey bee diseases and pest from beekeepers to the provincial apiculturist. This data would provide an understanding of which areas of the province are following the *Bee Industry Act* and honey bee management.
3) Coordinate locations of all confirmed cases of honey bee diseases and pests by the provincial apiculturist, which allow researchers to visualize where each confirmed case occurred and could lead to the identification of cluster locations for future research.
4) Bee management practices of each registered beekeeper in Nova Scotia. This includes the number of honey bee hive each registered beekeeper owns and where the coordinate locations of each hive. This may allow researchers to obtain a better understanding of how beekeepers manage their hives and to view is the size of the operation plays a role in honey bee health.

5) Climatic data such as temperature, precipitation, moisture index, potential evapotranspiration, and humidity index for all of Nova Scotia. Honey bee activities, such as hive cleaning and collecting pollen, depend on the climate and if the climate is not optimal for normal bee activity will be reduced (Abou-Shaara, 2014).
6) Solar insulation data may allow for a better understanding of which are in Nova Scotia receive the most direct solar radiation resulting in high solar insulation areas to become warmer and dry faster than areas of low solar insulation.

However, we do not live in a perfect world, meaning that proxy datasets – data that can approximate the necessary data because they are related in some way – need to be used but only if the proxy datasets are of good quality.

2.3 A Brief History of the Honey Bee in North America

Geographic variations such as climate and land formations have allowed the honey bee to evolve over time into 30 different subspecies, which helps these bees to survive in a variety of climates around the world. The dark European honey bee (*Apis mellifera millifera*) can be found across northern Europe, reaching from the British Isles to the Ural Mountain range in western Russia. The dark European honey bee subspecies has adapted to surviving cold, harsh winters, and living in forested regions. Because of these traits, it is no surprise that during the 1600s, when Europeans started colonizing the New World, they brought the dark European honey bee along with them to produce honey

(Sheppard, 1989). The subspecies thrived in the new environment and quickly spread across the wooded areas of the continent (Seeley, 2019).

Shortly after the introduction of the steam engine in the mid-1800s, North American beekeepers started to import thousands of mated queen bees and their hives of other subspecies from southern Europe and North Africa. During this massive importation of honey bees, three subspecies (*A. m. ligustica*, *A. m. carnica*, and *A. m. caucasica*) from south-central Europe became so popular that their genetics is found in most of today's honey bees (Schiff, Sheppard, Loper, & Shumanuki, 1994). This importation of bees came to a sudden stop in the United States in 1922 when the American Congress passed the *Honey Bee Act* to prevent the spread of Isle of Wight disease (*Acarapis woodi*). This Act restricted American beekeepers from importing queens and hives from selected countries and the ban remains in effect today (vanEngelsdorp & Meixner, 2010).

In 1987, *A. m. scutellate*, a honey bee subspecies native to eastern and southern Africa, was smuggled into Florida (Seeley, 2019). Since its introduction, this subspecies has thrived and influenced the genetics of honey bees located in the southeastern United States, but not the honey bees living in the northeastern United States due to the cooler temperatures (Rangel et al., 2016). However, some evidence indicates that this subspecies has been moving northward due to the rise in global temperatures (Seeley, 2019). Today, Canadian beekeepers import bees from all over the world, but New Zealand, Australia, Hawaii, California, and Chile are the primary sources for new queens and hives.

Since their introduction to North America – and to other parts of the world – the honey bee has become one of the most highly valued pollinators. It is estimated that honey bees, along with other pollinators, pollinate up to one-third of the plants used by humans for either food or other products. These crops include the crops used to feed cattle, pigs, and poultry (Aizen, Garibaldi, Cunningham, & Klein, 2009). If a plant is not pollinated during its pollination period, it will not bear any seeds, berries, or fruit. Therefore, there must be enough pollinators in the area to ensure that every crop is pollinated or farmers risk losing money (Bradbear & Food and Agriculture Organization of the United Nations, 2009). Aside from aiding farms and crop development, pollinators also play an essential role in ecosystems by pollinating an estimated 87.5 percent of all flowering plants (Ollerton, Winfree, & Tarrant, 2011).

These numbers demonstrate how important high-valued pollinators such as honey bees are to our global food system. Without honey bees, one-third of our food plants would struggle to grow, thus forcing our society to change rapidly to adapt to new foods that do not rely on such pollinators. We would not be the only species to suffer from the loss of honey bees: ecosystems will start to collapse as flowering, and food-bearing plants begin to disappear due to lack of pollination. Because of these reasons, it is essential to continue the efforts to understand honey bees and what affects them so that we can prevent their disappearance.

2.4 A “Bee”haviour Review

Honey bees and flowers have co-evolved over millions of years to ensure evolutionary success. Flowers have developed brightly coloured petals and sweet-tasting nectar to attract honey bees and other pollinators so they can pick up the pollen and transfer it to other flowers. In turn, honey bees’ eyesight has evolved to detect ultra-violet wavelengths, enabling them to distinguish the shapes and patterns of flowers. This ability to see ultra-violet wavelengths allows honey bees to see the Sun under cloudy conditions and to communicate flower locations through the “waggle dance”[2] to their hive-mates. Another evolutionary feature is the honey bee’s sense of smell, which is estimated to be 40 times better than a human’s, and plays a vital role in locating food (British Columbia Ministry of Agriculture, 2015).

Research into honey bee behaviour has determined that honey bees usually forage for nectar up to eight kilometres away from their hive and can fly at a speed of about 25 km/h (British Columbia Ministry of Agriculture, 2015; Ferguson, Northfield, & Lach, 2018; Requier, Jowanowitsch, Kallnik, & Steffan-Dewenter, 2019). However, environmental factors such as weather, food sources, and food quality play an important role in how far and fast a bee will fly to find food. The optimal weather conditions for bees are a temperature between 16°C - 30°C with little wind (Abou-Shaara, 2014); temperatures below this range will slow the bees while temperatures above 30°C will cause the bees to change

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[2] Waggle dance: a form of bee communication that relates information about location of nectar, pollen, water, and new nest-sites to other members of the colony.

from foraging nectar to foraging water and cooling efforts (Rader, Reilly, Bartomeus, & Winfree, 2013). Bees can visit up to 40 flowers per minute but will only focus on one flower species during a single collection trip; this behaviour is essential in the transfer of pollen from one plant to another plant of the same species and is vital for commercial crop growth (Abou-Shaara, 2014).

Honey production is a four-step process. The first step is the use of specialized tongues to gather the nectar from the flower and transport it back to the hive in a secondary stomach called the nectar stomach. The next step is transferring the nectar to the house bees – a worker bee that never leaves the colony – where they will once again transfer the nectar to another house bee. During the summer, honey bee colonies can have a population of between 50,000 to 80,000 bees (Canadian Honey Council, 2020). Depending on the nectar's composition, this transferring of nectar will occur multiple times before being stored within a honeycomb. Each transfer adds an enzyme to the mixture that helps turn nectar into honey. The third step involves the removal of water from the nectar. Water is removed by a bee standing over the nectar-filled cell and fanning its wings to encourage water to evaporate. The final step is placing a layer of wax over the cell – called capping – to act as protection and as a preservative (Hanson, 2016). It is after this stage that beekeepers will remove the honey from the hive.

It is in the best interest of the beekeeper to understand how to keep a beehive healthy, not just for financial gain, but for the benefit of the hive. Most bee diseases are fungal related and tend to thrive in damp areas, so it is important that hives and apiaries be located in dry, south-facing locations to reduce the development of diseases (Agriculture and Agri-Food Canada, n.d.; Bamford & Heath, 1989). If a hive is placed in a damp area, the hive's internal humidity levels could rise, which increases the chances of a disease outbreak within the hive and apiary (Conrad, 2017).

Bees should also have access to an abundant variety of flowers and plants for foraging (Agriculture and Agri-Food Canada, n.d.). Honey bees under nutrient stress will often steal honey from other hives to bring back to their hive, an action referred to as "robbing" (Lindstrom, Korpela, & Fries, 2008). This action of stealing honey from a hive increases the chance of a disease-free hive becoming infected because most fungal spores can survive in honey, and if a honey bee from a non-infected hive brings back infected honey to its hive, the uninfected hive will become infected. This spread of infection also works in the opposite way where honey bees carrying mites could transfer the mites from their body to a clean hive while robbing honey (Lindstrom, Korpela, & Fries, 2008).

2.5 The Diseases and Pests

Diseases and pests can cause great damage to honey bee colonies and in order to protect the honey bee population, it is important to understand how these diseases and pests develop and what effects they have on the colonies. The Nova Scotia Department of Agriculture provides beekeepers with a list of six designated honey bee diseases – chalkbrood, American foulbrood (AFB), European foulbrood, Nosema disease, sacbrood, and American foulbrood resistant oxytet – and 11 designated pests – Varroa mite and their two resistant subspecies, Asian mite, Honey bee tracheal mite, Small hive-bee, Africanized bees, Cape honey bee, Asian honey bee, Asian Nosema, and the Asian giant hornet. The *Bee Industry Act* (2007) requires beekeepers to report any signs of AFB or pests to the Department of Agriculture immediately (Nova Scotia Legislature, 2007). However, for the purpose of this literature review, four of the most common and significant honey bee diseases and pests – Chalkbrood, American Foulbrood, Varroa mites, and Nosema – are discussed because these are the diseases and pests Nova Scotian beekeepers are more likely to face.

2.5.1 Chalkbrood

Chalkbrood is one of the world's most common honey bee diseases (Aronstein, & Murray, 2010) and is caused by the fungus *Ascosphaera apis.* Fungus spores are picked up by worker bees while collecting nectar and brought into the hive when they return. The spores are then transported throughout the colony and can be found in the beeswax, pollen, honey, hive combs, and in bees and larvae, and can remain active for 15 years (Conrad, 2017). Although the spores are found throughout the hive, they are only lethal to the hive's larvae. The spores enter the larvae's mid-gut when it ingests infected honey, where the spores will germinate and start to grow. The spores will continue to grow inside the larvae consuming nutrients from it until the spores burst from the larvae's shell. Once the infection has broken the outer shell of the larvae, it will cover the carcass with a white mycelium layer containing millions of new spores. Eventually, the larvae carcass will dry and become mummified, thus the name chalkbrood (Food and Agriculture Organization of the United Nations, 2006).

The disease does not tend to destroy the colony but will increase the hive’s stress levels and decrease colony productivity: most hives can recover from the disease without the beekeeper’s aid. However, the same might not be said for an already stressed and struggling colony where the disease could lead to the hive’s collapse (Collison, & Sheridan. 2012).

A summary of the progression of chalkbrood was published by Plant Health Australia in 2016. According to the summary, there are several signs of the disease that beekeepers should keep an eye out for, especially during the spring and fall. The first is a chalky-white covering on larvae cells, which indicates that something is wrong with the larvae. The second sign of chalkbrood is dead, black or white, hardened, withered, and chalk-like – or mummy-like – larvae. The third sign is an enlarged larva protruding out of its cell. The final sign is scattered larvae surrounding the hive caused by the nurse bees removing the dead larvae from the hive (Plant Health Australia, 2016). Another way to determine if a colony has been infected with *A. apis* spores is by sending samples from the hive and the hive larvae to a lab to be tested (Evison, 2015).

Two environmental factors contribute to the activation of the *A. apis* spores. The first is the temperature of the hive. The average *A. apis* spore strain activation occurs in temperature ranging from 4 to 65°C, with the optimal growing temperatures between 25 to 37°C for vegetative growth and 31 and 35°C for sporulation. Temperatures below 4°C reduce spore activation, and inconsistency inactivation starts to occur at 40°C (Bamford & Heath, 1989; Flores et al., 1996; James, 2005). These temperature ranges are consistent with the temperatures found within honey bee hives. The second factor is the hive’s water activity. *A. apis* spore activation is associated with moist conditions and high relative humidity, which are often found in poorly ventilated colonies or hives located in poorly drained and shaded areas (Conrad, 2017; Yoder et al., 2016). Studies have shown that the optimal relative humidity level for spore germination occurs at 87%. When the hive does not contain enough water, the spores cannot germinate, which leads to a reduced growth rate (Yoder et al., 2016).

2.5.2 American Foulbrood

American foulbrood (AFB) is caused by the spore-forming bacterium *Paenibacillus larvae* (*P. larvae*) and has become one of the most widespread and destructive honey bee larvae diseases, usually resulting in the death of the colony (Fries, & Camazine, 2001; U.S. Department of Agriculture, 2019). It infects both strong and weak colonies, and hives can become infected anytime during the year. The disease can be found on every continent that houses honey bees and currently no known cure is available. Most antibiotics only affect the vegetative stage of the bacterium and not the infective spores; instead, many areas, including Nova Scotia, choose to burn infected hive materials as a way to prevent the spread of the disease (Morrissey et al., 2015).

AFB spores can remain infectious for more than 35 years and have an extremely high tolerance to heat, cold, drought, and humidity (Hasemann, 1961). This makes it very difficult to contain the spread of the spores. It is easy for bees and humans to spread dormant spores across large geographic areas, causing future outbreaks in areas not previously affected. The long-life cycle of AFB spores makes it challenging to determine where the spores came from without the help of enterobacterial repetitive intergenic consensus (ERIC) primers. ERIC primers look at the genetic make of the spores to determine where the strain originated and where the strain has been; however, ERIC primers do not allow for repeatable methods, which makes it very difficult to discriminate between strain types (Morrissey et al., 2015).

The disease infects larvae 12 to 36 hours after hatching and spreads its spores throughout the hive while nurse bees are removing the larvae’s remains (Genersch, 2010). The larvae usually die 11 days after egg laying (Lindstrom et al., 2008). The spores are spread between hives through common honey bee behaviours such as robbing, accidentally returning to the wrong hive, swarming into an already infected area, and coming into contact with infected water sources. Additionally, spores can be spread through beekeeper interaction with contaminated equipment; in fact, hives within apiaries are highly susceptible to becoming infected with AFB due to their close proximity to each other. The disease can quickly spread through an apiary, causing mass honey bee hive death (Fries, & Camazine, 2001; Fries, Lindstrom, & Korpela, 2006).

Another problem beekeepers face in protecting their bee colonies from AFB is that information that focuses on the environmental requirements needed for AFB spore germination is very limited (Alvarado, Phui, Elekonich, & Abel-Santos, 2013). We understand that a series of requirements are needed in order to trigger the germination signals in other types of bacterial diseases but little is known about the requirements needed for AFB spores (Paredes-Sabja, Setlow,

& Sarker, 2011). However, a study conducted in 2013 by Alvarado et al., revealed that some of the trigging requirements for the germination of *P. larvae* spores are the presence of L-tyrosine (an amino acid), uric acid, and a pH level between five and seven. The amount of L-tyrosine and uric acid in the gut of honey bees and larvae are not known but it is known that both L-tyrosine and uric acid are found in the food given to larvae (Wu, Zhou, Xue, Li, & Zhao, 2009). The pH level required for AFB spore germination matches the pH levels found in honey bee hives (Alvarado et al., 2013).

The National Bee Diagnostic Centre (2017) conducted a four-year study on the health of Canadian honey bees. The study looked at 225 honey bee colonies across Canada to record the health of Canadian honey bees. Of the 255 colonies, only 24 (9%) showed any signs of AFB; these 24 colonies were spread relatively evenly across the country.

Plant Health Australia (2019a) lists several signs and symptoms of AFB that beekeepers should watch for. The first is cell cappings that appear to be sunken in, darker coloured, and greasy; this change in capping appearances occurs when the larvae are decomposing within the cell. Another common sign is holes in the capping caused by nurse bees removing the dead brood from the hive. Infected brood will also appear different than non-infected brood. Brood that are infected become dark brown and are difficult to remove from cells. The final sign of the disease is the smell – thus, the name foulbrood; infected hives will start to release a sulphurous smell due to the decomposing larvae.

It is recommended that beekeepers check their hives twice a year – usually once in the spring and once in the fall – for the signs listed above (Ontario Ministry of Agriculture, Food, and Rural Affairs, 2019; Plant Health Australia, 2019a). To reduce the building of dormant spores counts, brood combs should be replaced every three or four years, and beekeepers should try to reduce or prevent using the same equipment for multiple hives. If an outbreak occurs, the beekeeper can use chemical controls – Oxytetracline and Terramycin are only allowed to be used in Nova Scotia during the spring and fall (Country Fields, 2019) – to slow the spread. But, as mentioned earlier, chemicals only affect the vegetated bacterium, not the spores, and therefore the chemicals should only be used as a short-term solution (Plant Health Australia, 2019a). The final method of treating infected hives is by burning all equipment – frames, bottom boards, and combs – and killing all the bees.

2.5.3 Varroa Mites

Varroa destructor and *Varroa jacobsoni* have become among the biggest pests to honey bees. Varroa mites can be found all over the world, with the exception of Australia (Sun, 2019). However, an infected hive was discovered aboard a ship from the United States travelling to Australia, but due to the fast action of local beekeepers and strong quarantine methods the mites were destroyed before spreading (Rooth, 2018). It is believed that the mites' native hosts were Asian cavity-nesting honey bees (*Apis cerana* and *Apis nigrocincta*) (de Guzman & Rinderer, 1999) and, therefore, did not cause much damage to the Asian honey bees (Warrit, Smith, & Lekprayoon, 2006). However, the pest can cause serious damage to the western honey bee population. The mites feed on honey bee hemolymph and can transmit diseases from one bee to the next. In fact, Varroa mites are known to transmit 12 of the known 20 honey bee viruses when the mites feed off a bee (Kevan, Hannan, Ostiguy, & Guzman-Novoa, 2006). An infected mite can transfer disease to an uninfected bee, and an uninfected mite can become infected when feeding off an infected bee (Ratti, 2015).

The mites are entirely dependent on the honey bee to complete their life cycle. The adult female mites enter a brood's cell before the cell is capped and lays its eggs at the bottom of the cell; the female mite will lay one male egg followed by five to six female eggs. The mother mite will then prepare a site on the brood for its offspring to feed, mature, and mate (Kozak, 2008; Ratti, 2011). As the honey bee brood matures and eats the provided food in the cell, the mite offspring will slowly become free and start feeding off the brood. The male offspring only function to fertilize their sister offspring and will usually die before ever leaving the cell; the female offspring will remain attached to the brood until the brood leaves the cell. Once the brood leaves the cell, the mature mites will attach themselves to other bees in the hive and begin feeding off them and any immature mites will quickly die. Mature female mites can live up to 80-100 days and go through two to three reproductive cycles (Kozak, 2008).

Varroa mites are hydrophilic, meaning that they rely heavily on water access. Studies have shown that the mites can lose water rapidly, 2% of their total water weight per hour, but still survive with a 37% water loss (Bruce, Needham, & Potts*,* 1997; Yoder*,* Sammataro, Peterson, Needham, & Bruce, 1999). This means that the mites prefer to live in environments that have a relative humidity between 60% and 80% - a percentage range that aligns with the relative humidity of honey bee hives (Kozak, 2008). Varroa mites also tolerate a range in temperature, although this tolerance varies across seasons and age. Mites prefer a temperature range of 22 to 43°C during the summer months and a temperature range of 16 to 36°C during the winter months. The Varroa mite offspring tolerance range correlates with the temperature tolerance range of honey bee broods (Le Conte, Arnold, & Desenfant, 1990).

The mites are quite mobile and can quickly spread throughout the hive. They can also easily be transferred from one hive to another if an infected honey bee either robs or drifts to an uninfected hive. Beekeepers can also transfer mites between hives. The mites can attach themselves to clothing, equipment, and vehicles and be carried across long distances (Plant Health Australia, 2019b).

2.5.4 Sacbrood

The sacbrood disease is caused by the sacbrood virus (SBV) and is commonly found in honey bee colonies in Europe and the United States but can be found throughout the world (Choi et al., 2010). The virus mainly affects a colony's larvae but also accumulates in adult worker bees' hypopharyngeal gland. The virus causes the larvae to not be able to break through its protective skin, and this causes a build-up of ecdysial fluid. The larvae do not pupate, which causes it to die within its shell (Li et al., 2019). It is this build-up of fluid within the sac that gives the virus its name (Grabensteiner et al., 2001). It is believed that the larvae become infected by ingesting the secretions from infected nurse bees (Bailey, & Fernando, 1972).

The disease has been linked to a number of colony stressors that have an effect on SBV, but it is most prominent during the spring when the outside temperature tends to fluctuate and will eventually disappear during the summer when temperatures are consistently warm and through natural hygienic behaviours of honey bees (Tentcheva et al., 2004). Tentcheva et al. (2004) argue that the quality of the pollen collected and consumed by honey bees could also have an effect on a colony's chances of becoming infected with SBV. The study suggested that there is some evidence that Varroa mites also play a role in the transmitting of the disease, but more research is needed to support their claim.

As mentioned earlier, infected colonies are usually able to recover from the disease; however, the disease can severely affect a colony if the colony is facing more than one stressor. When this occurs, beekeepers should either add more worker bees to the hive or move the hive to an area with more pollen opportunities (Plant Health Australia, 2019c).

2.5.5 Nosema

Nosema is a microsporidian fungus that infects the midgut cells of adult honey bees (Hendriksma, Bain, Nguyen, & Nieh, 2020). There are currently over 1200 species of known Nosema, two of which are limited to honey bees: *Nosema apis* and *Nosema ceranae*. *N. apis* was first discovered during the early 1900s and has become known as the biggest microsporidian parasite of the western honey bee. *N. ceranae* has traditionally been associated with the Asian honey bee (*Apis cerana)* but in 2005 *N. ceranae* spores were discovered in western honey bees, and since then numerous other reports have arisen (Fries, 1993; Goblirsch, 2018; Higes, Martin, & Meana, 2006; Williams, 2013). Nosema is the most common and widespread adult bees' disease.

The spores are transmitted horizontally among the colony's bee population. The spores infect the hive's cells and honey, which is then consumed by the bee. After a spore is ingested, it attaches itself to the bee's midgut cells and starts to absorb the cell's nutrients. The spore then splits into two, and both continue to absorb nutrients and divide until germination occurs, where the new spores will spread throughout the honey bee infecting new cells. This pattern will continue to occur until the honey bee dies due to a lack of nutrients. Once infected, honey bees can have up to 50 million fungus spores at the time of their death (Mussen, 2011).

Both types of Nosema have negative effects on the hive. It has been observed that *N. apis* can reduce the life span of a honey bee by 78% and can cause the bee to skip growth phases. Infected honey bees usually skip the brood rearing phase and start foraging at an abnormally young age (Mussen, 2011; vanEngelsdrop, & Meixner, 2010). If the hive's queen becomes infected, the hive will likely not survive the winter months. Infected bees lose the ability to control defecation and will often defecate within the hive (Moeller, 1972). The disease also affects a honey bee's orientation skills, thus affecting its ability to forage nectar successfully (Kralj, & Fuchs, 2010) and decreasing food-sharing between worker bees (Naug, & Gibbs, 2009)

Nosema is mainly a problem in temperate climates that have long, cool winters, which forces the colony to remain in the hive for longer periods, reducing the hive's cleanliness and leading to increased infection rates. The disease occurs more frequently during the spring due to the cooler outside temperatures and wetter conditions, which limits a bee's time spent outside of the hive. A build-up of spores occurs during the winter and spring months while the summer months see a decrease in spore counts (Moeller, 1972; Williams, 2013).

Beekeepers use several methods to control and manage *Nosema* outbreaks. One method is to use a natural antibiotic medicine – fumagillin dicyclohexylammonium – to control both *N. apis* and *N. ceranae* infections. However, this method is only a temporary cure to the disease by suppressing the spore's vegetative state: it does not kill mature spores (Katznelson & Jamieson, 1952; McGowan, 2012). After a year's treatment, spore levels return to previous levels (McGowan, 2012). An alternative method is fumigating old hives and combs with acetic acid, which kills Nosema spores in honey bee feces (Kelly, 2019). Another method to control the disease is by exposing beekeeping equipment to hot or cold temperatures. The beekeeper will need to expose the equipment to 60°C or higher for 15 minutes – or at 49°C for 24 hours – to kill *N. apis* spores, however, *N. ceranae* has a high thermotolerance, and for this strain, the beekeeper will need to expose the equipment at 60°C for one month. It has been shown that freezing temperatures (0°C or lower) have a greater killing effect on *N. ceranae* than *N. apis* (McGowan, 2012). The final method of controlling Nosema spores is by using resveratrol, an ecologically friendly phenolic compound that has shown to be effective in reducing *N. Ceranae* infections, lowering spore levels, and expanding an infected honey bee’s life expectancy (Costa, Lodesani, & Maistrello, 2010; Holt, & Grozinger, 2016).

Chapter 3: Case Study Area

3.1 Nova Scotia Geography

Nova Scotia is one of Canada's easternmost provinces and has been described as a "peninsula jutting into the North Atlantic Ocean" (Nova Scotia Department of Environment and Labour, 2002, p. 1). It is the second smallest province in Canada with an area of approximately 52,940 km^2 (or approximately 20,440 mi^2) (Statistics Canada, 2011) and is divided into 18 counties (Figure 1). The province has over 13,300 kilometres of coastline and shares a land border with New Brunswick of about 25 kilometres (Nova Scotia Department of Fisheries and Aquaculture, 2009). The province is home to 971,395 people, most of whom live in the Halifax Regional Municipality (HRM), which houses Nova Scotia's capital city, Halifax (Nova Scotia Finance and Treasury Board, 2019).

Despite its small size, Nova Scotia has a complex geological and glacial history. The province has 39 ecological classifications (Appendix I, A1.1), 47 geological formations, 84 major soil types, and houses at least 40,000 species of plants, animals and invertebrates (Nova Scotia Department of Environment and Labour, 2002). The province's temperature can be described as moderate due to the summer temperatures averaging at 17.9°C and the winter temperatures averaging at -2.9°C (Nova Scotia Environment - Climate Change Unit, 2020).

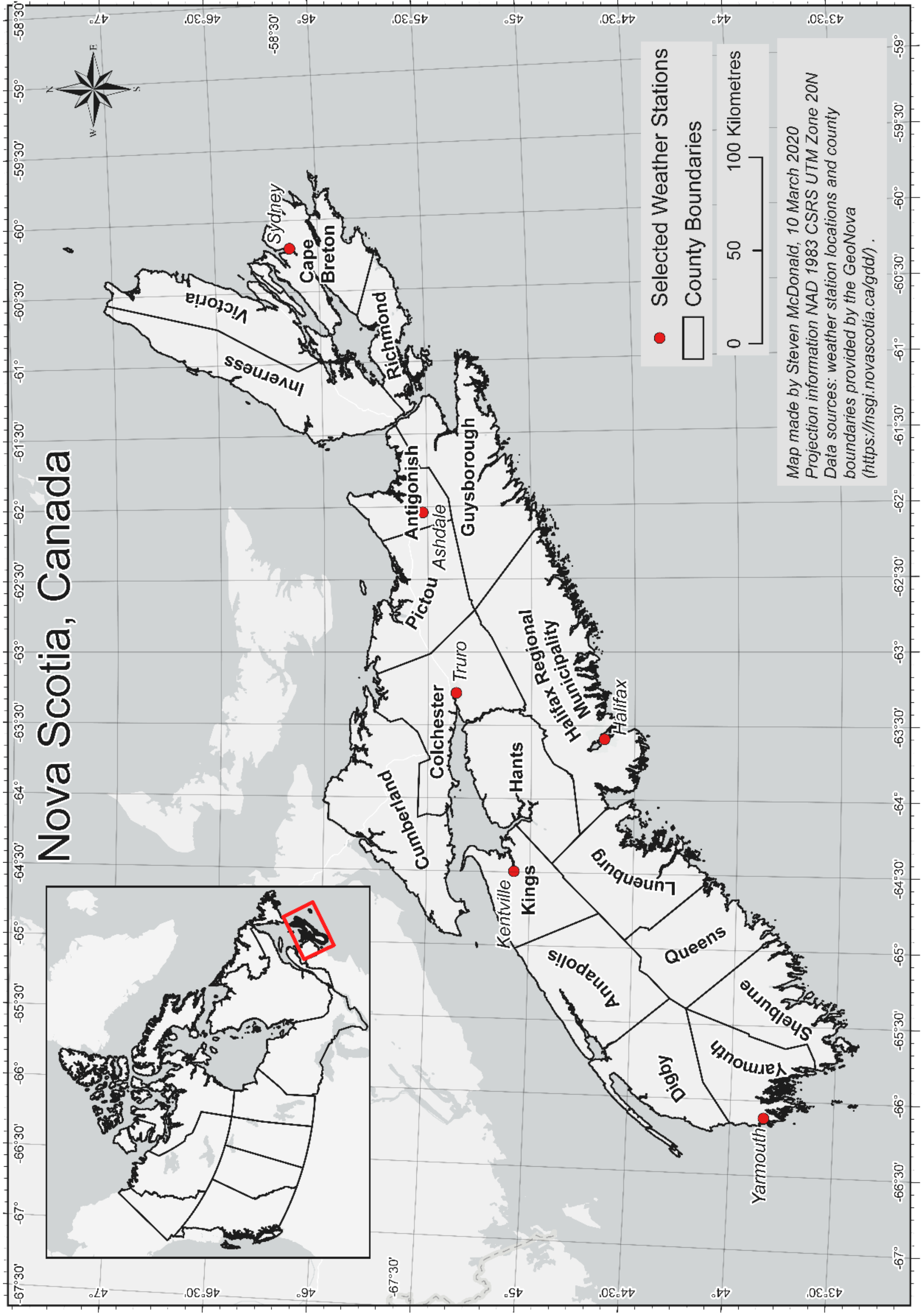
Nova Scotia experiences an average (i.e., mean) of 142 days of rain and 53 days of snow in a year with annual average precipitation of 138.5 centimetres (Nova Scotia Environment - Climate Change Unit, 2020) (Figure 2). However, towns found closer to the ocean experience more consistencies in temperature and weather than areas found further inland.

As mentioned previously, the optimal range of temperatures for honey bees is between 16°C - 30°C (Abou-Shaara, 2014). Nova Scotia's average summertime temperature is just within this range, which means that honey bee colonies in Nova Scotia can forage at optimal conditions during the summer months. During the fall, winter and spring, however, Nova Scotian honey bee activity is reduced due to the average temperatures being below the optimal threshold. Climatic data for the province are available; however, the data only represent the conditions at the locations of the weather stations. Data may be collected for the specific area of a weather station but can be used as a proxy for the surrounding areas. The climatic averages for six weather stations in Nova Scotia between 1981 to 2010 can be seen in the climographs in Figure 2, with Figure 1 showing the locations of the six weather stations.

Nova Scotia contains a variety of microclimates – climates that vary from the surrounding area - which could affect honey bee health. Microclimates are usually caused by three main factors, the difference in the amount of solar radiation and water an area receives, and the amount of thermal insolation an area has (Zhoa, Sailor, & Wentz, 2018). Topography, soil, water bodies, vegetation, and artificial structures all affect a role in a region's microclimate

Figure 1

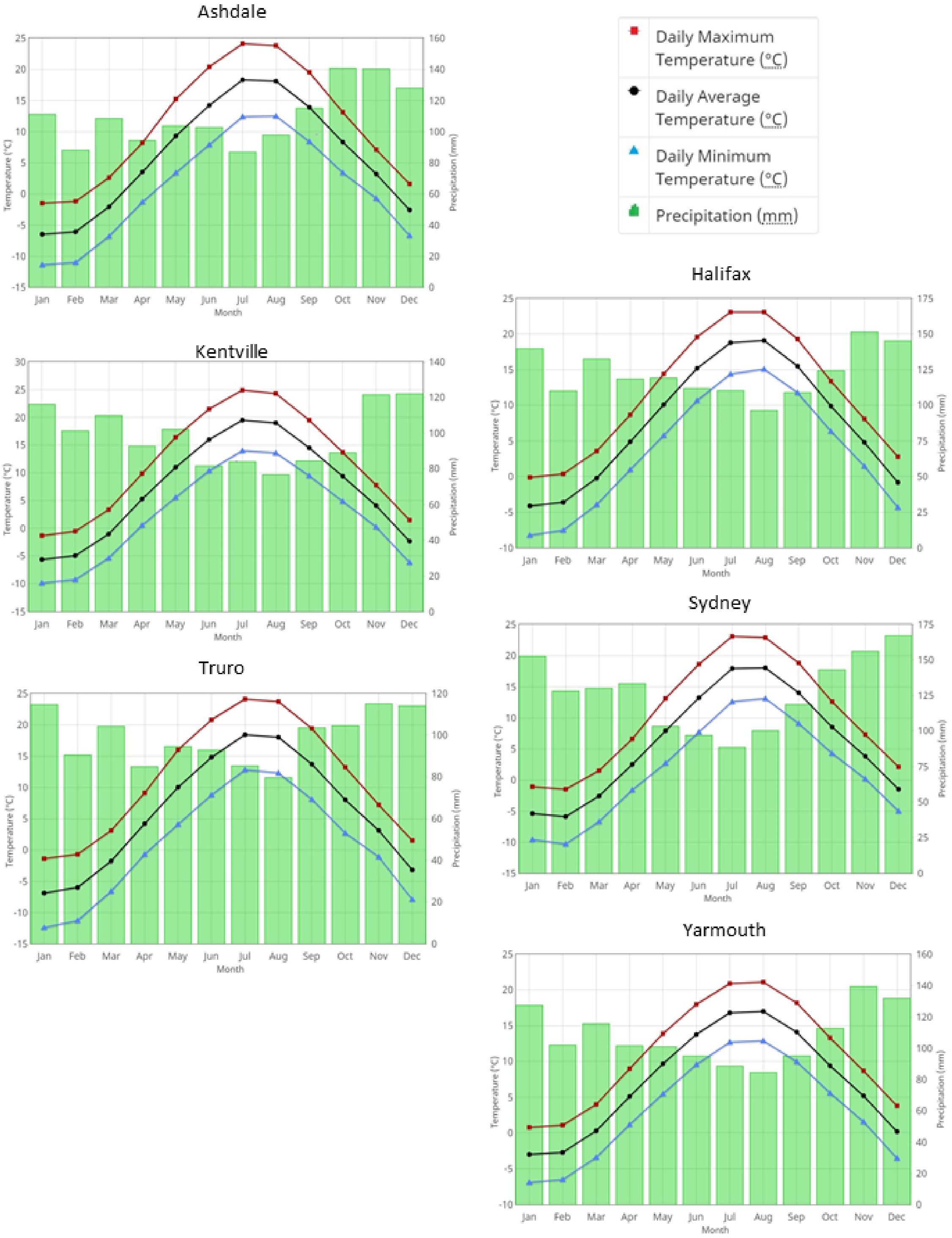
Map of Nova Scotia's counties and selected weather stations



Map made by Steven McDonald, 10 March 2020
Projection information NAD 1983 CSRS UTM Zone 20N
Data sources: weather station locations and county boundaries provided by the GeoNova (https://nsgi.novascotia.ca/gdd/) .

Figure 2

Climographs for six Nova Scotian weather stations, 1981 to 2010.



(Environment and Climate Change Canada, 2019)

(Charrier, Ngao, Saudreau, & Ameglio, 2015). For example, in the northern hemisphere, most north-facing surfaces do not receive direct solar radiation thus causing these surfaces to remain cooler than south-facing surfaces that receive more direct solar radiation. The same occurs with areas that have more vegetation versus areas with low vegetation as vegetation acts as a canopy that intercepts the Sun's rays from reaching the Earth's surface, keeping the area cool.

Cities and other dense urban areas tend to experience warmer temperatures – often referred to as urban heat island effect – than less-dense rural areas. According to Salata et al. (2017), this difference in temperature has been attributed to a number of sources, such as the closeness of large buildings reducing wind movement, the material used in buildings absorbing or reflecting solar radiation towards the ground, and a greenhouse effect caused by an increase in air pollution. However, rural areas also experience microclimate variation, especially in Nova Scotia (Nova Scotia Department of Agriculture, 2010a).

Since there is a potential relationship between wetter areas and the development of honey bee diseases, Nova Scotia is particularly vulnerable to the development of diseases such as chalkbrood and Nosema, which rely on the humidity of the hive to survive and reproduce. Canadian beekeeping best management practices state that beehives should be placed on south-facing surfaces with good drainage to avoid having hives sitting on soils that remain damp thus causing the air near the ground to stay humid longer (Agriculture and

Agri-Food Canada, n.d.). Several factors affect how quickly an area dries – such as soil type and drainage, bedrock type, and the period of direct sunlight – and could indirectly affect normal hive activity by keeping the hive's outside humidity level higher than it would be on dry soil (Akinci, Ozalp, & Turgut, 2013; Monteith, 1965). Soil drainage is described as the rate of the soil being free of water, which greatly influences plant growth and nutrient cycles (Levine, Knox, & Lawrence, 1994). These factors may not directly affect the hive's humidity level but may have an indirect effect on honey bee activities such as collecting nectar and hive cleaning (Plant Health Australia, 2016; Rader et al., 2013).

Other factors contribute to how well soils drain: slope, texture, stoniness, clay content, and climate all affect the rate of drying (Zhao, Ashraf, & Meng, 2012). Nova Scotia's Department of Lands and Forestry's (2017) *Ecological Land Classification for Nova Scotia Map* classifies Nova Scotia soils into three types of drainage: well-drained, poorly drained, and imperfectly drained. As summarized by Huggett (2017), the permeability – the amount of water that seeps through a rock body – of the underlying bedrock also plays a role in determining how much water an area holds. Igneous and metamorphic rocks are resistant to permeation unless they are significantly fractured, which means water tends to sit on the bedrock, causing the surrounding soils to remain wetter longer. In general, sedimentary rocks tend to be more permeable than igneous or metamorphic rocks; however, the permeability rates of sedimentary rocks vary greatly and are dependent on the amount of clay content within the rock (Huggett, 2017).

To reduce colony loss caused by floods and standing waters, it is essential for beekeepers to know and understand where flood plains are located. Floods occur when a river's discharge is unable to transport water quickly enough within the confines of the riverbanks, thus causing the water level to rise above its maximum water capacity and flow over the banks into the surrounding area. This flooded area is referred to as the river's flood plain. Most flood plains are made up of three parts: the first is the river, which provides water to the area, the second is the floodplain where the excess water from the river flows into, and the third is the flood fringe, which defines the limits of the flood plain (Goudie, 2004). Most flood plains are used for agriculture proposes because of the nutrient-rich sediment – called alluvium – deposited during floods; however, this nutrient-rich sediment can retain moisture longer than other types of soils that could lead to the development of honey bee diseases (Earle & Panchuk, 2019).

There are a number of reasons why a flood may occur in Nova Scotia – heavy rainfall, high tides, and storm surges, for example, but like most other Canadian water bodies, flooding tends to occur more frequently in late spring and early summer when high river discharge levels occur due to snowmelt, in contrast to the winter months, which experience the lowest discharge levels caused by freezing conditions. (Nova Scotia Environment, 2020). Due to Nova Scotia's high level of annual precipitation and mild winter temperatures, a flood could occur in some Nova Scotia rivers during the winter months. However, it is challenging to predict when floods will happen and how large they will be. There are three buffer zones for floods – five metres, 10 metres, and 20 metres – which indicate the areas that could be covered in water, respectively (Nova Scotia Department of Lands and Forestry, 2006a). It is in the best interest of Nova Scotia beekeepers to be aware of these buffers and avoid placing honey bee hives near waterways.

Soil particle size also plays a role in determining the severity of floods. The rate that water drains from the soil is dependent on how porous the soil is (Rieu, & Sposito, 1991). Soils that contain coarser sediments like sand have larger pores allowing the empty spaces to connect and allowing water to drain through the soil at a faster rate. Soils that contain finer sediments like clay have smaller pores that do not readily connect, which causes water to drain at a much slower rate than that of coarser sediment (Lipiec, Kus, Stowinska-Jurkieqicz, & Nosalewicz, 2006). Several studies have explored the relationship between slope, aspect, and evapotranspiration (Bosquillia et al., 2019; Jackson, 1967; Leung, & Ng, 2013).

It has been established that both slope and aspect affect the amount of solar radiation an area receives, thus affecting the area's evapotranspiration rate (Jackson, 1967; Leung, & Ng, 2013). Jackson (1967) estimated that the evapotranspiration rate depends largely on a surface's slope degree and aspect. Surfaces with a high slope degree tend to have a higher evapotranspiration rate than areas that have a low slope degree. Jackson also pointed out that, in the northern hemisphere, north-facing slopes experience a lower evapotranspiration rate than the south-facing surface because of the different amount of solar insulation the areas receive (Bosquillia et al., 2019; Jackson, 1967). The use of slope and aspect has been previously used to study honey bee diseases and pests. For example, Makori et al. (2017) created four map layers to represent Kenya's slope, elevation, hillshade, and aspect to provide a proof of concept that by using GISystems and land-use suitability could obtain a better understanding of the spatial distribution of honey bee pests in Kenya which in turn could help Kenya's honey bee industry. However, due to the limited access to good high-quality datasets – such as the datasets listed on pages 15 and 16 and the datasets used in Makori et al. (2017) and von Buren, Oehen, Kuhn, and Erler (2019) studies – proxy datasets were used for this research. The use of proxy datasets in this research's final land-use suitability map was not ideal; the map is not as good as if high-quality datasets were available. Instead, the map acts as a proof of concept to show that GIS could be used to help in the management honey bees.

3.2 Nova Scotia Honey Bee Population

The Nova Scotia Legislature approved the Bee Industry Act in 2005 as a way to promote, maintain, and protect the bee industry within the province and to provide information about pests, diseases, and environmental and economic factors that might affect bee hives by forbidding the importation of honey bee colonies and beekeeping equipment from outside the province (Nova Scotia Legislature, 2005). The Act also provides the Department of Agriculture with the power to create quarantine districts due to a disease outbreak, which has not occurred in Nova Scotia since the *Bee Industry Act* was approved. Due to an increase in demand (Nova Scotia Beekeeper's Association, 2016a), Nova Scotia has seen an average yearly increase in beehives (Table 1). Table 1 also shows that the distribution of colonies in Nova Scotia is uneven: Kings County continuously houses the most beehives while Richmond Country and Shelburne County have the smallest number of colonies.

Table 1

Number of honey bee colonies per county in Nova Scotia, 2011 to 2018

	TOTAL NUMBER OF HONEY BEE COLONIES							
	2011	2012	2013	2014	2015	2016	2017	2018
NOVA SCOTIA	20688	19973	21863	23301	25350	28652	25928	25316
ANNAPOLIS	2968	3413	3427	3156	3482	3862	2432	2038
ANTIGONISH	242	362	370	246	495	569	747	555
CAPE BRETON	99	89	52	25	84	107	78	94
COLCHESTER	2846	2006	2295	1803	2499	3015	2753	3027
CUMBERLAND	1809	928	1075	896	983	1272	1115	1214
DIGBY	24	9	37	54	118	61	136	132
GUYSBOROUGH	74	83	77	52	58	141	151	111
HRM	262	393	473	474	580	677	663	533
HANTS	1957	1682	2698	2588	3321	3719	3345	3355
INVERNESS	16	16	53	77	118	128	198	185
KINGS	7700	9860	9801	12337	11694	12680	11347	11852
LUNENBURG	359	387	572	664	666	874	1380	749
PICTOU	2265	683	888	853	1119	1289	1270	1117
QUEENS	0	0	0	0	28	143	185	221
RICHMOND	0	0	0	0	6	15	13	23
SHELBURNE	2	3	10	13	22	11	9	10
VICTORIA	61	55	31	42	51	53	69	65
YARMOUTH	4	4	4	21	26	36	37	35

(Data retrieved from FOIPOP request 2019-01151-AGR)

Table 2 shows the number of hives in nine of Canada’s 10 provinces (Newfoundland and Labrador did not report any honey production to Agriculture and Agri-Food Canada (2018)). The table shows that Nova Scotia has the seventh-largest number of colonies in Canada, and the largest number of colonies in Atlantic Canada.

Table 2

Total number of honey bee colonies in each Canadian province, 2013 to 2017

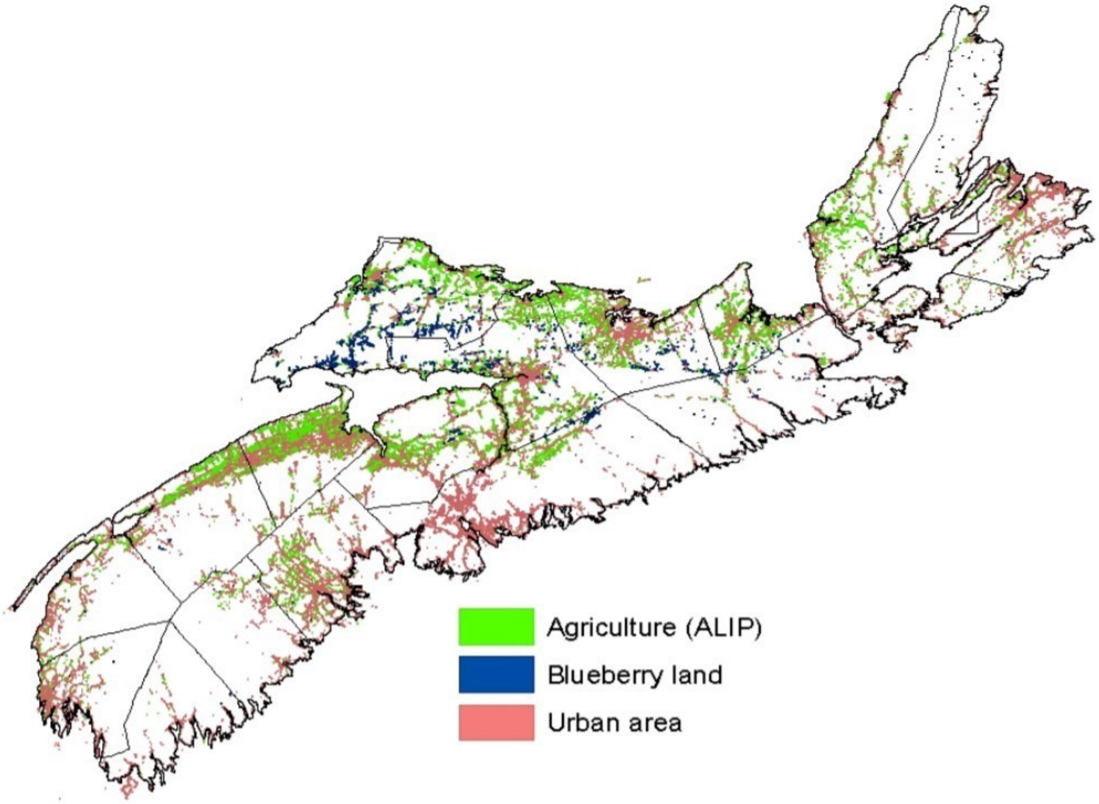
	TOTAL NUMBER OF HONEY BEE COLONIES				
	2013	2014	2015	2016	2017
CANADA	669760	696553	725854	765255	786650
PRINCE EDWARD ISLAND	4432	3777	4005	4920	6300
NOVA SCOTIA	21863	23301	25350	28652	25928
NEW BRUNSWICK	4318	5441	6710	7000	7100
QUEBEC	47203	49635	54294	64426	63500
ONTARIO	97500	112800	101135	97342	105244
MANITOBA	73800	78700	90909	102030	111802
SASKATCHEWAN	100000	95000	101000	112000	115000
ALBERTA	278100	282900	296880	309000	311000
BRITISH COLUMBIA	42544	44999	45571	39885	40776

Adapted from *Statistical Overview of the Canadian Honey and Bee Industry, 2017* (Agriculture and Agri-Food Canada, 2018; FOIPOP request 2019-01151-AGR)

The uneven distribution of colonies seems to correlate with some of Nova Scotia’s distribution of agricultural land. As seen in Figure 3, most of Nova Scotia’s farms can be found in Kings County, Cumberland County, Colchester County, and Hants County (Nova Scotia Department of Agriculture, 2010b). The 2011 Statistics Canada Census of Agriculture showed that Nova Scotia has 1.9 percent (3,905 farms) of all Canadian farms, which used 412,000 hectares of land (Figure 3). In 2017, Canada produced 61.6 billion dollars in farm cash receipts, with Nova Scotia contributing 565 million dollars (Nova Scotia Finance and Treasury Board, 2018). Fruit farms were the most common type of farm in Nova Scotia while poultry and hatcheries were the least common. Apiculture accounted for 0.8 percent of all Nova Scotia farms, keeping in mind that this number only represents the number of beekeepers who have 50 or more colonies (Nova Scotia Beekeeper’s Association, 2016b).

Figure 3

Agriculture and urban land development in Nova Scotia



Adapted from *Profile of Agricultural Land Resources in Nova Scotia.* (Devanney, & Nova Scotia Department of Agriculture, 2010b, p. 7)

In 2017, Nova Scotia accounted for 3.6 percent of all Canadian honey bee colonies and six percent of all Canadian beekeepers (Campbell & Canadian

Honey Council, 2018). During the same year, Nova Scotia honey bees produced over 509,892 pounds of honey (Sproule, 2018), which was 0.5 percent of the total Canadian honey production (Campbell & Canadian Honey Council, 2018). However, honey production is not the primary source of income for beekeepers where $3 million of the 2015 sector's total reported income came from renting hives to farms that rely on pollinator activity for their crops (Cunningham, 2017). This situation underscores the relationship between bees and crops needing pollination and how healthy hives are important to the larger agricultural industry and the province's economy.

In accordance with the Nova Scotia *Bee Industry Act*, beekeepers have been reporting honey bee diseases and pests to the Department of Agriculture. A breakdown of all the disease and pest cases that have been reported between 2010 and 2018 can be seen in Table 3. Information about 2013 is not available due to an interdepartmental re-staffing that occurred in the Department of Agriculture resulting in loss of that year's information (as determined in an Access to Information request, FOIPOP 2019-00049-AGR). During that period, 128 cases were reported to the department, and the majority of the cases (88 reported cases) were chalkbrood-related. The next highest reported disease is sacbrood at 12 reported cases. Colchester County has almost double the number of disease and pest cases – 41 reported cases – than the next highest county – Hants County with 22 reported cases. However, Nova Scotia's Provincial Agriculturalist's office is located in Colchester County, which could be contributing to the high number of diseases and pests reported in that county.

These numbers may not represent the total number of honey bee diseases and pests within the province. Some beekeepers may not report a honey bee disease or pest because reporting it may affect their livelihood.

Table 3

Number of reported honey bee diseases and pests* to the Department of Agriculture, 2010 to 2018, excluding 2013.

	American Foulbrood	Chalkbrood	European Foulbrood	K-Wing	Mites	Sacbrood	Scale	Varroa Mite	Wax Moth	Grand Total
Annapolis	1	1								2
Antigonish		1		2						3
Colchester	4	28	2		2	2	1	1	1	41
Cumberland		7			1					8
Digby								1		1
Guysborough		4				3				7
Halifax		8	1			3		1	1	14
Hants	1	21								22
Kings	3	12			1	3		1	1	21
Lunenburg		1			1					2
Pictou		5				1		1		7
Grand Total	**9**	**88**	**3**	**2**	**5**	**12**	**1**	**5**	**3**	**128**

*Beekeeper observing hives will report signs of disease to the provincial apiculturist who would visit the hive to confirm and identify disease or pest (Data retrieved from FOIPOP 2019-00049-AGR)

Table 4 shows that the number of reported cases of honey bee diseases and pests is increasing. In 2010, five cases were reported compared to 40 in 2018. It is unclear why the number of cases is rising, but the increase correlates with the Department of Agriculture's interdepartmental re-staffing in 2013, which could have resulted in an increase in reported diseases and pests. It is also possible that due to continuous growth in hive numbers, disease and pest occurrences could also be increasing. Figure 4 shows the percentage of each county's reported diseases and pests by the total number of colonies from 2014 to 2018. The complete table created from the FOIPOP 2019-00049-AGR documentation can be viewed in Appendix II, Table A2.1.

Table 4

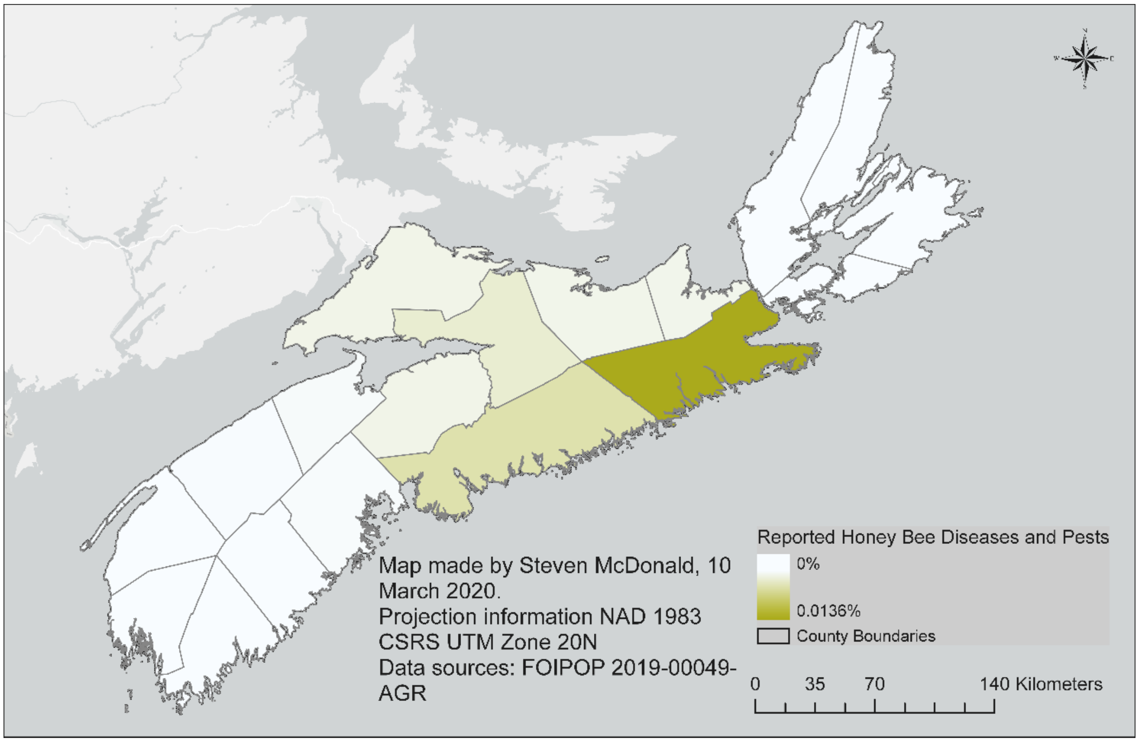
Number of reported honey bee diseases and pests* to the Department of Agriculture by year

	2010	**2011**	**2012**	**2014**	**2015**	**2016**	**2017**	**2018**
Annapolis	1						1	
Antigonish				1		2		
Colchester		3	5	3	5	10	6	9
Cumberland			1		1		1	5
Digby	1							
Guysborough								7
Halifax		1		1	2		5	5
Hants	1			2	1	5	4	9
Kings	2			3	3		9	4
Lunenburg		1			1			
Pictou				1	2		3	1
Total	**5**	**5**	**6**	**11**	**15**	**17**	**29**	**40**

*Beekeeper observing hives will report signs of disease to the provincial apiculturist who would visit the hive to confirm and identify disease or pest (Data retrieved from FOIPOP 2019-00049-AGR)

Figure 4

Percentage of reported honey bee diseases and pests by the total number of colonies, 2014 to 2018.



Average annual percentages were determined by adding the number of colonies between 2014 to 2018 in each county divided by five. The same calculation was done to the number of reported diseases and pests. To determine the percentage of diseases and pests, the percent of reported diseases and pests was divided by the percent of colonies. Due to the dataset's low quality, these percentages are too low to determine if Guysborough municipality is not a good location for honey bees.

However, the number of reported and confirmed cases of honey bee diseases and pests could be lower than the true number of diseases and pests occurring within the province. Traynor et al. (2016) conducted a six-year study on the spread and occurrence of Varroa mites and Nosema through randomly selecting apiary samples across the United States. They discovered that 91.7% of the sampled apiaries contained Varroa mites and 52.5% contained Nosema spores. The study also discovered that Varroa mite infections usually peaked in the late summer and early fall while Nosema spores had no peak period meaning that the disease is present in the hives throughout the year. Another study found that out of 603 US apiaries, 66% of them contained Varroa mites (Ryabov et al. 2017). These studies show that there is a high likelihood that occurrences of honey bee diseases and pests are not being reported to the provincial apiculturist thus reducing the quality of the data being used by beekeepers, the province, researchers, and other stakeholders.

Chapter 4: Methodology

4.1 Data Collection

Due to the limited access to the high-quality datasets needed to conduct a thorough analysis to determine whether the location of honey bee hives affect the chances of becoming infected with a disease or pest, proxy datasets were used to show a proof of concept that the MCDA method could work. These datasets were obtained through two sources. The first was through Freedom of Information and Protection of Privacy (FOIPOP) applications submitted to the Nova Scotia provincial government and an Access to Information and Privacy (ATIP) request submitted to the Canadian federal government departments. Three FOIPOP applications were submitted to gather information about the Nova Scotia honey bee industry, and one ATIP request was completed to obtain climatic data (Table 5). The three FOIPOP requests were successful in obtaining data; however, the data could not be visualized in map format due to the lack of enough specific geographic information to identify Nova Scotia beehive locations and honey bee disease and pest cases. The data obtained from the FOIPOP requests may not accurately represent the total number of honey bee diseases and pests in Nova Scotia for several reasons: some beekeepers may not know what to look for, some colonies may not show signs of being infected with a disease or pest during the beekeeper's inspection, or a beekeeper may not report a disease or pest in fear of repercussions. The ATIP climate data request did not provide any data meaningful to this study.

The second method of data collection was executed by searching through both federal and provincial open-source data portals to obtain geographic and regional information about Nova Scotia relating to the information identified in the literature review (Table 6). Honey bee diseases and pests rely on damp conditions to produce and grow. However, after completing a thorough search of the open data portals, it was determined that there were not enough high-quality datasets that matched the conditions for honey bee disease and pest growth outlined in the literature review. Thus, the next step was to locate high-quality datasets that could be used as proxies and could be used as a proof of concept to explore whether GISystems could be used to locate high risk – and low risk – geographic areas by identifying areas that retain water longer. Datasets that contained data about Nova Scotia’s soil types, aspect, slope, bedrock, surface direction, flood plains, and bodies of water were deemed to be of high quality and matched some of the conditions needed for the development of honey bee diseases and pests outlined.

Table 5

Information gathered through government access to information requests

Act	Request Number	Department	Description
FOIPOP	2019-00049-AGR	Nova Scotia’s Department of Agriculture	Reported Nova Scotia honey bee hive disease and pest cases*, including the geographic location of each case and the report date(s), reported to the Department of Agriculture by Nova Scotian beekeepers from 2005 to 2018.
FOIPOP	2019-00454-AGR	Nova Scotia’s Department of Agriculture	The number of imported bee colonies in each county, including where the queen came from, number of hives per county, and number of lost beehives per county (due to winter, colony death/failure, etc.) reported to the Department of Agriculture between 2010 to 2018.
FOIPOP	2019-01151-AGR	Nova Scotia’s Department of Agriculture	The number of bee colonies in each of Nova Scotia's 18 counties between 2010 to 2018 reported to the Department of Agriculture.
Access to Information and Privacy	A-2019-01545**	Environment and Climate Change Canada	Access to the interpolated map of Nova Scotia's Climatic Data (temperature, precipitation, etc.), ranging from January 1, 2010, to December 31, 2018.

*Beekeeper observing hives will report signs of disease to the provincial apiculturist who would visit the hive to confirm

**was not successful in obtaining data

Table 6

List of datasets used throughout this research

Dataset Name	Producer	Format	Description
Census Tract	Statistics Canada	Vector Polygons (ESRI Shapefile)	A defined geographic region for collecting information about the population found within the region.
Ecological Land Classification version 2015	Department of Lands and Forestry	Vector Feature Classes (ESRI Geodatabase)	This map is a tool that identifies, describes, and visualizes Nova Scotia's features such as elevation, climate, topography, soil, vegetation, and bedrock formation.
Enhanced Digital Elevation Model	Department of Lands and Forestry	Raster (ESRI Grid)	A tool to create a 3D representation of Nova Scotia's terrain. This DEM product has a resolution of 20 metres developed by using the topogrid command in ArcInfo version 7.1.
Geological Map of the Province of Nova Scotia	Department of Lands and Forestry	Vector Polygon (ESRI Shapefile)	A digital map containing layers of Nova Scotia's geological features such as bedrock, faults, rock type, isotope age, and geological contacts.
Nova Scotia Topographic Database - Water Features	Internal Services	Vector Polyline and Polygon (ESRI Shapefile)	A map of Nova Scotia’s water features such as rivers, islands, and lakes.
Wet Areas Mapping & Flow Accumulation Channel	Department of Lands and Forestry	Raster (ESRI Grid)	A research project conducted by the University of New Brunswick's Forest Watershed Research Centre to map and predicts where water flows and accumulate in the landscape.

4.2 Technology

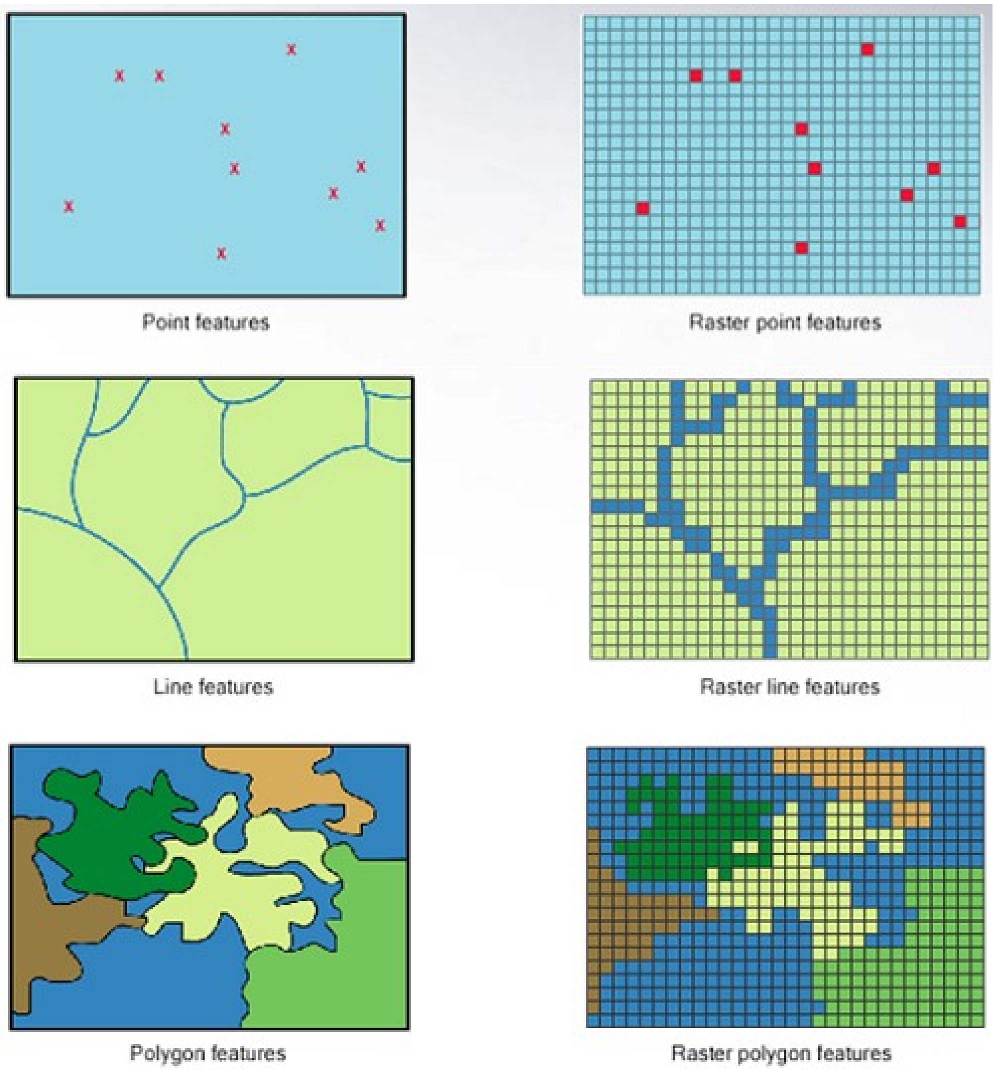
Esri’s ArcGIS Pro™ version 2.3.3 software package was used to create and complete the suitability analysis used in this research. This specific GISystems software was employed for a number of reasons. First, Dalhousie University offers a support program for using Esri software and has an Esri subscription that allows students and faculty to download the program onto their personal computers. Second, I have an undergraduate certificate in geographic techniques, which was obtained using Esri software.

4.3 Choosing the Model

GISystems commonly incorporate two different models to represent spatial objects – vector and raster – each of which has its own advantages and disadvantages. Vector data models use points, lines, and polygons to represent locations. Points are often used to represent a single object in a specific location such as trees in a park, while lines are used to represent continuous objects such as roads and rivers. Polygons represent regions of homogenous objects such as counties, soil type, and land-use zones. The raster data model portrays land features in a matrix of cells containing a single value to represent a measurement at each cell location (Figure 5) (Longley et al., 2015). Raster data layers with a higher resolution have more cells in a unit area than a low-resolution raster. Data stored in the vector data model are at their strongest when representing discrete objects through points, lines, and polygons to characterize the objects and are often used to understand social, economic, and administrative geographic trends. Raster data models, in this case a 2.5D surface, have trouble capturing discrete objects due to the grid of cells but are at their strongest when representing resources and environmental trends because each cell has one value assigned to it (Longley et al., 2015).

Figure 5

The vector and raster model depiction of spatial features



(Humboldt State University, 2017)

While data stored in both vector and raster models were used in this research, data represented by the raster data model were determined to be the most effective method to identify suitable and vulnerable areas for honey bee hives in Nova Scotia, assuming that suitability or vulnerability is consistent with the continuous field view of the world. As briefly mentioned in the above paragraph, the cells in a raster matrix are assigned a single value to represent what is being portrayed in the raster dataset (Esri, 2016). The raster approach is beneficial because it allows each cell to be assigned a value and the data visualized in a continuous field[3] view, which best represents the surface. Thus, by using data with finer spatial resolution, the end result will be a more finely grained and nuanced picture of soil moisture content in Nova Scotia.

Raster data models can be combined to show how two different environmental factors correlate for different data types (nominal, ordinal, interval, and ratio) as long as the values have been converted to compatible levels of measurement. For example, a raster dataset could show an area’s land-use, and each cell would represent either grasslands, fields, or a highway based on the value assigned to that cell. For example, If a researcher wanted to determine whether a possible relationship exists between elevation and land-use, the researcher could add the standardized ordinal cell values from two raster datasets together to see whether patterns exist between elevation and land-use. This method of combining multiple raster layers through overlay together has

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[3] Continuous fields are data about objects that are not spatially discrete and appear on a continuous surface without well-defined breaks. An example of a continuous field is elevation.

various uses such as land suitability, land-use, determining flood plain, and impact assessment. This land suitability analysis was conducted by combining multiple raster datasets together to determine areas suitable for honey bee hives.

Land suitability analysis is used to identify suitable regions within a given study area that fit the study's criteria. This analysis involves overlaying and adding the values from several layers into one map. Each layer contains data about a specific factor that affects the purpose of the study. For example, if farmers want to identify which areas are the best for corn, they might include a layer that contains data about the soil types, soil depth, slope, aspect, and total seasonal rainfall (Akinci et al., 2013). However, there are some limitations to land suitability analysis, the most important being access to credible and relevant data (Vetro et al., 2016). The map produced is only as good as the data used in it, and if only a little or inaccurate data are available, the map will not be as valid as it could be (Vetro et al., 2016).

4.4 Layer Preparation

Nine raster model layers were created for the land suitability model. However, before a layer could be created, two steps needed to be completed before using the datasets described earlier. The first step was to create a raster grid that would be applied to all the raster layers. Ensuring that every layer used the same grid will allow for easier overlay analysis of the layers. For this research, a grid size with a resolution of 20 metres was chosen. This resolution was selected because the Enhanced Digital Elevation Model (DEM) of Nova Scotia already uses this resolution, and instead of risking losing data by changing the DEM’s cell size, it was decided that it would be best to use that grid as the base for all future raster models.

The second step needed before creating layers was to standardize the cell value to be applied to the grid of cells. The range value used for this research was an interval scale of one to 10, where the value of one equals the optimal condition for a beehive location, and the value of 10 equals the worst condition for a beehive location. The division of one to 10 was determined based on the variable related to disease and pest development. Variables that contribute to water retention, such as soils that have poor drainage, are assigned a higher value of 10 while soils that are well drainage are assigned a value of one. The interval distance between two and three is the same distance as it is for one and two. This distancing means that if a variable has a value of five, it means that the variable is neither the best nor the worst variable for disease and pest development. The cells that represent water features were assigned a value of 20, a value outside the standardized cell value range, because placing beehives in water is not recommended.

4.5 Layer Creation

The literature review identified that several of the honey bee diseases studied in this research are fungal and can be often found flourishing in damp areas. Thus, it is important to be able to identify regions in Nova Scotia where the ground surface stays wetter longer than other areas by using high-quality datasets that provide data on the conditions outlined in the dream data list and literature review. For example, having access to good climatic data tells us what the normal climatic conditions are during the bee season and could provide a better understanding of how climate affects honey bee diseases and pests. However, since good, high-quality climate datasets are limited, proxy datasets needed to be used for this research to provide a proof of concept that GIS could be used in honey bee management. To create a land-use suitable map to identify poor honey bee hive locations, nine raster layers (Appendix III, Figure B1.1) were created from the datasets listed in Table 6, using the previously determined grid resolution and the standardized cell value range. Class changes for all layers can be viewed in Table 7.

The first layer created was an aspect map of all of Nova Scotia. Aspect is used to determine the compass direction – north, northeast, east, southeast, south, southwest, west, northwest, and flat – of a downward slope. This layer was created by using the DEM dataset and the ArcGIS Pro™ aspect tool. The tool applies an algorithm that analyzes a cell's surrounding eight cells to determine that cell's aspect, the compass direction perpendicular to the best fit of a tilted plane passing through the focal cell.(Esri, 2019). The aspect was used to identify the north, flat, and south-facing surfaces because, as discussed earlier, beekeepers are advised to place their beehives on south-facing surfaces to ensure that the apiary receives as much direct sunlight as possible to keep the area as dry as possible (Agriculture and Agri-Food Canada, n.d.).

Table 7

Layers, variables, and assigned ranking used to create the layers used in this research

Layer	Variable	Assigned Ranking	Description
Aspect	North	10	Less suitable
	Northeast	10	Less suitable
	East	5	High suitable
	Southeast	1	Most suitable
	South	1	Most suitable
	Southwest	1	Most suitable
	West	5	High suitable
	Northwest	10	Less suitable
	Flat	1	Most suitable
Slope	0-3%	10	Less suitable
	3.1-15%	7	Average suitable
	15.1-30%	5	Good suitable
	30.1-60%	3	High suitable
	> 60.1%	1	Most suitable
Soil Drainage	Well drainage	1	Most suitable
	Imperfect drainage	5	High suitable
	Poor drainage	10	Less suitable
	Water	20	Not suitable
Bedrock	Igneous	10	Less suitable
	Metamorphic	10	Less suitable
	Sedimentary	1	Most suitable
	Unconsolidated sedimentary	5	High suitable
5-metre flood plain	Inside the flood range	10	Less suitable
	Outside the flood range	1	Most suitable
10-metre flood plain	Inside the flood range	10	Less suitable
	Outside the flood range	1	Most suitable
20-metre flood plain	Inside the flood range	10	Less suitable
	Outside the flood range	1	Most suitable
Lakes	Lakes	10	Less suitable
	Land	1	Most suitable
Rivers	Rivers	10	Less suitable
	Land	1	Most suitable

Once the layer was created, the cell values needed to be standardized by using the reclassify tool. Any north-facing surfaces – north, northeast, and northwest – were assigned the value of 10, and south-facing surfaces – south, southeast, and southwest – were assigned the value of one, and east and west-facing surfaces were assigned the value of five. Flat surfaces were assumed to have no solar radiation obstructions and were assigned the value of one. The values reflect the amount of sunlight each surface received during the day; given the fact that Nova Scotia is in the Northern Hemisphere where north-facing surfaces receive little to no direct sunlight, while south-facing surfaces receive sunlight all day. East and west-facing surfaces receive a half-day of sunlight (Gardashov et al., 2020; Hetrick, Ricj, & Weiss, 1993; Maleki, Hizam, & Gomes, 2017; Reuter, Keresbaum, & Wendroth, 2005).

The second layer created determined the slope of Nova Scotia's geography. Once again, this layer made use of the Nova Scotia DEM dataset and the ArcGIS Pro™ slope tool. Like the aspect tool used in the previous layer, slope employs an algorithm that identifies the gradient of a cell by determining the best fit tilted plane through the focal cell based on neighbouring cell values. Once the layer was generated, the provided value range needed to be grouped together based on Nova Scotia's Department of Lands and Forestry's (2017) *Ecological Land Classification* for Nova Scotia. According to the land classification, a level area has a gradient of zero to three percent, gentle slopes have a gradient of 3.1 to 15 percent, moderate slopes' are 15.1 to 30 percent, steep slopes are 30.1 to 60 percent, and extreme slopes have a gradient of 60.1 or higher percent. After using the described classification to group the cell values, the cells were then standardized. Level slopes were reclassed to have the value of 10, gentle slopes' new values are seven, moderate slopes' new values are five, steep slopes were reclassified to have the value of three, and finally, extreme slopes were assigned the new value of one. The values were based on how fast the different slopes drain water, the steeper the slope, the faster water drains (Fariborzi, Sabzevari, Noroozpour, & Mohammadpour, 2019; Morbidelli, Saltalippi, Flammini, & Govindaraju, 2018).

The soil drainage layer was created by using the information gathered by the Nova Scotia Department of Lands and Forestry's (2017) *Ecological Land Classification* version 2015 dataset. The goal of a land classification layer is to define and provide a standard vocabulary that describes the characteristics of the ecosystem throughout Nova Scotia. Information about each ecosystem's environmental variables – such as soil, landforms, climate regimes, hydrology, and biological variables – plants and animals – was gathered by the department to aid in land management decisions. Ecological land classifications also deal with understanding the spatial relationship between classes and ecosystems. This means that the Department of Lands and Forestry released a geodatabase – a single large electronic file that stores the layers and maps produced for a project – of all the collected information.

The literature review revealed that soil drainage could also affect a beehive's health. If the soil remains damp for a long period of time, the outside humidity may affect bee behaviour and hive humidity level which could increase the chances of honey bee disease and pest development (Abou-Shaara, Owayss, Ibrahim, & Basuny, 2017; Edwards-Murphy, Magno, Whelan, O’Halloran, & Popovici, 2016; Hill, 2018). For example, Varroa mites rely heavily on water access and tend to live in areas with a high humidity level – 60% to 80% humidity. Therefore, it is important to know which soils drain slower thus reducing the surface humidity. The *Ecological Land Classification* geodatabase was used to map Nova Scotia’s soil drainage patterns. This layer classified soil drainage in Nova Scotia into four categories: well drained, poor drainage, imperfect drainage, and water. Well-drained soils dry out quickly, poorly drained soils retain water for longer periods of time, and imperfect drained soils see water being removed from it more slowly in relation to the water supply (Nova Scotia Department of Lands and Forestry, 2017).

The soil drainage layer was originally viewed as polygons (vector model), which meant that it needed to be converted into a raster model. To achieve this step, the grid described in the previous section was applied to the vector layer. Each cell was then given a value to represent the soil drainage; well-drained soils received the value of one, poorly drained soils were assigned the value of 10, imperfect soils were assigned the value of five, and water was given the value of 20.

The next step was the creation of a raster model of Nova Scotia’s bedrock, which can affect ground level humidity (Harman, & Cosans, 2019; Huggett, 2017). This was achieved by using the 2006 *Geological Map of the Province of Nova Scotia* provided by the Department of Lands and Forestry. The geological map contained information about the bedrock, geological contact, faults, isotope, and other geological information (Nova Scotia Department of

Lands and Forestry, 2006b). The map divided Nova Scotia's bedrock into four categories: igneous, metamorphic, sedimentary, and unconsolidated sediment. To make the raster model, the geological map's bedrock attributes were selected and isolated from the rest of the map. This step was completed by using the select by attribute and the create a new layer option from selected tools in ArcGIS Pro™.

Once this step was finished, the determined raster model grid was then applied to the vector model. As discussed in chapter 3, the three different types of bedrock have different permeability rates. Sedimentary rocks have the highest permeability rate while igneous and metamorphic rocks have the lowest permeability rate (Huggett, 2017); unconsolidated sediment also have a high permeability rate but is made up of unstable sediment. With this knowledge and assuming that there is a thin layer of overburden and the bedrock is close to the surface (Akumu, Baldwin, & Dennis, 2019), cells that represent sedimentary bedrock were assigned the value of one, both igneous and metamorphic bedrock was assigned the value of 10, and unconsolidated sediment was assigned the value of five because of its unstableness, which could cause a beehive to collapse.

The next three maps were created by using Wet Areas Mapping & Flow Accumulation Channel, which provided three raster layers showing the flood plains in Nova Scotia at three different heights: five metres, 10 metres, and 20 metres. The raster grid described in the above section was then used to turn the three layers into three raster models. Once completed, the values of the cell representing water were reclassified to the value of 10 and the cells representing land were assigned the value of one. The final two maps were created by using the Nova Scotia Topographic Database - Water Features shapefile. The shapefile contained a vector layer that shows where all the water features – lakes, rivers, and ponds, – are located in Nova Scotia. The layer was then converted into a raster format, and the cells representing water features were reclassified to have the value of 10, and the cell representing land were assigned the value of one.

Once the nine layers were created, they were overlaid (combined) to form one layer. To achieve this outcome, ArcGIS Pro™ weighted overlay tool was used. The weighted overlay tool allows researchers to overlay several raster layers using a scale that weights each layer according to the desired value. Table 8 shows the assigned weights for each of the nine layers.

Table 8

Weighted overlay weights assigned to each layer to determine vulnerability

Layer	Weight (%)
Aspect	15
Slope	8
Soil Drainage	20
Bedrock	14
5-metre flood plain	9
10-metre flood plain	9
20-metre flood plain	9
Lakes	8
Rivers	8

The aspect layer was given a weight of 15 percent because the Sun has a direct effect on how fast an area dries through evaporation. In order for a gram of water to evaporate, it must receive 585 calories of heat from multiple sources: the Sun, heat from the Earth, and wind (Monteith, 1965). Areas in direct sunlight receive more heat than shadowed areas; thus, in the northern hemisphere, south-facing surfaces dry faster than north-facing surfaces because the Sun is located to the south at latitude 23.5 degrees north or higher. The slope layer was assigned the weight of eight percent because although steeper slopes drain faster than gentle slopes, beekeeping best practises suggests that beehives be places of level surfaces to reduce the chances of the hive tipping (Agriculture and Agri-Food Canada, n.d.).

The soil drainage layer was assigned the highest weight of 20 percent because it is the most relevant layer in determining the answers to the questions posed in this research. Another reason for assigning this value is that honey bee hives are located close to the ground and, depending on the amount of clay within the soil, soil tends to hold water for longer periods of time than bare rock. Bedrock was given a weight of 14 percent because of the permeability rate of sedimentary, igneous, and metamorphic rocks. Metamorphic and igneous rock have a much lower permeability rate than sedimentary rocks, which means that the soil on top of metamorphic and igneous rocks will retain water longer.

The three flood plain layers were assigned the lowest weighted values (Table 8) because these layers show the potential flood zones. These low values do not mean that a flood will occur or reach that height. The rationale behind assigning each flood plain layer the same value is that they add up when overlaid, so the five-metre range will have the value of 30, the 10-metre range will have the value of 20, and the 20-metre range will have the value of 10 (Figure 6). The lake and river layers were both assigned the weight of eight percent because placing beehives in water is not a common, nor advised, beekeeping practice. Thus, when these layers are overlaid with the other seven layers, cells representing water already have high unsuitability value.

Figure 6

Overlay of the 5-metre, 10-metre, and 20-metre flood range layers

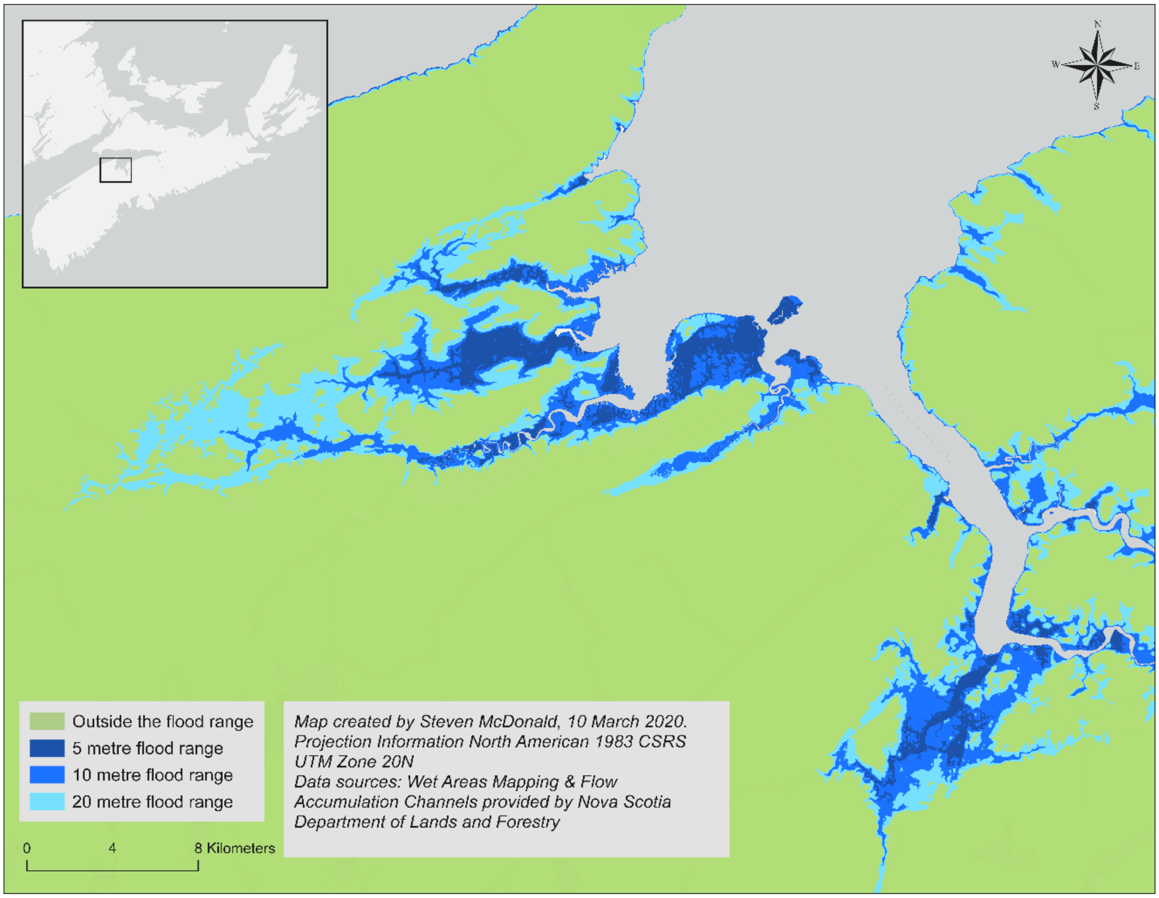
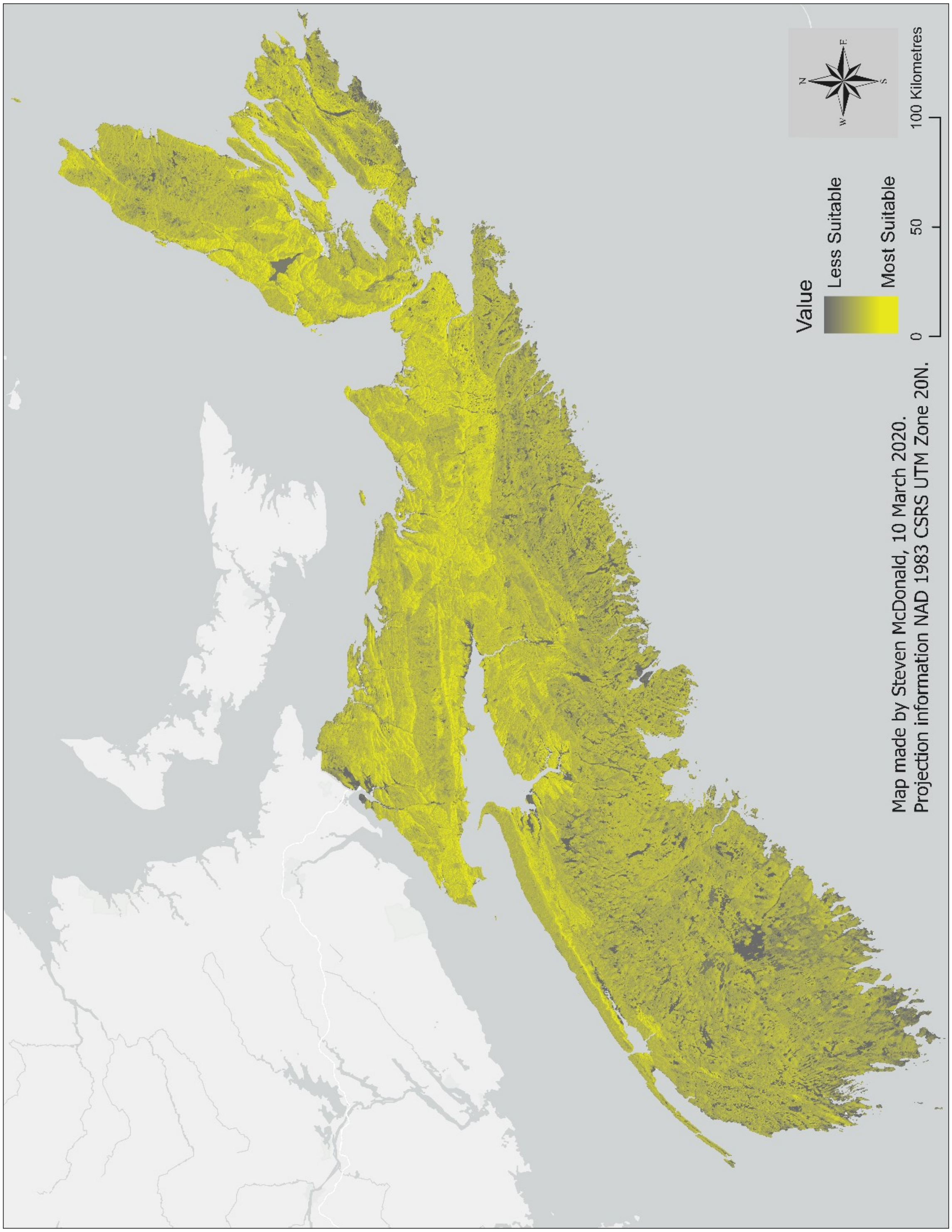


Figure 7

Potential location of honey bee operations in Nova Scotia based on suitability



Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.

Chapter 5: Results

5.1 Nova Scotia Honey Bee Location Suitability

Using the publicly available data provided, an overlay map identifying areas in Nova Scotia where growth and development of honey bee diseases and pests might occur more frequently than others is presented in Figure 7. The darker grey regions represent places where honey bee disease and pests are more likely to occur, while the brighter yellow areas identify better locations for honey bee health. The map clearly shows that western and central Nova Scotia (Kings, Annapolis, Digby, Yarmouth, Shelburne, Queens, Lunenburg, and Guysborough counties, and Halifax Regional Municipality (HRM)) contain more vulnerable land for honey bee hives than other areas of the province (Figure 8). These regions have more imperfect and poor soil drainage than other areas and, according to the *Ecological Land Classification version 2015,* the ecosystems tend to be wetter. Furthermore, this region's bedrock is made up of mostly metamorphic and igneous rock, which have poor permeability.

Figure 8

Potential location of honey bee operations in Hants, Kings, Annapolis, Digby, Yarmouth, Shelburne, Queens, and Lunenburg Counties based on suitability*

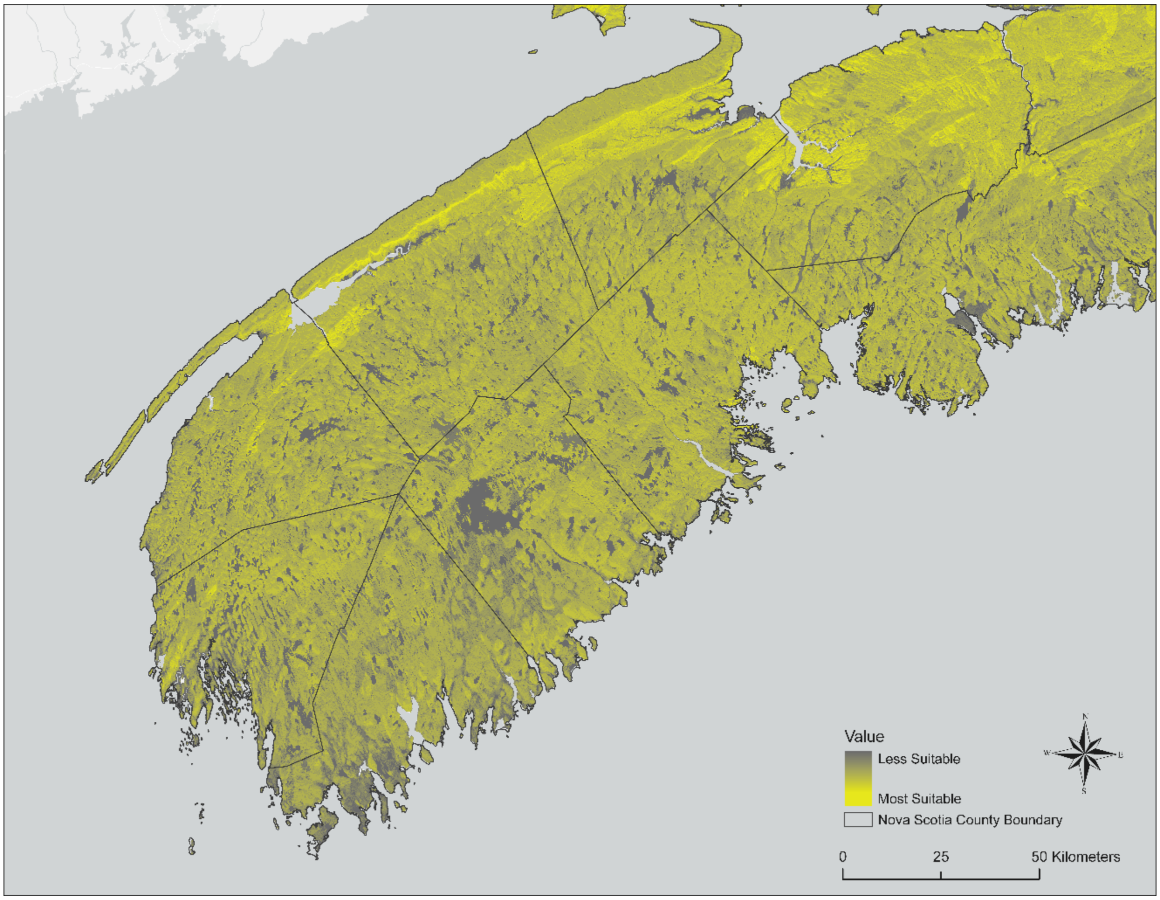
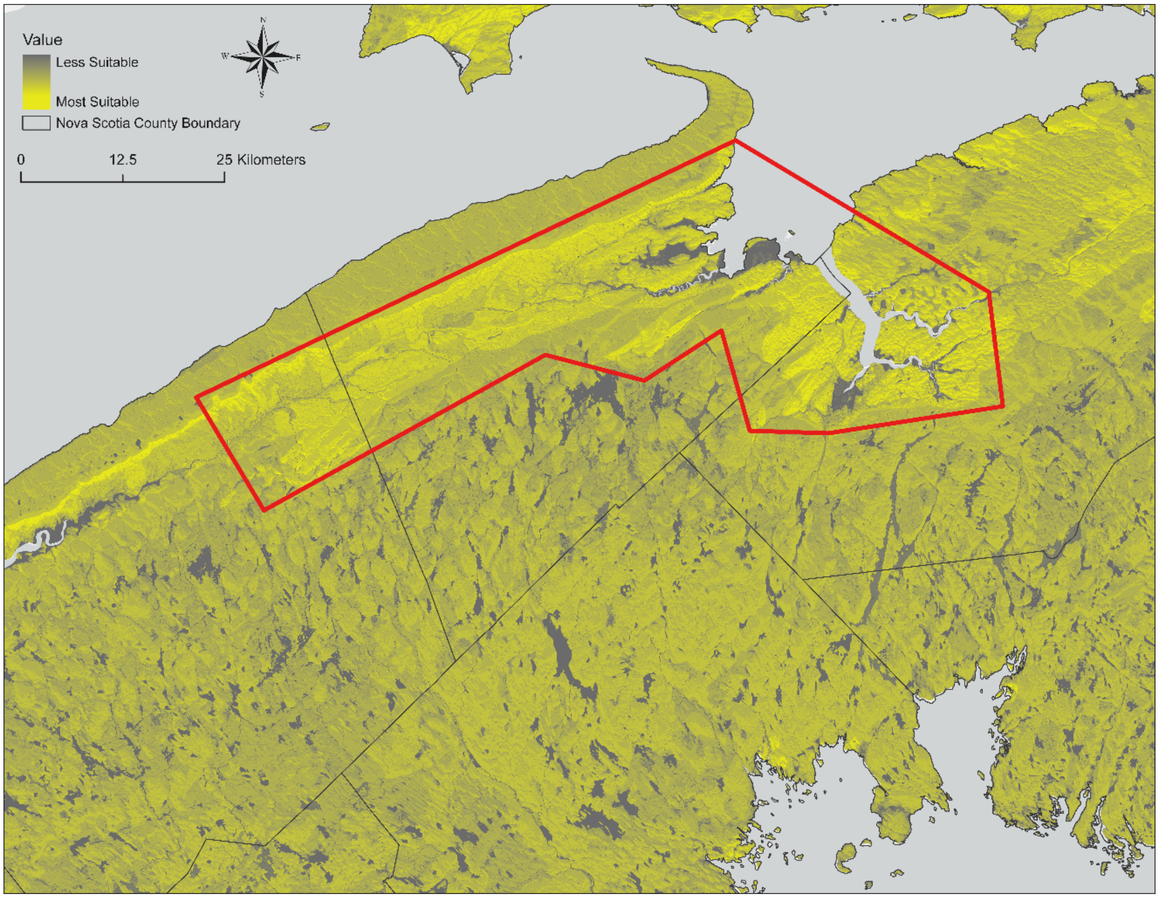


*Figure 1 provides the location of the listed counties.

However, a stretch of land that exists within western Nova Scotia is best suited for honey bees, namely the Annapolis Basin (Figure 9). According to Figure 7, this region contains the most suitable land for honey bee hives. The basin sits upon sedimentary bedrock with well to imperfect soil drainage.

Figure 9

Highlight of the Annapolis Basin for honey bee operations in Western Nova Scotia



Hants, Colchester, Cumberland, and Pictou counties (Figure 10) contain suitable land for honey bee health. Historically, these counties have house honey bees and the area appears to have good locations for honey bee hives. This region is mostly made up of sedimentary bedrock, except for a stretch of metamorphic bedrock in northern Colchester. The soils in these counties are predominately well-drained. However, a curved stretch of land in east Colchester, west Pictou, Antigonish and Guysborough counties (Figure 11) matches the

Annapolis Basin’s suitability for honey bees. These regions are made up of well-drained soils and sedimentary rock.

Figure 10

Potential location of honey bee operations in central Nova Scotia based on suitability

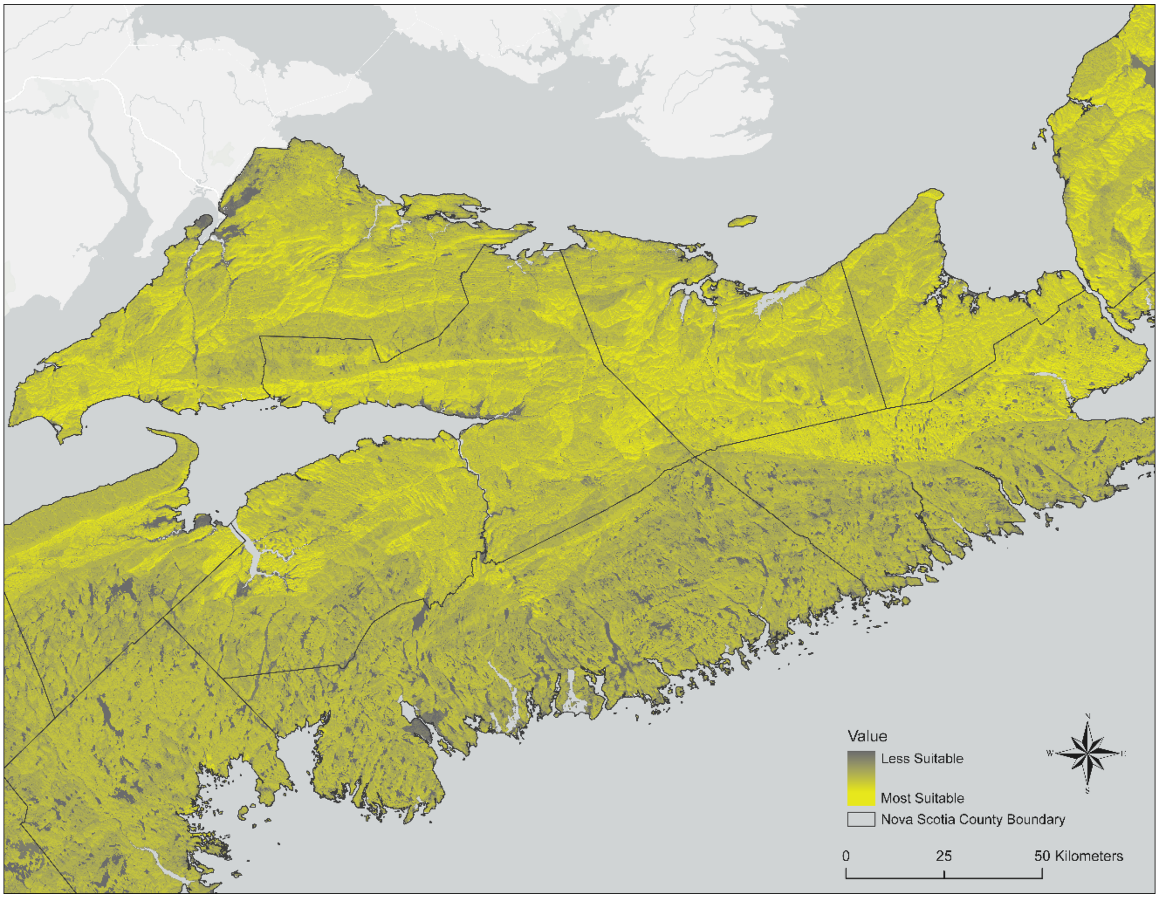
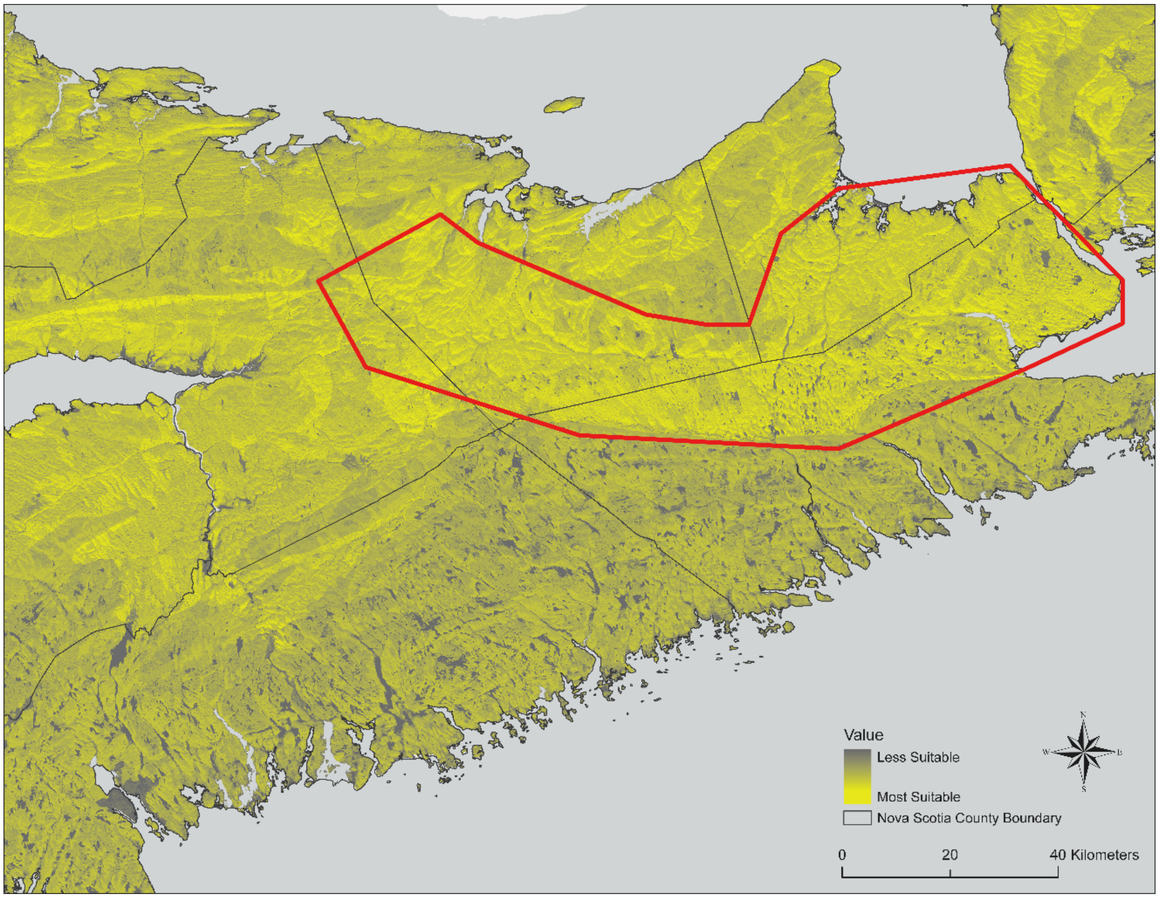


Figure 11

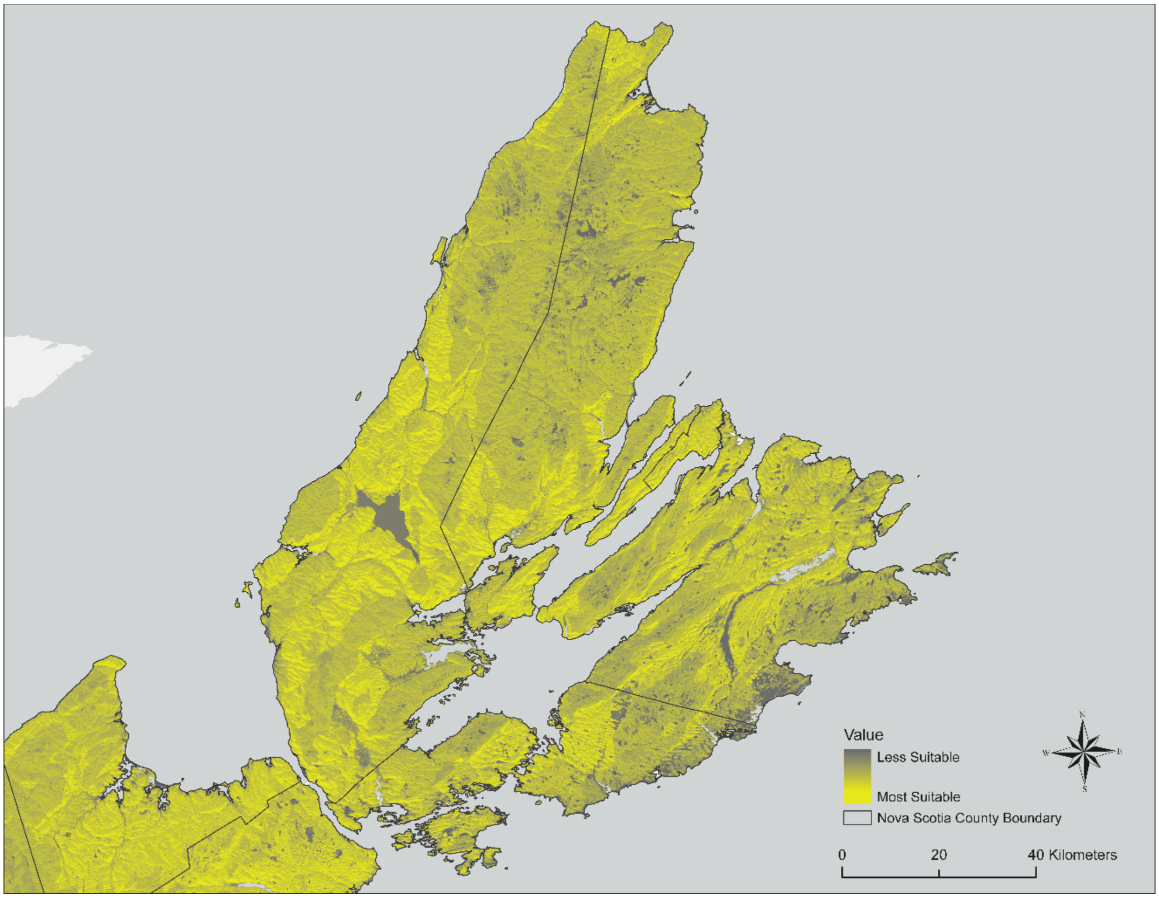
Highlight of the suitable crescent for honey bee operations in central and eastern Nova Scotia



Cape Breton's four counties (Figure 12) - Inverness, Victoria, Cape Breton, and Richmond – contain generally suitable land for honey bees. Inverness County has the most suitable land in Cape Breton, while Victoria County has the least amount of suitable land on the island. The island is mostly made up of well-drained soils with a few imperfect drained soils scattered throughout. Cape Breton's bedrock consists mostly of sedimentary rock, with the exception of the Cape Breton Highlands, where metamorphic and igneous rocks predominate.

Figure 12

Potential location of honey bee operations in Cape Breton based on suitability



Chapter 6: Discussion

6.1 The Use of GIS in Honey Bee Disease Management

This thesis is a continuation of the discussion on whether GIScience and GISystems can be used as methods to obtain a better understanding of common honey bee diseases and pests such as chalkbrood, Nosema, and Varroa mites, which then could be used by beekeepers and governments to make better informed decisions. However, due to the limited understanding of the environmental requirement needed for AFB, the land-use suitability map derived from this analysis may not be helpful to beekeepers as presented. Instead, a map showing where – using coordinates– confirmed AFB cases have occurred could provide useful for future research into the environmental conditions needed for AFB.

This thesis has shown that GIS has the potential to be applied to common beekeeping practices by being able to identify regions that promote the growth and development of common honey bee diseases and pests. For example, from Table 1, the highest number of honey bee colonies in Nova Scotia is located in Kings County, even though Figure 6 reveals that this county has a high percentage of unsuitable land for honey bees, with the exception of the Annapolis Basin. However, as Figure 3 illustrated, Kings County also contains a substantial area of farmland – especially within the Annapolis Basin – and as rental of hives to farmers is the primary source of income for beekeepers, it is no surprise that this county has such a high number of bee colonies. Interestingly, from 2014 to 2018, not a single honey bee disease or pest was reported in Kings County.

Guysborough County has one of the smallest honey bee colony populations – 0.004 percent of the total colonies in Nova Scotia in 2018 – but over four years has experienced the highest percentage of disease and pests reported compared to any other county. A preliminary argument could be made that because Guysborough County is a relatively damp area, honey bee diseases and pests are more prone to occur there. However, the exact location of the reported diseases and pests is not known, nor are other factors that may account for the high reporting rate, which makes it impossible to ascertain whether climate alone contributes to the disease and pest rate.

Two counties in Nova Scotia could support more honey bee colonies: Antigonish and Inverness. As of 2018, a small number of honey bee colonies were located within the counties – 555 and 185, respectively. Figure 6 shows that these counties have large areas of drier land that could support more healthy colonies. As both counties also have large suitable agricultural lands, an argument can be made that they could provide enough food and pollen to support more honey bee colonies, assuming that other factors such as the available market for farm produce warranted more extensive farming.

However, this thesis has also shown that access to high-quality data is critical when conducting any type of research, especially when the research involves high valued species such as the honey bee. If there was better access to high-quality data, such as the locations of past disease and pest cases and climatic data, clusters of disease and pest cases could have been identified, which would have allowed for a better understanding of honey bee health in Nova Scotia. This thesis urges Nova Scotia beekeepers and the Nova Scotia government to collect and make available – while respecting privacy – important data that could be used to help to protect and improve the honey bee global population. A good starting place would be to use the data quality assessment schemes introduced on page seven of this thesis, such as Berners-Lee's (2006) five-star file format assessment and Viscusi et al.'s, (2014) scheme to assess the datasets. By ensuring that every dataset uses the same file format, is complete, accurate, traceable, current, compliant, and understandable, a better understanding of honey bee disease and pests could be achieved. This outcome will also provide beekeepers and the provincial agriculturist with the ability to predict and prevent future honey bee disease and pest outbreaks in Nova Scotia.

6.2 Information Credibility, Relevance, Legitimacy and Access

The first objective of this thesis was to contribute to the understanding of how to protect and improve honey bee populations by applying GIS techniques to better understand where honey bee diseases and pests might occur. The second objective for this research was to assess the quality of publicly available data that is related to Nova Scotia honey bee health and to promote the collection and openness needed to aid in decision making. Cash et al., (2003) argued that the quality of the relationship between research and decisions made by policymakers is characterized by three key features of information: credibility, relevance (also referred to as salience), and legitimacy.

According to Cash et al., credibility is the quality of a piece of information and the authority of the individual who produced that information. For instance, someone who is well known to be an expert in a particular field will usually have more credibility than a non-expert. Relevance refers to how useful the information is in making a decision; decision-makers and scientists need to ask themselves if the information they are looking at is aiding in making a decision or is the information unsuitable or inconsequential. Finally, legitimacy relates to balance and fairness of information that incorporates the values, interests, and beliefs of everyone involved in a decision, all the while presenting information without bias, as much as possible. These three elements are closely related, and Sarkki et al., (2014) argue that enhancing one element will have some sort of trade-offs on the other two elements.

Sarkki et al., (2014) identified four general trade-off categories between credibility, relevance and legitimacy. The first trade-off is connected to a researcher’s personal time, which is understanding how that person wants to use their time. Does the individual want to spend most of their time publishing peer-reviewed research or contributing to policy work? A second trade-off is between the clarity and complexity of research and policy. Providing pictures and figures can help to understand the research and aid in providing a clear message (relevance), but this approach can result in loses of credibility or oversimplifies the complexity of the research (credibility and legitimacy). Another trade-off occurs between the speed and quality of research output and policy development. Policy development often requires timely and rapid responses to questions for evidence to make decisions (relevance) but research is often time-consuming to complete to ensure that the results are correct (credibility) and the need to include as many stakeholders as possible (legitimacy). A final trade-off is a push-pull trade-off between policy and research. This trade-off focuses on how supply-driven research, which enables the identification of issues and the development of the solutions needed for the identified issues (credibility and legitimacy), while demand-driven research supplies more recent information for policymaking (relevance). However, there are more trade-offs between credibility, relevance, and legitimacy than are discussed in the article (Sarkki et al., 2014)

The data used in this research balances each of the three elements in different ways, and the credibility of this research comes with understanding the source of the data. All of the information used in this thesis was obtained from the Nova Scotia Government, which means the datasets were created with the provincial government's agenda and standards in mind. Some datasets have more credibility than others because the sources have more credibility than others; the *Ecological Land Classification* geodatabase has high credibility due to the method used to collect and validate the data. Teams were sent across Nova Scotia to collect samples. The information received in FOIPOP 2019-00049-AGR has a different credibility level because of the possibility that individual beekeepers did not report diseases or pests.

Finding relevant information for both decision-makers and researchers relies on being able to access whether the science is based on up-to-date data and on the usefulness the information has to the discussion. Information accessibility is concerned with understanding how individuals can access and use information (Joseph & Cook, 2008). Lor and Britz (2007) argue that as an information society, we are limited by the extent of access to and communication between policymakers and academia when it comes to making good decisions. Lor and Britz (2007) believe that large paywalls restricting access to research publications and field-specific language reduce the discussion between policy-makers and researchers by making it difficult for policymakers to access information created within academia. Meanwhile, government policies and confidentiality can remove academics from truly understanding why a decision was made.

A recent movement for open data, i.e., usually data from public bodies granting unrestricted access, has led to the opening of new and improved communication opportunities between policymakers, academia, and the general public (Arzberger et al., 2004; Janssen, Charalabidis, & Zuiderwijk, 2012). According to Janssen et al., (2012), open data have the potential to generate higher public investment by allowing governments to become more transparent and to be held accountable by citizens, thus becoming a more trustworthy government. Open data also provides researchers and other public institutions the ability to reuse data collected by the government and not have to collect the same data again, thus saving time, energy, and money. However, some disadvantages or barriers to open data remain. A major hurdle is the lack of uniform policy for the quality of the released data from government bodies; some open datasets require considerable work by researchers to create usable data, while other datasets can be used right away or require minimal modification before being used (Arzberger et al., 2004).

Another major initiative that is changing the relationship between policymakers, academia, and the general public is the concept of open access. Open access is the removal of barriers to research literature and thus allowing anyone to read up-to-date research produced in academia (Tatem, 2017), which can be achieved through publishing research literature by open-access publishers, such as *PLOS ONE*, and aggregated data on an open-access website or repository. For example, the maps produced in this thesis could be uploaded to a trusted website where beekeepers could explore them in more detail to locate areas were placing beehives would be less likely to be affected by diseases and pests.

Information plays a vital role in our society and having access to credible, relevant, and legitimate information makes for a better understanding of the issues honey bees are currently facing. Without access to good and current information, stakeholders are not able to obtain a complete understanding of the issues our society is facing, which then affects how the issue is handled and resolved. Each party should be able to access the same information so that the best resolution can be determined and implemented. The results of this thesis show the importance of access to credible, relevant, and legitimate information. If this information was accessible, a more in-depth GIS methodology could have been applied to the industry, which could allow stakeholders to improve the health of the honey bee population and Nova Scotia’s bee industry.

6.3 Limitations and Future Research

As mentioned throughout this thesis, the quality of available data was a huge limiting factor, which required the use of proxy datasets to explore the possibility of GIScience and GISystems being used as a method to track and predict honey bee disease and pest outbreaks. The output generated in this spatial analysis provides a good understanding of where ground-level humidity may be high, and therefore where poor locations for honey bee health exist, but the results are limited by the quality of data available on open data portals and freedom of information legislation. The analysis could provide a more detailed and useful picture of the province's suitability if better information and data were made available to the public. One of the biggest limitations to the final suitability output is the lack of access to either the address or coordinates of where each reported honey bee disease or pest case occurred. This information would have allowed for a deeper understanding of the geographic distribution of honey bee diseases and pests in Nova Scotia and identify where possible clusters of diseases and pests occur. When asked why the exact location of each reported case could not be provided, the Provincial Apiculturist stated that that type of information is confidential and could not be made public (J. Sproule, personal communication, April 12, 2019). If this data were available an output could be created to show where each reported case could have been made and through GIS analysis clusters of statistically high or low incidents could have been identified for future research. The reported disease and pest map could have also been a layer in the final map in this study to provide an understanding of whether wet areas spatially correlate with honey bee disease and pest cases.

Another limitation of this research is that the specific locations of the honey bee colonies in Nova Scotia are not known. Access to this information would have allowed for further analysis of whether or not beekeepers are optimizing the land or if they are siting a large number of colonies in one region. The development of a map that shows where colonies are situated could allow Nova Scotian beekeepers to place hives in underutilized regions. We know that Kings County has the largest honey bee colony population in Nova Scotia, but we do not know if the hives are located within the Annapolis Basin. With the exact location of colonies, that information could have been used as a way to promote the growth of Nova Scotia’s bee industry because it would allow us to develop a better understanding of how Nova Scotian beekeepers are placing their beehives.

The suitability output also does not take climatic data into account. Environment and Climate Change Canada does provide an open data portal for the data collected by its weather stations across Canada and Nova Scotia is home to 85 stations, each collecting weather data at hourly, daily, or monthly intervals. However, to access this data, researchers must download hundreds, if not thousands, of comma-separated values (CSV) files for the required interval and the data may be incomplete for any given station. For example, Baddeck Bell station in Nova Scotia only records data for one day a month while other weather stations like the Bridgewater station stopped recording data in September 2012

(Environment and Climate Change Canada, 2020). An ATIP request was made to Environment and Climate Change Canada for the interpolated data on Nova Scotia's climate between 2010 and 2018 but, the department could not fulfill the request because "no records were found concerning this request" (ATIP A-2019-01545).

Including climatic data, such as temperature and precipitation, would have allowed for a better understanding of the relationship climate has to honey bee disease and pests because honey bee activity relies on the temperature and activity reduced during the colder winter months. This reduction of activity could account for the development of certain diseases such as Nosema. Future research into this topic could examine the effects Nova Scotia's climate may have on the honey bee population within the province by potentially using software that could be used to automatically download and format the data from selected Canadian weather stations (LaZerte, 2018).

Future research should include communication with all stakeholders, including beekeepers and growers who need bees to pollinate crops, in Nova Scotia's bee industry. By conducting interviews with beekeepers, further understanding of how honey bee diseases and pests affect beekeeper's livelihoods and how the diseases and pests affect the honey bee population and what measures are taken to avoid pests and disease. This increased understanding would have aided in this thesis' credibility, and overall appreciation of the importance of the honey bee industry has on the economy as well as on the environment. Future research into this topic should aim to obtain input from beekeepers through either interviews or surveys.

Chapter 7: Conclusion

This research is a continuation of the development of understanding of honey bee diseases and pests in wet environments by applying GIS methods to identify locations within Nova Scotia that are optimal for disease and pest development. Honey bee diseases develop in damp areas and with this understanding in mind, proxy geospatial datasets were collected and a land suitability map was produced that highlights the potential locations that meet a range of suitable conditions for honey bee diseases and pests. However, a more detailed and accurate map could have been produced if higher-quality datasets were available. The map produced in this thesis showed that four areas in Nova Scotia – Annapolis Basin, eastern Colchester County, western Pictou County, and Inverness County –are the optimal locations for the honey bee. These areas are considered to be optimal locations for hive location because they tend to be drier, thus, the development of diseases and pests is less likely to occur.

However, this method is not the only way GIScience and GISystems can be used to understand honey bee diseases and pests. Geographic Information Systems can be used in future research to obtain a better understanding of Nova Scotia's honey bee industry. Galbraith et al., (2015) used radar and LiDAR to track honey bee density and the spatial variation in hive placement. Honey bee disease and pest locations have been identified by using GIS to assess the suitability and distribution patterns of the disease and pest in southern Italy (Zoccali et al., 2017). Von Buren et al., (2019) were able to use the coordinates of apiaries and reported brood diseases to produce a density map that showed the areas most susceptible to brood diseases. The multi-criteria analysis used in this research can be applied to other honey bee diseases and pests studies to allow researchers and beekeepers to gain a better understanding of the land suitability for honey bee diseases and pests.

Numerous studies have shown that spatial analysis is an effective method for studying the relationships between two, or more, variables (Martin, Ortega, Otero, & Arce, 2016; Quddus, 2013; Wang & Yin, 1997) and as seen in this thesis, analysis in GISystems can be applied to the relationship between environmental conditions and honey bee diseases and pests by identifying regions that fit the conditions needed for disease and pest development. By identifying these regions, beekeepers are able to protect their beehives from diseases and pests by avoiding placing hives in locations that are susceptible to diseases and pests. By knowing these locations, beekeepers can protect their livelihoods as well as the surrounding ecosystems. However, this outcome depends largely on the type and quality of data used to understand the relationship. As mentioned throughout this thesis, information credibility, relevance, and legitimacy play an important role in determining the effectiveness of a study.

The use of open data has become common in spatial studies (Johnson, Sieber, Scassa, Stephens, & Robinson, 2017). Open data have allowed for a greater understanding of the relationship between multiple variables by giving researchers easy access to already collected data. But, as discussed throughout this thesis, not all open data have the same quality level. Some open data portals contain low-quality datasets that require extra time and effort to make them usable, or they contain language – such as abbreviations – that only a small number of individuals can understand. These factors limit the credibility, relevancy, and legitimacy of the datasets available through open data portals by reducing the overall accessibility and usability of required data.

The Open Government Working Group (2009) – a group of 30 open government advocates – proposed eight principles that government agencies should use when releasing high-quality open data. The principles state that data is open when it is complete (with respect to privacy, security, and privilege limitations), is not aggregated or modified by the government body, is made available as quickly as possible, is available to a wide range of users, is accessible by machine, is available to everyone with no requirement of registration in a user-friendly format (e.g., CVS), and is license-free. By using these principles, government agencies can ensure that the data they produce will be of high-quality and will allow for a better understanding of and solutions for current issues.

GISystems are a powerful tool used to view geospatial relationships between variables and could be applied to more studies on honey bee diseases and pests to gain a better understanding of what is affecting one of the most important pollinators for the agriculture industry and for the environment. The map created from the analysis executed in this thesis demonstrates how a weighted overlay method could be used to determine the land suitability of an entire province by using open data. By creating several raster layers that each represent different environmental factors – in the case of this thesis soil drainage, bedrock drainage, aspect, slope, flood ranges, lakes, and rivers – and by using a standardized value scale for each factor before overlaying the raster layers gives researchers the ability to visualize geospatial relationships never seen before. This thesis assessed several different environmental factors that pertain to how long soils retain water and are able to use GISystems to identify key areas within Nova Scotia that fit and do not fit the necessary requirements for the development and growth of honey bee diseases and pests as well identifying areas that, alternatively, meet the requirements for increased potential for honey bee colony health. The areas that are less prone to ground surface dampness are the locations that beekeepers should be placing their hives if they want to reduce the chances of infection by the diseases and pests discussed in this thesis and potentially relieve some financial and time management stress on beekeepers.

However, a more detailed understanding of the relationship between honey bee diseases and pests and environmental factors could have been achieved with access to higher quality data. Without high-quality datasets that provide the exact known locations of past honey bee diseases and pests cases, it is nearly impossible to predict future disease and pest cases in Nova Scotia. Because each county in Nova Scotia encompasses large and varied areas, data at the county level does not provide sufficient resolution to be able to properly predict future cases. If a finer resolution of reported disease and pest cases was made available, a density map could be made, which would allow for future research into areas that have a high density of disease and pest cases.

Access to climatic data will also allow for a fuller understanding of the relationship(s) between honey bees diseases and pests occurrences and precipitation and temperature. Precipitation has a direct effect on how wet an area becomes and by using this data to identify regions that receive extensive rainfall, beekeepers can obtain a better understanding of where not to place their hives. Nova Scotia is home to nine climatic zones and numerous microclimates, therefore, knowing the interaction between climate and water retention of the ground surface is a critical relationship. Due to technical limitations, solar insolation maps could not be created; however, solar insolation maps could be used to identify areas that receive the most sunlight, which will allow for an area to dry faster than an area in shadows.

Our understanding of what is occurring to the global honey bee population is limited by the volume of high-quality, credible, relevant, and legitimate information and data accessible to the general public, researchers, and decision makers. This current limitation of information not only puts the global honey bee population in danger, but it also endangers our way of life and the ecosystems we live in and enjoy. Honey bees pollinate one-third of the plants used directly or indirectly by humans (Aizen et al., 2009) and by not sharing and communicating information about the factors that contribute to honey bee colony health, we risk losing one of the world’s most important pollinators. This situation explains why it is important that conversation surrounding honey bees and how to protect and improve their global status needs to continue and why credible, relevant, and legitimate information about honey bees needs to be available to everyone.

References

Abejew, T. A., & Zeleke, Z. M. (2017). Study on the beekeeping situation, the level of beekeepers knowledge concerning local honeybee subspecies, their productive characteristics, and behavior in Eastern Amhara Region, Ethiopia. *Advances in Agriculture,* 6354250. DOI: 10.1155/2017/6354250.

Abou-Shaara, H. F. (2014). The foraging behaviour of honey bees, *Apis mellifera*: A review. *Veterinarni Medicina, 59*(1), 1-10. DOI: 10.17221/7240-VETMED

Abou-Shaara, H. F., Owayss, A. A., Ibrahim, Y. Y., & Basuny, N. K. (2017). A review of impacts of temperature and relative humidity on various activities of honey bees. *Insectes Sociaux, 64*, 455-463. DOI: 10.1007/s0040-017-0573-8

Agriculture and Agri-Food Canada. (n.d.). Canadian best management practices for honey bee health: Industry analysis & Harmonization. Retrieved from http://www.honeycouncil.ca/images2/pdfs/BMP_manual_-_Les_Eccles_Pub_22920_-_FINAL_-_low-res_web_-_English.pdf

Agriculture and Agri-Food Canada. (2018). Statistical overview of the Canadian honey and bee industry, 2017. Retrieved from http://www.agr.gc.ca/eng/horticulture/horticulture-sector-reports/statistical-overview-of-the-canadian-honey-and-bee-industry-2017/?id=1539180642166#1.3

Aizen, M. A., Garibaldi, L. A., Cunningham, S. A., & Klein, A. M. (2009). How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. *Annals of Botany, 103*(9), 1579-1588. DOI: 10.1093/aob/mcp076

Akinci, H., Ozalp, A. Y., & Turgut, B. (2013). Agricultural land use suitability analysis using GIS and AHP technique. *Computers and Electronic in Agriculture, 97*, 71-82. DOI: 10.1016/j.compag.2013.07.006

Akumu, C. E., Baldwin, K., & Dennis, S. (2019). GIS-based modeling of forest soil moisture regime classes: Using Rinker Lake in northwestern Ontario, Canada as a case study. *Geoderma, 351*(1), 25-35. DOI:10.1016/j.geoderma.2019.05.014

Albrecht, C. M., Elmegreen, B., Gunawan, O., Hamann, H. F., Klein, L. J., Lu, S., Mariano, F., Seibenschuh, C., & Schmude, J. (2020). Next-generation geospatial-temporal information technologies for disaster management. *IBM Journal of Research and Development, 64*(1/2), 5:1-5:12. DOI: 10.1147/JRD.2020/2970903

Alvarado, I., Phui, A., Elekonich, M. M., & Abel-Santos, E. (2013). Requirement for *In Vitro* germination of *Paenibacillus larvae* spores. *Journal of Bacteriology, 195*(5), 1005-1011. DOI: 10.1128/JB.01958-12

Amiri, F., & Shariff, A. R. B. M. (2012). Application of geographic information systems in land-use suitability evaluation for beekeeping: A case study of Vahregan watershed (Iran). *African Journal of Agricultural Research, 7*(1), 89-97. DOI: 10.5897/ajar10.1037

Antoniou, V., & Skopeliti, A. (2015). Measures and indicators of VGI quality: An overview. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2*(3/W5), 345-351. DOI:10.5194/isprsannals-II-3-W5-345-2015

Aronstein, K. A., & Murray, K. D. (2010). Chalkbrood disease in honey bees. *Journal of Invertebrate Pathology, 103*, S20-S29. DOI: 10.1016/j.jip.2009.06.018

Arthur, A. D., Li, J., Henry, S., & Cunningham, S. A. (2010). Influence of woody vegetation on pollinator densities in oilseed Brassica fields in an Australian temperate landscape. *Basic and Applied Ecology, 11*(5), 406-414. http://dx.doi.org/10.1016/j.baae.2010.05.001

Arzberger, P., Schroeder, P., Beaulieu, A., Bowker, G., Casey, K., Laaksonen, L., Moorman, D., Uhlir, P., & Wouters, P. (2004). An international framework to promote access to data. *Science, 303*(5665), 1777-1778.

Bailey, L., & Fernando, E. F. W. (1972). Effects of sacbrood virus on adult honey bees. *Annals of Applied Biology, 72*(1), 27-35. DOI: 10.1111/j.1744-7348.1972.tb01268.x

Bamford, S. & Heath, L. A. F. (1989). The effects of temperature and pH on the germination of spores of the chalkbrood fungus, *Ascophaera apis*. *Journal of Apicultural Research, 28*(1), 36-40. DOI: 10.1080/00218839.1989.11100818

Berners-Lee, T. (2006). Linked data-design issues. Retrieved from https://www.w3.org/DesignIssues/LinkedData.html

Bosquillia, R. W. D., Neale, C. M. U., Duarte, S. N., Longhi, S. J., Ferraz, S. F. B., Muller-Karger, F. E., & McCarthy, M. J. (2019). Evaluation of evapotranspiration variations as a function of relief and terrain exposure through multivariate statistical analysis. *Ecohydrology & Hydrobiology, 19*(2), 307-315. DOI: 10.1016/j.ecohyd.2018.11.001

Bowman, S. (2020). Evaluating enterprise GIS requirements. Retrieved from https://www.esri.com/news/arcuser/0205/evaluating1of2.html

Bradbear, N., & Food and Agriculture Organization of the United Nations. (2009). *Bees and their role in forest livelihoods: A guide to the services provided by bees and the sustainable harvesting, processing and marketing of their products*. Rome, Italy: Food and Agriculture Organization of the United Nations.

British Columbia Ministry of Agriculture. (2015, August). Bee behaviour during foraging. *Apiculture Bulletin 111*. Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/animal-and-crops/animal-production/bee-assets/api_fs111.pdf

Bruce, W. A., Needham, G. R., & Potts, W. J. E. (1997). The effects of temperature and water vapor activity on water loss by *Varroa jacobsoni. American Bee Journal 137*(6), 461-463.

Cai, L., & Zhu, Y. (2015). The challenges of data quality and data quality assessment in the big data era. *Data Science Journal, 14*, 2. DOI: 10.5334/dsj-2015-002

Campbell, A., & Canadian Honey Council. (2018). What's all the buzz about honey bee pollination? Retrieved from https://www.hortcouncil.ca/wp-content/uploads/2018/03/Allan-Campbell-Whats-all-the-buzz-about-Honey bee-pollination.pdf

Canadian Honey Council. (2020). Bee facts. Retrieved from https://honeycouncil.ca/bee-facts/

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jager, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America, 100*(14), 8086-8091. DOI: 10.1073/pnas.123132100

Charrier, G. Ngao, J., Saudreau, M., & Ameglio, T. (2015). Effects of environmental factors and management practices on microclimates, winter physiology, and frost resistance in trees. *Frontiers in Plant Science, 6*, 259. DOI: 10.3389/fpls.2015.00259

Chen, D., Wong, H., Belanger, P., Moore, K., Peterson, M., & Cunningham, J. (2015). Analyzing the correlation between deer habitat and the component of the risk for Lyme disease in eastern Ontario, Canada: A GIS-based approach. *International Journal of Geo-Information, 4*(1), 105-123. DOI: 10.3390/ijgi4010105

Choi, Y. S., Lee, M. Y., Hong, I. P., Kim, H. K., Lee, K. G., & Lee, M. L. (2010). Occurrence of sacbrood virus in Korean apiaries from *Apis cerana* (Hymenoptera: Apidae). *Journal of Apiculture, 25*(3), 187-191.

Clark, M. E., Rose, K. A., Levine, D. A., & Hargrove, W. W. (2001). Predicting climate change effects on Appalachian trout: Combining GIS and individual-based modeling. *Ecological Applications, 11*(1), 161-178. DOI: 10.1890/1051-0761(2001)011[0161:PCCEOA]2.0.CO;2

Collison, C. & Sheridan, A. (2012). A closer look – Chalkbrood II. *Bee Culture, 140*(2), 21-23.

Country Fields. (2019). Bee medications. Retrieved from https://www.countryfields.ca/pages/bee-medications

Conrad, R. (2017). On honey bees and fungi. *Bee Culture, 145*(8), 75,77-79.

Costa, C., Lodesani, M., & Maistrello, L. (2010). Effect of thymol and resveratrol administered with candy or syrup on the development of *Nosema ceranae* and on the longevity of honey bees *(Apis mellifera* L.) in laboratory conditions. *Apidologie, 41*(2), 141-150. DOI: 10.1051.apido.2009070

Crosby, P. B. (1988). *Quality is free: The art of making quality certain*. New York: McGraw-Hill.

Cunningham, C. (2017). *Enhancing ecosystem services mapping with primary data: Opportunities to expand Nova Scotia's managed pollination services capacity* (Unpublished master's thesis). Dalhousie University, Halifax, Canada. Retrieved from http://hdl.handle.net/10222/72789

Cutler, G. C., & Scott-Dupree, C. D. (2016). Bee ecotoxicology and data veracity: Appreciating the GLP process. *BioScience, 66*(12), 1066-1069. DOI: 10.1093/biosci/biw136 de Guzman, L. I., & Rinderer, T. E. (1999). Identification and comparison of *Varroa* species infesting honey bees. *Apidologie, 30*(2-3), 85-95.

Deming, W. E. (1986). *Out of the crisis*. Cambridge, MA: Centre for Advanced Engineering Study. Massachusetts Institute of Technology.

Devanney, & Nova Scotia Department of Agriculture. (2010). Profile of agricultural land resources in Nova Scotia. Retrieved from https://novascotia.ca/agri/documents/business-research/AL1000%20Nova%20Scotia.pdf

Doublet, V., Labarussias, M., de Miranda, J. R., Moritz, R. F., Paxton, R. J. (2015). Bees under stress: Sublethal doses of a neonicotinoid pesticide and pathogens interact to elevate honey bee mortality across the life cycle. *Environmental Microbiology, 17*(4), 969-983. DOI: 10.1111/1462-2920.12426

Douglas, J., Hunt, T., Abery, N., Allen, M. (2009). Application of GIS modelling to quantify fish habitats in lakes. *Lakes & Reservoirs: Research & Management, 14*(2), 171-174. https://doi.org/10.1111/j.1440-1770.2009.00400.x

Earle, S., & Panchuk, K. (2019). *Physical geology* (2nd ed.). Victoria, B.C: BCcampus.

Edwards-Murphy, F., Magno, M., Whelan, P. M., O'Halloran, J., & Popovici, E. M. (2016). b+WSN: Smart beehive with preliminary decision tree analysis for agriculture and honey bee health monitoring. *Computer and Electronics in Agriculture, 124*, 211-219. DOI: 10.1016/j.compag.2016.04.008

Environment and Climate Change Canada. (2019). Canadian climate normals: 1981-2010 climate normals & averages. Retrieved from https://climate.weather.gc.ca/climate_normals/

Environment and Climate Change Canada. (2020). Station results – historical data. Retrieved from https://climate.weather.gc.ca/historical_data/search_historic_data_stations_e.html?searchType=stnProv&timeframe=1&lstProvince=NS&optLimit=yearRange&StartYear=2010&EndYear=2020&Year=2020&Month=3&Day=6&selRowPerPage=50

Esri. (2016). What is raster data? Retrieved from https://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/what-is-raster-data.htm

Esri. (2019). How aspect works. Retrieved from https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-aspect-works.htm

Even, A., & Shankaranarayanan, G. (2009). Utility cost perspectives in data quality management. *The Journal of Computer Information Systems, 50*(2), 127-145. DOI: 10.1080/08874417.2009.11645391

Evison, S. E. F. (2015). Chalkbrood: Epidemiological perspectives from the host-parasite relationship. *Current Opinion in Insect Science, 10*, 65-70. DOI 10.1016/j.cois.2015.04.015

Fang, B. (2015). A GIS-multicriteria approach to analyzing noise and visual impact of wind farms (Unpublished master's thesis). University of Waterloo, Waterloo, Canada. Retrieved from https://central.bac-lac.gc.ca/.item?id=TC-OWTU-9185&op=pdf&app=Library

Fariborzi, H., Sabzevari, T., Horoozpour, S., & Mohammadpour, R. (2019). Prediction of the subsurface flow of hillslopes using a subsurface time-area model. *Hydrogeology Journal, 27*, 1401-1417. DOI: 10.1007/s10040-018-1909-9

Ferguson, J. A., Northfield, T. D., & Lach, L. (2018). Honey bee (*Apis mellifera*) pollen foraging reflects benefits dependent on individual infection status. *Microbial Ecology, 76*(2), 482-491. DOI: 10.1007/s00248-018-1147-7

Flores, J. M., Ruiz, J. A., Ruz, J. M., Puerta, F., Busto, M., Padilla, F., & Campano, F. (1996). Effect of temperature and humidity of sealed brood on chalkbrood development under controlled conditions. *Apidologie, 27*(4), 185-192. DOI: 10.1051/apido:19960401

Food and Agriculture Organization of the United Nations. (2006). Honey bee diseases and pest: A practical guide. Retrieved from http://www.fao.org/3/a-a0849e.pdf

Food and Agriculture Organization of the United Nations. (2019). Declining bee population pose threat to global food security and nutrition. Retrieved from http://www.fao.org/news/story/en/item/1194910/icode/

Fries, I. (1993). *Nosema apis* – A parasite in the honey bee colony. *Bee World, 74*(1)*,* 5-19. DOI: 10.1080/0005772X.1993.110099149

Fries, I., & Camazine, S. (2001). Implications of horizontal and vertical pathogen transmission for honey bee epidemiology. *Apidologie, 32*(3), 199-214. DOI: 10.1051/apido:2001122

Fries, I., Lindstrom, A., & Korpela, S. (2006). Vertical transmission of American foulbrood (*Paenibacillus larvae*) in honey bee (*Apis mellifera*). *Veterinary Microbiology, 114*(3-4), 269-274. DOI: 10.1016/j.vetmic.2005.11.068

Galbraith, S. M., Vierling, L. A., & Bosque-Perez, N. A. (2015). Remote sensing and ecosystem services: Current status and future opportunities for the study of bees and pollination-related services. *Current Forestry Reports, 1*(4), 261-274. https://doi.org/10.1007/s40725-015-0024-6

Gallant, A. L., Euliss, N. H., & Browning, Z. (2014). Mapping large-area landscape suitability for honey bees to assess the influence of land-use change on sustainability of National Pollination Services. *PLoS ONE, 9*(6), e99268. https://doi.org/10.137/journal.pone.0099268

Gardashov, R., Eminov, M., Kara, G., Kara, E. G. E., Mammadov, T., & Huseynova, X. (2020). The optimum daily direction of solar panels in the highlands, derived by an analytical method. *Renewable and Sustainable Energy Reviews, 120*, 109668, DOI: 10.1016/j.rser.2019.109668

Gasco-Hernandez, M., Martin, E. G., Reggi, L., Pyo, S., Luna-Reyes, L. (2018). Promoting the use of open government data: Cases of training and engagement. *Government Information Quarterly, 35*(2), 233-242. DOI: 10.1016/j.gip.2018.01.003

Genersch, E. (2010). American foulbrood in honey bees. *Journal of Invertebrate Pathology, 103*(1), S10-S19. DOI: 10.1016/j.jip.2009.06.015

Giannini, T. C., Acosta, A. L., Garofalo, C. A., Saraiva, A. M., Alves-Dos-Santos, I., & Imperatriz-Fonseca, V. L. (2012). Pollination services at risk: Bee habitats will decrease owing to climate change in Brazil. *Ecological Modelling, 244*(1), 127-131. Hhtp://dx.doi.org/10.1016/j.ecolmodel.2012.06.035

Goblirsch, M. (2018). *Nosema ceranae* disease of the honey bee (*Apis mellifera*). *Apidologie, 49*(1), 131-150. DOI: 10.1007/s13592-017-0535-1

Goodchild, M. F. (1987). A spatial analytical perspective on geographical information systems. *International Journal of Geographical Information Systems, 1*(4), 327-334. DOI: 10.1080/02693798708927820

Goodchild, M. F. (2004). GIScience, geography, form, and process. *Annals of the Association of American Geographers, 94*(4), 709-714. DOI: 10.1111/j.1467-8306.2004.00424.x

Goudie, A. S. (2004). Floodplain. In *Encyclopedia of geomorphology* (Vol. 1, pp. 381-384). London, UK: Routledge.

Grabensteiner, E., Ritter, W., Carter, M. J., Davison, S., Pechhacker, H., Kolodziejek, J., Boecking, O., Derakshifar, H., Moosebeckhofer, R., Licek, E., & Nowotny, N. (2001). Sacbrood virus of the honey bee (*Apis mellifera*): Rapid identification and phylogenetic analysis using reverse transcription-PCR. *Clinical and Diagnostic Laboratory Immunology, 8*(1), 93-104. DOI: 10.1128/CDLI.8.193-104.2001

Guerra, M., Walker, E., Jones, C., Paskewitz, S., Cortinas, M. R., Stancil, A., Beck, L., Bobo, M., & Kitron, U. (2002). Predicting the risk of Lyme disease: Habitat suitability for *Ixodes scapularis* in the north central United States. *Emerging Infectious Diseases, 8*(3), 289-297. DOI: 10.3201/eid0803.010166

Hanson, J. [It's Okay to be Smart]. (2016, March 28). *How do bees make honey*? [Video File]. Retrieved from https://www.youtube.com/watch?v=nZlEjDLJCmg

Harman, C., & Cosans, C. L. (2019). A low-dimensional model of bedrock weathering and lateral flow coevolution in hillslopes: 2. Controls on weathering and permeability profiles, drainage hydraulics, and solute export pathways. *Hydrological Processes, 33*(8), 1168-1190. DOI: 10.1002/hyp.13385

Harrison, T. M., Pardo, T. A., & Cook, M. (2012). Creating open government exosystems: A research and development agenda. *Future Internet, 4*(4), 900-928. DOI: 10,3390/fi4040900

Hasemann, L. (1961). How long can spores of American foulbrood live? *American Bee Journal, 101*, 298-299.

Health Canada. (2014). Update on neonicotinoid pesticides and bee health. Retrieved from https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/cps-spc/alt_formats/pdf/pubs/pest/_fact-fiche/neonicotinoid/neonicotinoid-eng.pdf

Hendriksma, H. P., Bain, J. A., Nguyen, N., & Nieh, J. C. (2020). Nicotine does not reduce *Nosema ceranae* infection in honey bees. *Insectes Sociaux*, 1-11. DOI: 10.1007/s00040-020-00758-5

Hetrick, W. A., Rich, P. M., & Weiss, S. B. (1993). Modeling insolation on complex surfaces. *Thirteenth Annual ESRI User Conference,* (2), 447-458.

Higes, M., Martin, R., Meana, A. (2006). *Nosema ceranae*, a new microsporidian parasite in honey bees in Europe. *Journal of Invertebrate Pathology, 92(*2), 93-95. DOI: 10.1016/j.jip.2006.02.005

Hill, A. (2018). *Agricultural intensification in the Midwest: Impacts on regional surface humidity* (Unpublished master's thesis). Minnesota State University, Mankato, United States. Retrieved from https://cornerstone.lib.mnsu.edu/etds/776/

Holt, H. L., & Grozinger, C. M. (2016). Approaches and challenges to managing Nosema (Microspora: Nosematidae) parasites in honey bee (Hymenoptera: Apidae) colonies. *Journal of Economic Entomology, 109*(4), 1487-1503. DOI: 10.1093/jee/tow103

Hooge, P. N., Eichenlaub, W. M., & Solomon, E. K. (2001). Using GIS to analyze animal movements in the marine environment. *Spatial Processes and Management of Marine Populations.* Alaska Sea Grant College Program, Anchorage Alaska, 37-51

Horn, C., Pitman, D., & Potter, R. (2019). An evaluation of the visualisation and interpretive potential of applying GIS data processing techniques to 3D rock art data. *Journal of Archaeological Science: Reports, 27*, 101971. DOI: 10.1016/j.jasrep.2019.101971

Hopkins, L. D. (1977). Methods for generating land suitability maps: A comparative evaluation. *Journal of the American Institute of Planners, 43*(4), 386-400. DOI: 10.1080/01944367708977903

Huggett, J. (2017). *Fundamentals of geomorphology* (4th ed.). New York: Routledge.

Humboldt State University. (2017). Raster to vector. Retrieved from http://gsp.humboldt.edu/OLM_2017/Lessons/GIS/08%20Rasters/RasterToVector.html

Jackson, R. J. (1967). The effect of slope, aspect, and albedo on potential evapotranspiration from hillslopes and catchments. *Journal of Hydrology, 6*(2), 60-69.

James, R. R. (2005) Temperature and chalkbrood development in the alfalfa leaf cutting bee, *Megachile rotundata*. *Apidologie, 36*(1), 15-23. DOI: 10.1051/apido:2004065

Janssen, M., Charalabidis, Y., & Zuiderwijk, A. (2012). Benefits, adoption barriers and myths of open data and open government. *Information Systems Management, 29*(4), 258-268. DOI: 10.1080/10580530.2012.716740

Jarnevich, C. S., Esaias, W. E., Ma, P. L. A., Morisette, J. T., Nickeson, J. E., Stohlgren, T. J., Holcombe, T. R., Nightingale, J. M., Wolfe, R. E., & Tan, B. (2013). Regional distribution models with lack of proximate predictors: Africanized honey bees expanding north. *Diversity and Distributions, 20*(2), 193-201. DOI: 10.1111/ddi.12143

Johnson, P. A., Sieber, R., Scassa, T., Stephens, M., & Robinson, P. (2017). The cost(s) of geospatial open data. *Transactions in GIS*, *21*(3). DOI: 10.1111/this.12283

Joseph, J., & Cook, D. P. (2008). Medical ethical and policy issues arising from RIA. *Political Science*. DOI: 10.4018/978-1-59904-857-4.ch031

Katznelson, H. & Jamieson, C. A. (1952). Control of nosema disease of honey bees with fumagillin. *Science, 115*(2977), 70-71. DOI: 10.1126/science.115.2977.70

Kelly, P. (2019). Tips tricks and tools: Fumigating with acetic acid to decontaminate brood chambers. Retrieved from http://www.uoguelph.ca/honey bee/education-fumigation.shtml

Kevan, P., Hannan, M. A., Ostiguy, N., & Guzman-Novoa, E. (2016). A summary of the Varroa-virus disease complex in honey bee. *American Bee Journal, 156*(8), 694-697.

Klein, S., Cabirol, A., Devaud, J. M., Barron, A. B., & Lihoreau, M. (2017). Why bees are so vulnerable to environmental stressors. *Trends in Ecology and Evolution*, *32*(4), 268-278. DOI: 10.1016/j.tree.2016.12.009

Kostyk, A., Zhou, W., & Hyman, M. R. (2019). Using surveytainment to county declining survey data quality. *Journal of Business Research, 95*, 211-219. DOI: 10.1016/j.jbusres.2018.10.024

Kozak, P. R. (2008). Influence of the winter environment on the biology and control of *Varroa destructor* Anderson and Trueman in honey bee colonies *Apis mellifera* L (Unpublished master's thesis). The University of Manitoba, Winnipeg, Canada. Retrieved from https://central.bac-lac.gc.ca/.item?id=MR48993&op=pdf&app=Library

Kralj, J., & Fuchs, S. (2010). *Nosema sp.* influences flight behavior of infected honey bee (*Apis mellifera*) foragers. *Apidologie, 41*(1), 21-28. DOI: 10.1051/apido/2009046

Lawrence, B. M., Stevenson, M. R., Oxley, J. A., Logan, D. B. (2015). Geospatial analysis of cyclist injuring trends: An investigation in Melbourne, Australia. *Traffic Injury Prevention, 16*(5), 513-518. DOI: 10.1080/15389588.2014.973947

LaZerte, S. (2018). Weathercan: R package for downloading weather data from Environment and Climate Change Canada. Retrieved from https://github.com/ropensci/weathercan

Le Conte, Y., Arnold, G., & Desenfant, P. H. (1990). Influence of brood temperature and hygrometry variations on the development of the honey bee ectoparasite *Varroa jacobsoni*. *Environmental Entomology, 19*(6), 1780-1785. DOI: 10.1093/ee/19..6.1780

Leung, A. K., & Ng, C. W. W. (2013). Analysis of groundwater flow and plant evapotranspiration in a vegetated soil slope. *Canadian Geotechnical Journal, 50*(12), 1204-1218. DOI: 10.1139/cgj-2013-0148

Levine, E., Knox, R., & Lawrence, W. (1994). Relationships between soil properties and vegetation at the northern experimental forest, Howland, Maine. *Remote Sensing of Environment, 47*(2), 231-241. DOI: 10.1016/0034-4257(94)90158-9

Li, J., Wang, T., Evans, J. D., Rose, R., Zhao, Y., Li, Z., Li, J., Huang, S., Heerman, M., Rodriguez-Garcia, C., Banmeke, O., Brister, J. R., Hatcher, E. L., Cao, L., Hamilton, M., & Chen, Y. (2019). The phylogeny and pathogenesis of sacbrood virus (SBV) infection in European honey bees, *Apis mellifera. Viruses, 11*(61). DOI: 10.3390/v11010061

Lindstrom, A., Korpela, S., & Fries, I. (2008). The distribution of *Paenibacillus larvae* spores in adult bees and honey and larval mortality, following the addition of American foulbrood diseased brood or spore-contaminated honey in honey bee (*Apis mellifera*) colonies. *Journal of Invertebrate Pathology, 99*(1), 82-86. DOI: 10.1016/j.jip.2008.06.010

Lipiec, J., Kus, J., Stowinsha-Jurkiewicz, A., & Nosalewicz, A. (2006). Soil porosity and water infiltration as influenced by tillage methods. *Soil and Tillage Research, 89*(2), 210-220. DOI: 10.1016/j.still.2005.07.012

Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2015). *Geographic information science & systems* (4th ed.). Danvers, MA: John Wiley & Sons, Inc.

Lor, P. J., & Britz, J. J. (2007). Is a knowledge society possible without freedom of access to information? *Journal of Information Science, 33*(4), 387-397. DOI: 10.1177/0165551506075327

Makori, D. M., Fombong, A. T., Abdel-Rahman, E. M., Nkoba, K., Ongus, J., Irungu, J., Mosomtai, G., Makau, S., Mutanga, O., Odindi, J., Raina, S., Landmann, T. (2017). Predicting spatial distribution of key honey bee pests in Kenya using remotely sensed and bioclimatic variables: Key honey bee pests distribution models. *International Journal of Geo-Information, 6*(3). DOI: 10.3390/ijgi6030066

Malczewski, J. (2004). GIS-based land-use suitability analysis: A critical overview. *Progress in Planning, 62*(1), 3-65. DOI: 10.1016/j.progress.2003.09.002

Maleki, S. A. M., Hizam, H., & Gomes, C. (2017). Estimation of hourly, daily, and monthly global solar radiation on inclined surfaces: Models re-visited. *Energies, 10*(1), 134. DOI: 10.3390/en10010134

Maris, N. M. N., Mansor, S., & Shafri, H. Z. M. (2008). Apicultural site zonation using GIS and multi-criteria decision analysis. *Pertanika Journal of Tropical Agricultural Science, 31*(2), 147-162.

Martin, B., Ortega, E., Otero, I., & Arce, R. M. (2016). Landscape character assessment with GIS using map-based indicators and photographs in the relationship between landscape and roads. *Journal of Environmental Management, 180*(15), 324-334. DOI: 10.1016/j.jenvman.2016.05.044

Martin E. G., Law, J., Ran, W., Helbrig, N., & Birkhead, G. S. (2017). Evaluating the quality and usability of open data for public health research: A systematic review of data offerings on 3 open data platforms. *Journal of Public Health Management and Practices, 23*(4), e5-e13. DOI: 10.1097/PHH.0000000000000388

McGowan, J. (2012). Viability assessment and cryopreservation of the honey bee (*Apis mellifera)* parasite, *Nosema ceranae* (Unpublished master's thesis). University of Guelph, Guelph, Canada.

Medeiros, G., & Holanda, M. (2019). Solutions for data quality in GIS and VGI: A systematic literature review. In *World Conference on Information Systems and Technologies* (pp. 645-654). Cham: Springer. DOI: 10.1007/978-3-030-16181-1_61

Meyer, S. P. (2017). Complementary and alternative medicine (CAM): Single, multiple and high-density function locations in intermediately sized centers in Ontario, Canada. *HSOA Journal of Alternative, Complementary & Integrative Medicine, 3*(2), 1-9. DOI: 10.24966/ACIM-7562/100027

Moeller, F. E. (1972). Effects of emerging bees and of winter flights on *Nosema* disease in honey bee colonies. *Journal of Apicultural Research, 11*(2), 117-120. DOI: 10.1080/00218839.1972.11099709

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology, 19*, 205-234.

Morbidelli, R., Saltalippi, C., Flammini, A., & Govindaraju, R. S. (2018). Role of slope on infiltration: A review. *Journal of Hydrology, 557*, 878-886. DOI: 10.1016/j.hydrol.2018.01.019

Morris, A. (2015, August 18). What is killing America's bees and what does it mean for us? *RollingStone.* https://www.rollingstone.com/culture/culture-news/what-is-killing-americas-bees-and-what-does-it-mean-for-us-41456/

Morrissey, B., Helgason, T., Poppinga, L., Funfhaus, A., Genersch, E., Budge, G. E. (2015). Biography of *Paenibacillus larvae*, the causative agent of American foulbrood, using a new multilocus sequence typing scheme. *Environmental Microbiology, 17*(4), 1414-1424. DOI: 10.1111/1462-2920.12625

Moudry, V., & Devillers, R. (2020). Quality and usability challenges of global marine biodiversity databases: An example for marine mammal data. *Ecological Informatics, 56*, 101051. DOI: 10.1016/j.ecoinf.2020.101051

Mussen, E. C. (2011). Diagnosing and treating Nosema disease. *Extension Apiculturist.* Retrieved from http://entomology.ucdavis.edu/files/147621.pdf

National Bee Diagnostic Centre. (2017). Canadian national honey bee health survey. Retrieved from https://www.gprc.ab.ca/doc.php?d=2017NHBHS

Naug, D., & Gibbs, A. (2009). Behavioral changes mediated by hunger in honey bees infected with *Nosema ceranae. Apidologie, 40*(6), 595-599. DOI: 10.1051/apido/2009039

Norstrom, M. (2001). Geographical information system (GIS) as a tool in surveillance and monitoring of animal diseases. *Acta Veterinaria Scandinavica, 94*, 79-85. DOI: 10.1186/1751-0147-42-S1-S79

Nova Scotia Beekeeper's Association. (2016a). Nova Scotia blueberry producers say more honey bees essential for industry. Retrieved from https://nsbeekeepers.ca/industrynewsDetail.php?117

Nova Scotia Beekeeper's Association. (2016b). Interesting Nova Scotia statistics. Retrieved from http://www.nsbeekeepers.ca/industrynewsDetail.php?110

Nova Scotia Department of Agriculture. (2010a)..Climate and soil considerations: Resource kit for Nova Scotia farmers. Retrieved from https://novascotia.ca/thinkfarm/documents/fsheets/02-climate-soil-considerations.pdf

Nova Scotia Department of Agriculture. (2010b). An overview of the Nova Scotia agriculture and agri-food industry. Retrieved from https://novascotia.ca/agri/documents/business-research/AO0102%202010%20NS%20Ag%20Overview%20w%20Appendices.pdf

Nova Scotia Department of Environment and Labour. (2002). Natural landscapes of Nova Scotia: Summary descriptions. Retrieved from https://novascotia.ca/nse/protectedareas/docs/landscapes_report.pdf

Nova Scotia Department of Fisheries and Aquaculture. (2009). Province releases state of Nova Scotia's coast report. Retrieved from https://novascotia.ca/news/smr/2009-12-10-coastal.asp

Nova Scotia Department of Lands and Forestry. (2006a). Enhanced digital elevation model, Nova Scotia, Canada. Retrieved from https://novascotia.ca/natr/meb/download/dp055.asp

Nova Scotia Department of Lands and Forestry. (2006b). Geological map of the province of Nova Scotia. Retrieved from https://novascotia.ca/natr/meb/download/dp043.asp

Nova Scotia Department of Lands and Forestry. (2017). Ecological land classification for Nova Scotia. Retrieved from https://novascotia.ca/natr/forestry/ecological/pdf/Ecological-Land-Classification-guide.pdf

Nova Scotia Department of Lands and Forestry. (2019). Ecological landscape analysis. Retreved from https://fernow.novascotia.ca/elareports/

Nova Scotia Environment. (2020). What is a flood? Retrieved from https://novascotia.ca/nse/climate-change/nsfaf-flooding.asp

Nova Scotia Environment - Climate Change Unit. (2020). Climate data for Nova Scotia. Retrieved from https://climatechange.novascotia.ca/climate-data?tid=10#climate-data-map

Nova Scotia Finance and Treasury Board. (2018). Farm income, 2017. Retrieved from https://novascotia.ca/finance/statistics/news.asp?id=13870

Nova Scotia Finance and Treasury Board. (2019, September 30). Nova Scotia's population reaches all-time high. Retrieved from https://novascotia.ca/news/release/?id=20190930008

Nova Scotia Legislature. (2005). Bee industry Act: Bill no. 173. Retrieved from https://nslegislature.ca/legc/bills/59th_1st/3rd_read/b173.htm

Nova Scotia Legislature. (2007). Bee industry regulations made under Section 17 of the Bee Industry Act. *Bee industry Act: Bill no. 173.* Retrieved from https://novascotia.ca/just/regulations/regs/beeindustry.htm

Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos, 120*(3), 321-326. DOI: 10.1111/j.1600-0706.2010.18644.x

Ontario Ministry of Agriculture, Food, and Rural Affairs. (2019). Ontario treatment recommendations for honey bee disease and mite control. Retrieved from http://www.omafra.gov.on.ca/english/food/inspection/bees/2017-treatment.htm

Open Government Working Group. (2009). The 8 principles of open government data. Retrieved from https://opengovdata.org/

Paredes-Sabja, D., Setlow, P., & Sarker, M. R. (2011). Germination of spores of Bacillales and Clostridiales species: Mechanism and proteins involved. *Trends in Microbiology, 19*(2), 85-94. DOI: 10.1016/j.tim.2010.10.004

Plant Health Australia. (2016). Chalkbrood disease fact sheet. Retrieved from https://www.planthealthaustralia.com.au/wp-content/uploads/2016/02/Chalkbrood-disease-FS.pdf

Plant Health Australia. (2019a). American foulbrood. Retrieved from https://beeaware.org.au/archive-pest/american-foulbrood/#ad-image-0

Plant Health Australia. (2019b). Varroa mites. Retrieved from https://beeaware.org.au/archive-pest/varroa-mites/#ad-image-0

Plant Health Australia. (2019c). Sacbrood virus. Retrieved from https://beeaware.org.au/archive-pest/sacbrood/#ad-image-0

Prokudin, D., Levit, G., & Hossfeld, U. (2019). Selection methods for geodata visualization of metadata extracted from unstructured digital data for scientific heritage studies. In *International Conference on Digital Transformation and Global Society* (pp. 542-553). Cham: Springer. DOI: 10.1007/978-3-030-37858-5_36

Quddus, M. (2013). Exploring the relationship between average speed, speed variation, and accident rates using spatial statistical models and GIS. *Journal of Transportation Safety & Security, 5*(1), 27-45. DOI: 10.1080/19439962.2012.705232

Rader, R., Reilly, J., Bartomeus, I., & Winfree, R. (2013). Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. *Global Change Biology, 19*(10), 3103-3110. DOI: 10.1111/gcb.12264

Rangel, J., Giresi, M., Pinto, M. A., Baum, K. A., Rubink, W. L., Coulson, R. N., & Johnston, J. S. (2016). Africanization of a feral honey bee (*Apis mellifera*) population in south Texas: Does a decade make a difference? *Ecology and Evolution, 6*(7), 2158-2169. DOI: 10.1002/ece3.1974

Ratti, V. (2011). Local stability analysis of a mathematical model of the honey bee – Varroa mite – acute paralysis complex (Unpublished master’s thesis). University of Guelph, Guelph, Canada. Retrieved from https://central.bac-lac.gc.ca/.item?id=MR71497&op=pdf&app=Library

Ratti, V. (2015). Predictive modeling of the disease dynamics of the honey bee – *Varroa destructor* – virus systems (Unpublished doctoral dissertation.) University of Guelph, Guelph, Canada. Retrieved from https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/9227/Ratti_Vardayani_201508_PhD.pdf;jsessionid=7D72112A2614A5AED4CFF24B9457A378?sequence=1

Requier, F., Jownaowitsch, K. K., Kallnik, K., & Steffan-Dewenter, I. (2019). Limitation of complementary resources affects colony growth, forgaing behavior, and reproduction in bumble bees. *Ecology,* e02946. DOI: 10.1002/ecy.2946

Reuter, H. I., Kersebaum, K. C., & Wendroth, O. (2005). Modelling of solar radiation influenced by topographic shading – evaluation and application for precision farming. *Physics and Chemistry of the Earth, Parts A/B/C, 30*(1-3), 143-149. DOI: 10.1016/j.pce.2004.08.027

Rieu, M., & Sposito, G. (1991). Fractal fragmentation, soil porosity, and soil water properties: I theory. *Soil Science Society of America Journal, 55*(5), 1231-1238. DOI: 10.2136/sssaj1991/03615995005500050006x

Rooth, M. (2018, June 29). Varroa mite detected at Port of Melbourne on a ship from United States. *ABC News.* Retrieved from https://www.abc.net.au/news/rural/2018-06-29/varroa-mite-detected-in-melbourne/9923972

Ruikkala, T., Aalto, I., Peltoniemi, M., Salmivaara, A., Tuominen, S., & Muukkonen, P. (2019). Applying open GIS data to study wetland forests and ditches in Finland. In *GIS Applications in Teaching and Research: Final Report of MSc Course at the Department of Geosciences and Geography, University of Helsinki, Spring 2019.* Retrieved from https://helda.helsinki.fi/bitstream/handle/10138/309007/KujalaMuukkonen_C17_GIS.pdf?sequence=1#page=45

Ryabov, E. V., Childers, A. K., Chen, Y., Madella, S., Nessa, A., vanEngelsdorp, D., & Evans, J. D. (2017). Recent spread of Varroa destructor virus-1, a honey bee pathogen, in the United States. *Scientific Reports, 7*, 17447. DOI: 10.1038/s41598-017-17802-3

Salata, F., Golasi, I., Petitti, D., Vollaro, E. L., Coppi, M., & Vollaro, A. L. (2017). Relating microclimate, human thermal comfort and health during heat waves: An analysis of heat island mitigation strategies through a case study in an urban outdoor environment. *Sustainable Cities and Society, 30*, 79-96. DOI: 10.1016/j.scs.2017.01.006

Sarkki, S., Niemela, J., Tinch, R., Hove, S. V. D., Watt, A., & Young, J. (2014). Balancing credibility, relevance and legitimacy: A critical assessment of trade-offs in science-policy interfaces. *Science and Public Policy, 41*(2), 194-206. DOI: 10.1093/scipol/sct046

Scannapieco, M., & Catarci, T. (2002). Data quality under a computer science perspective. *Archivi Computer*, *2*, 1-15.

Schiff, N. M., Sheppard, W. S., Loper, G. M., & Shimanuki, H. (1994). Genetic diversity of feral honey bee (Hymenoptera: Apidae) population in southern United States. *Annals of the Entomological Society of America, 87*(6), 842-848. DOI: 10.1093/aesa/87.6.842

Seeley, T. D. (2019). *The lives of bees: The untold story of the honey bee in the wild.* Princeton, New Jersey: Princeton University Press.

Sheppard, W. S. (1989). A history of the introduction of honey bee races into the United States. *American Bee Journal, 129*(9), 617-619, 664-666.

Sproule, J. (2018, March 3). NSDA report on the status of NS Honey bee industry. NS Department of Agriculture. Retrieved from http://www.perennia.ca/wp-content/uploads/2018/04/nsda-report-on-the-status-of-ns-honey-bee-industry.pdf

Statistics Canada. (2011). Focus on geography series, 2011 census: Province of Nova Scotia. Retrieved from https://www12.statcan.gc.ca/census-recensement/2011/as-sa/fogs-spg/Facts-pr-eng.cfm?Lang=Eng&GK=PR&GC=12

Sun, M. (2019, September 2019). The threat of varroa mite is real; But these Australian beekeepers are ready to face it. *ABC News*. Retrieved from https://www.abc.net.au/news/2019-09-18/the-beekeepers-ready-to-fight-varroa-mite-in-australia/11505370

Suryanarayanan, S., & Kleinman, D. L. (2011). Disappearing bees and reluctant regulators. *Issues in Science and Technology, 27*(4), 33-36.

Swetnam, R. D., Fisher, B., Mbilnyi, B. P., Munishi, P. K., Willcock, S., Ricketts, T., Mwakalila, S., … Lewis, S. L. (2011). Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of Environmental Management, 92*(3), 563-574. DOI: 10.1016/j.jenvman.2010.09.007

Tatem, A. J. (2017). Worldpop, open data for spatial demography. *Scientific Data, 4*, 170004. DOI: 10.1038/sdata.2017.4

Tauberer, J. (2014). *Open government data: The book.* Retrieved from https://opengovdata.io/

Tentcheva, D., Gautheir, L., Zappulla, N., Dainat, B., Cousserans, F., Colin, M. E., & Bergoin, M. (2004). Prevalence and seasonal variations of six bee viruses in *Apis mellifera* and Varroa destructor mite populations in France. *Applied and Environmental Microbiology. 70*(12), 7185-7191. DOI: 10.1128/AEM.70127185-7191.2004

Touart, L. W., & Maciorowski, A. F. (1997). Information needs for pesticide registration in the United States. *Ecological Applications, 7*(4), 1086-1093. DOI: 10.1890/1051-0761(1997)007[1086:INFPRI]2.0.CO;2

Traynor, K. S., Rennich, K., Forsgren, E., Rose, R., Pettis, J., Kunkel, G., Madella, S., Evans, J., Lopaz, D., & vanEngelsorp, D. (2016). Multiyear survey targeting disease incidence in US honey bee. *Apidologie, 47*, 325-247. DOI: 10.1007/s13592-016-0431-0

Ubaldi, B. (2013). Open government data" Towards empirical analysis of open government data initiatives. In *OECD Working Papers on Public Governance*. Paris; OECD Publishing. DOI: 10.1787/5k46bj4f03s7-en

U.S. Department of Agriculture. (2019). American foulbrood disease. Retrieved from https://www.ars.usda.gov/northeast-area/beltsville-md-barc/beltsville-agricultural-research-center/bee-research-laboratory/docs/american-foulbrood-disease/

Unwin, D. J. (1995). Geographical information systems and the problem of "error and uncertainty." *Progress in Human Geography, 19*(4), 549-558. DOI: 10.1177/030913259501900408

Unwin, D. J. (1996). GIS, spatial analysis, and spatial statistics. *Progress in Human Geography, 20*(4), 540-551. DOI: 10.1177/030913259602000408

Vanegas, M. (2017). The silent bee hive: How the decline of honey bee populations shifted the Environmental Protection Agency's pesticide policy towards pollinators. *Ecology Law Quarterly, 44*(2), 311-341. https://doi.org/10.15779/Z38GQ6R199

vanEngelsdorp, D., & Meixner, M. D. (2010.) A historical review of managed honey bee populations in Europe and the United States and the factors that may affect them. *Journal of Invertebrate Pathology, 103*(1), S80-95. DOI: 10.1016/j.jip.2009.06.011

vanEngelsorp, D., Traynor, K. S., Lichtenberg, E. M., Chen, Y., Saegerman, C., & Cox-Foster, D. L. (2017). Colony collapse disorder (CCD) and bee age impact honey bee pathophysiology. *PLoS One, 12*(7), e0179535. DOI: 10.1371/journal.pone.0179535

Vetro, A., Canova, L., Torchiano, M., Minotas, C. O., Iemma, R., Morando, F. (2016). Open data quality measurement framework: Definition and application to open government data. *Government Information Quarterly, 33*(2), 325-337. DOI: 10.1016/j.giq.2016.02.001

Viscusi, G., Spahiu, B., Maurino, A., & Batini, C. (2014). Compliance with open government data policies: An empirical assessment of Italian local public administrations. *IOS Press Content Library, 19*(3,4), 263-275. DOI: 10.3233/IP-140338

von Buren, R. S., Oehen, B., Kuhn, N. J., & Erler, S. (2019). High-resolution maps of Swiss apiaries and their applicability to study spatial distribution of bacterial honey bee brood diseases. *PeerJ 7*, e6393. DOI: 10.7717/peerj.6393

Wang, X., & Yin, Z. Y. (1997). Using GIS to assess the relationship between land use and water quality at a watershed level. *Environment International, 23*(1), 103-114.

Wang, Y. F., & Strong, D. M. (1996). Beyond accuracy: What data quality means to data consumers. *Journal of Management Information Systems, 12*(4), 5-33. DOI: 10.1080/07421222.1996.11518099

Warrit, N., Smith, D. R., & Lekprayoon, C. (2005). Genetic subpopulation of *Varroa* mites and their *Apis cerana* hosts in Thailand. *Apidologie, 37*(1), 19-30. DOI: 10.1051/apido:2005051

Williams, G. R. (2013). *Nosema ceranae* in western honey bees *(Apis mellifera):* Biology and management (Unpublished doctoral dissertation). Dalhousie University, Halifax, Canada. Retrieved from http://hdl.handle.net/10222/21716

Wu, L., Zhou, J., Xue, X., Li, Y., & Zhao, J. (2009). Fast determination of 16 amino acids and their content changes in royal jelly during storage using ultraperformance liquid chromatography. *Journal of Food Composition and Analysis, 22*(3), 242-249. DOI: 10.1016/j.jfca.2008.10.022

Yoder, J. A., Sammataro, D., Peterson, J. A., Needham, G. R., & Bruce, W. A. (1999). Water requirements of adult females of the honey bee parasitic mite, *Varroa jacobsoni* and implications for control. *International Journal of Acarology, 25*(4), 329-335. DOI: 10.1080/01647959908684171

Yoder, J. A., Nelson, B. W., Main, L. R., Lorenz, A. L., Jajack, A. J., & Aronstein, K. A. (2016). Water activity of the bee fungal pathogen *Ascosphaera apis* in relation to colony conditions. *Apidologie, 48*(2), 159-167. DOI: 10.1007/s13592-016-0461-7

Zhao, Q., Sailor, D. J., & Wentz, E. A. (2018). Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. *Urban Forestry and Urban Greening, 32*, 81-91. DOI: 10.1016/j.ufug.2018.03.022

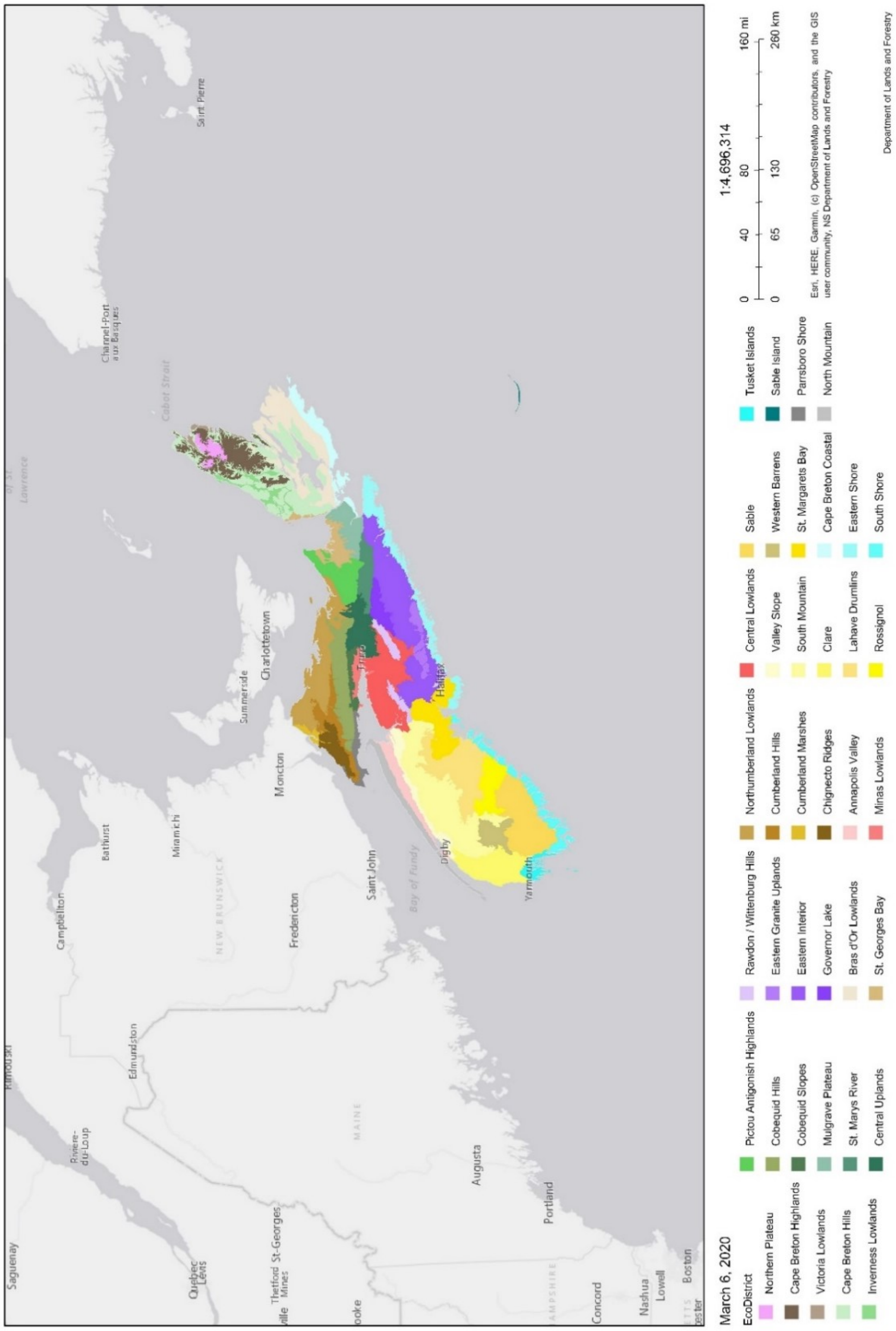
Zhao, Z., Ashraf, M. I., & Meng, Fan-Rui. (2012). Model prediction of soil drainage classes over a large area using a limited number of field samples: A case study in the province of Nova Scotia, Canada. *Canadian Journal of Soil Science, 93*(1), 73-83. DOI: 10.4141/cjss2011-095

Zoccali, P., Malacrino, A., Campolo, O., Laudani, F., Algeri, G. M., Giunti, G., Strano, C. P., Benelli, G., Palmeri, V. (2017). A novel GIS-based approach to assess beekeeping suitability of Mediterranean lands. *Saudi Journal of Biological Sciences, 2*(5), 1045-1050. DOI: 10.1016/j.sjbs.2017.01.062

Appendix I: Chapter 3 Nova Scotia Geography

Figure A1.1

Nova Scotia Ecological Landscape Analysis Map



(Nova Scotia's Department of Lands and Forestry, 2019)

Appendix II: Chapter 3 Nova Scotia Honey Bee Population

Table A2.1

Distribution of the reported honey bee diseases and pests in Nova Scotia by county and year

	2010	2011	2012	2014	2015	2016	2017	2018
American Foulbrood	**3**			**1**		**2**		**3**
Annapolis	1							
Colchester						2		2
Hants	1							
Kings	1			1				1
Chalkbrood	**1**	**2**	**2**	**10**	**14**	**12**	**17**	**30**
Annapolis							1	
Antigonish				1				
Colchester		2	2	3	5	7	3	6
Cumberland					1		1	5
Guysborough								4
Halifax				1	2		2	3
Hants				2	1	5	4	9
Kings	1			2	2		5	2
Lunenburg					1			
Pictou				1	2		1	1
European Foulbrood			**2**				**1**	
Colchester			2					
Halifax							1	
K-Wing						**2**		
Antigonish						2		
Mites		**2**	**1**				**1**	**1**
Colchester		1					1	
Cumberland			1					
Kings								1
Lunenburg		1						
Sacbrood			**1**			**1**	**6**	**4**
Colchester			1			1		
Guysborough								3
Halifax							2	1
Kings							3	
Pictou							1	

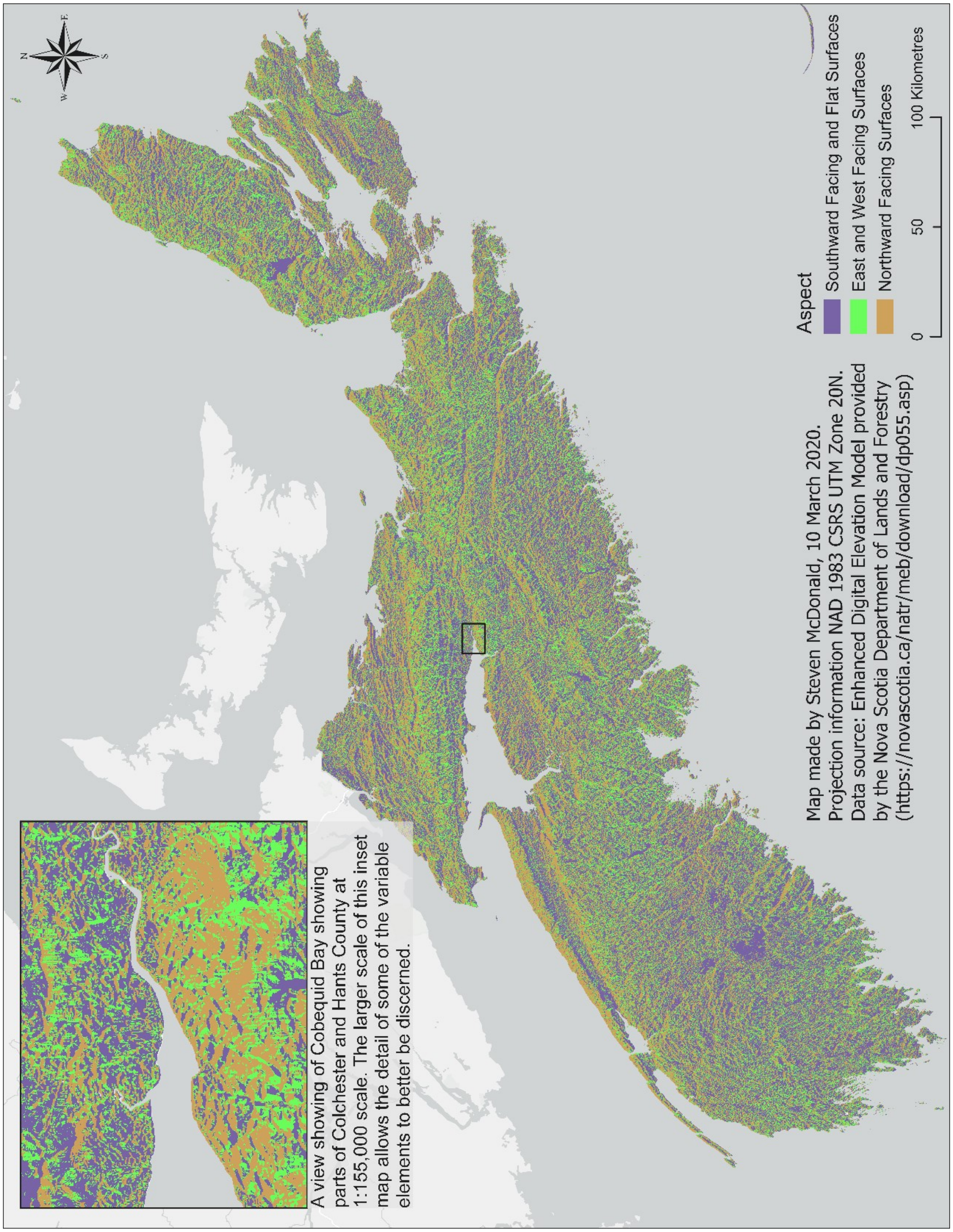
	2010	2011	2012	2014	2015	2016	2017	2018
Scale							**1**	
Colchester							1	
Varroa Mite	**1**				**1**		**2**	**1**
Colchester							1	
Digby	1							
Halifax								1
Kings					1			
Pictou							1	
Wax Moth		**1**					**1**	**1**
Colchester								1
Halifax		1						
Kings							1	

(FOIPOP 2019-00049-AGR)

Appendix III: Chapter 5 Layer Creation

Figure A3.1

Aspect layer created to show the surface direction in Nova Scotia.

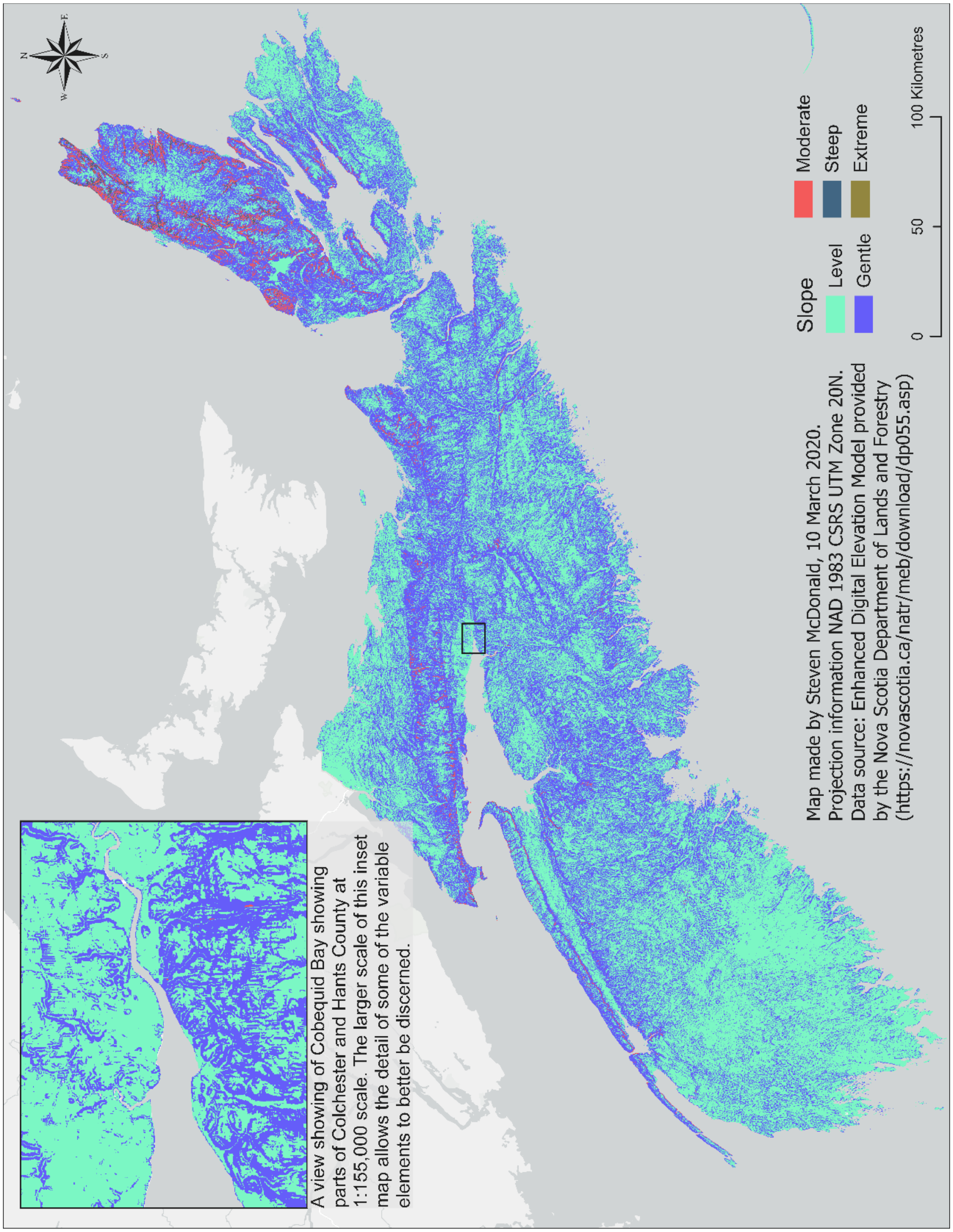


Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Enhanced Digital Elevation Model provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/meb/download/dp055.asp)

A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Figure A3.2

Slope layer showing the gradient surface slope in Nova Scotia

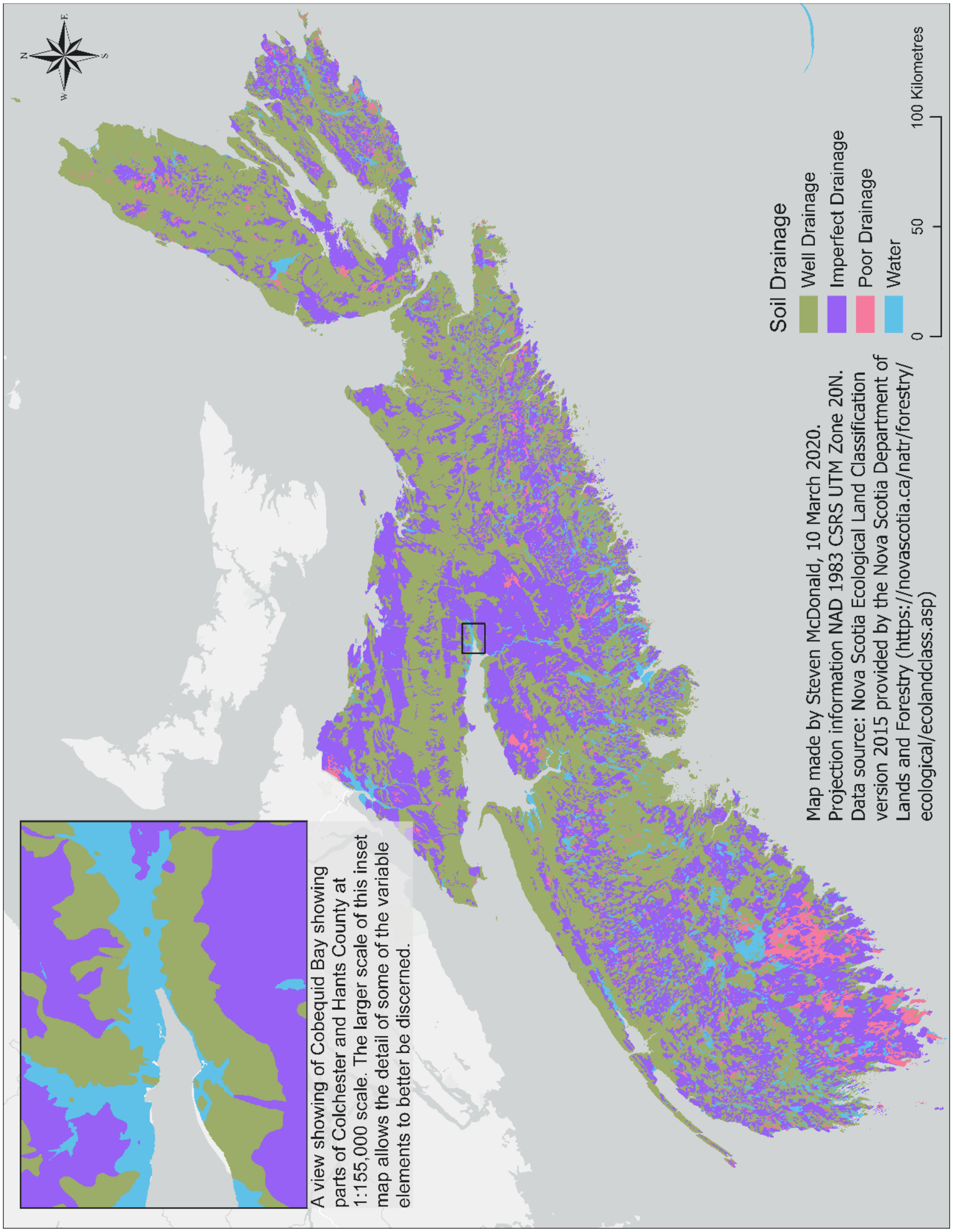


A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Enhanced Digital Elevation Model provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/meb/download/dp055.asp)

Figure A3.3

Soil drainage layer showing the different drainage regions in Nova Scotia

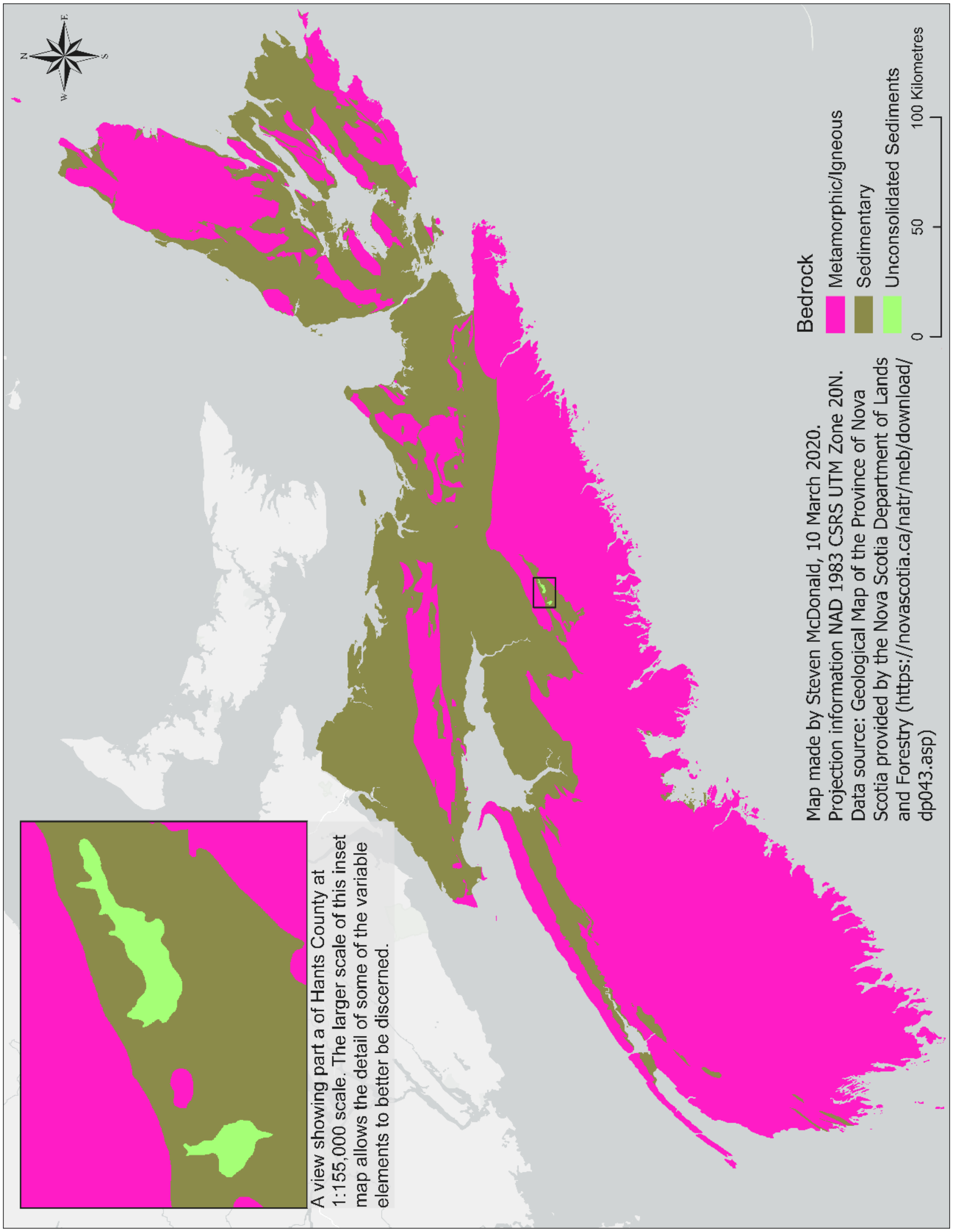


A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Ecological Land Classification version 2015 provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/forestry/ecological/ecolandclass.asp)

Figure A3.4

Bedrock layer representing the location of the bedrock types in Nova Scotia

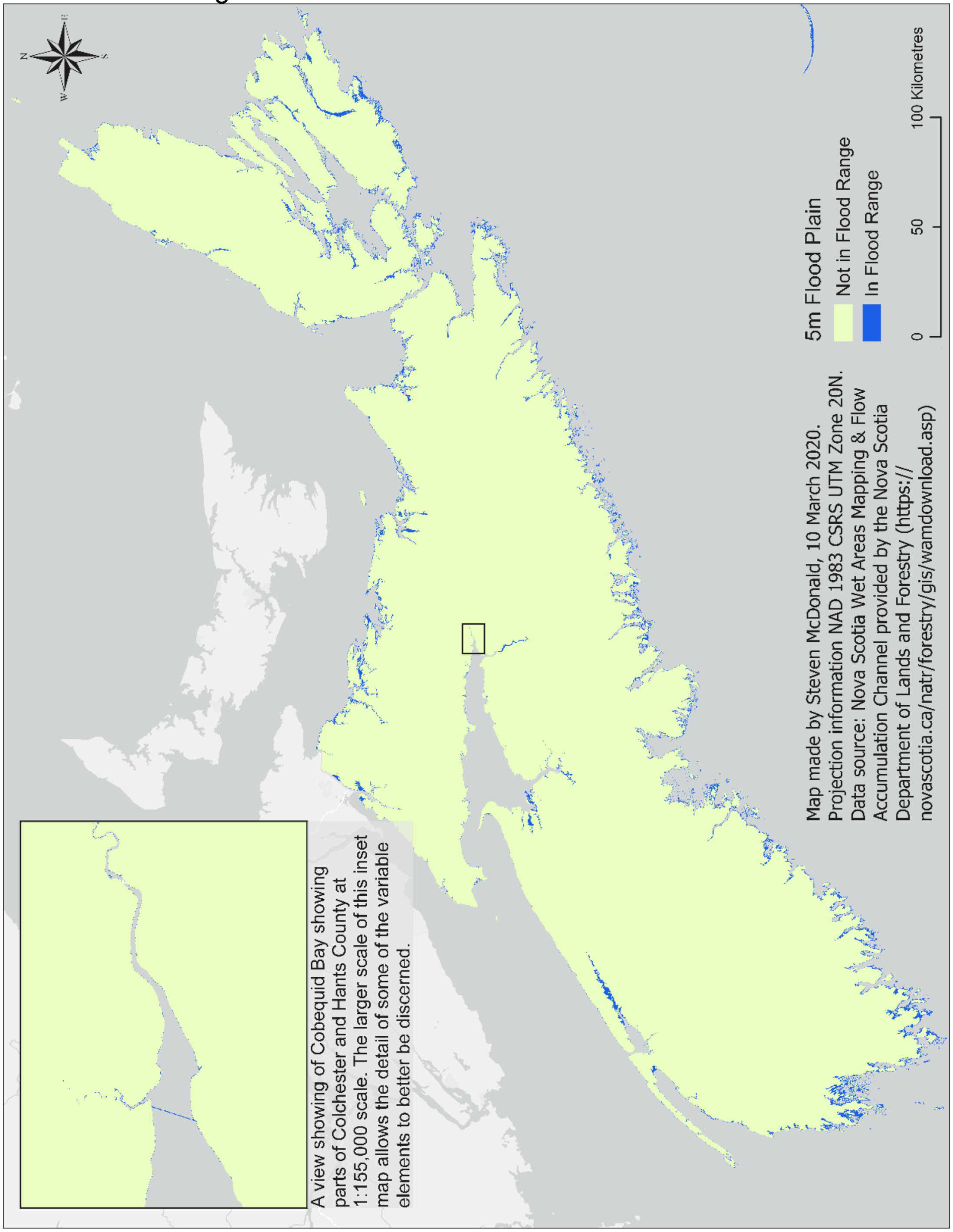


Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Geological Map of the Province of Nova Scotia provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/meb/download/dp043.asp)

A view showing part a of Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Figure A3.5

5-metre flood range in Nova Scotia

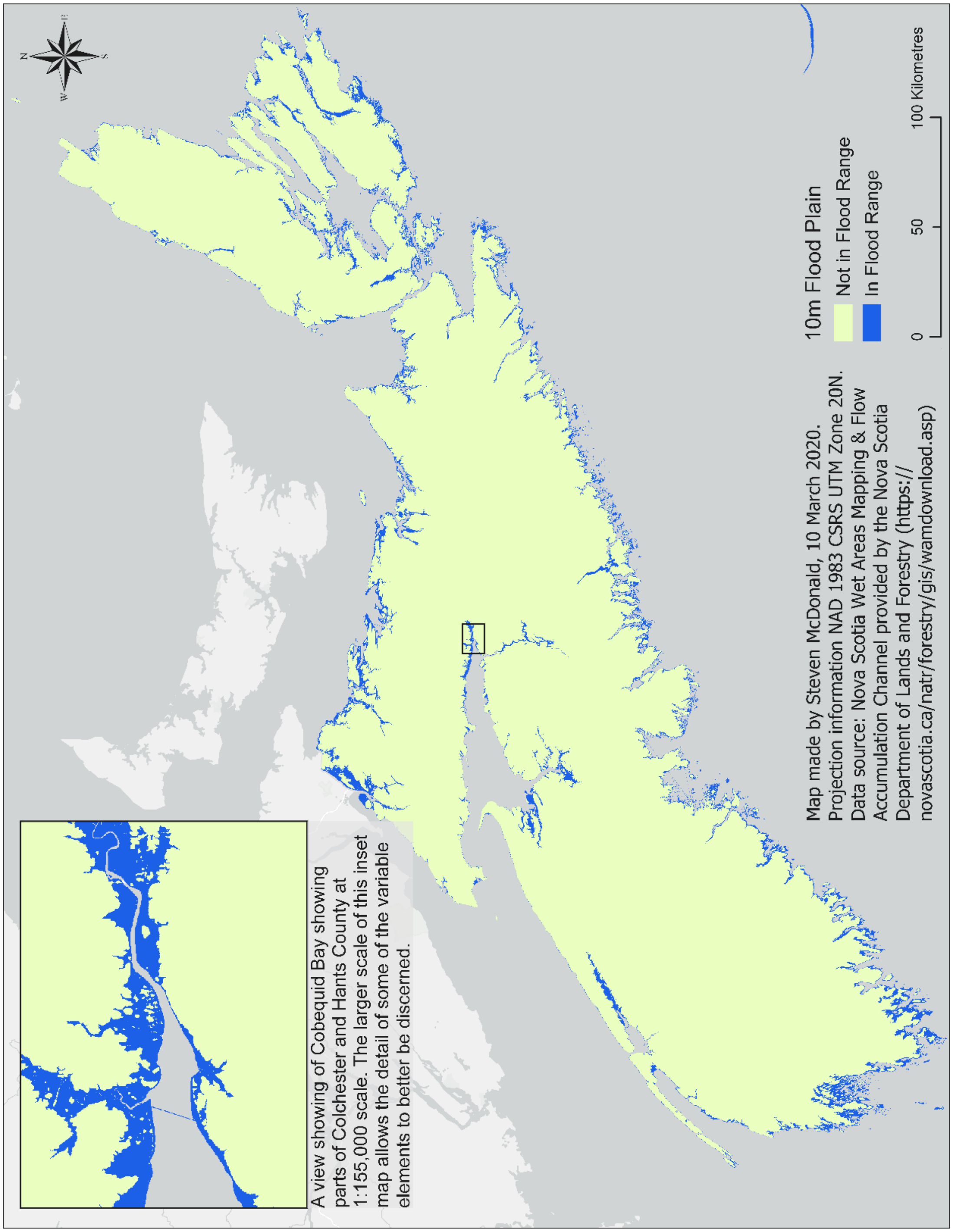


A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to be better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Wet Areas Mapping & Flow Accumulation Channel provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/forestry/gis/wamdownload.asp)

Figure A3.6

10-metre flood range in Nova Scotia

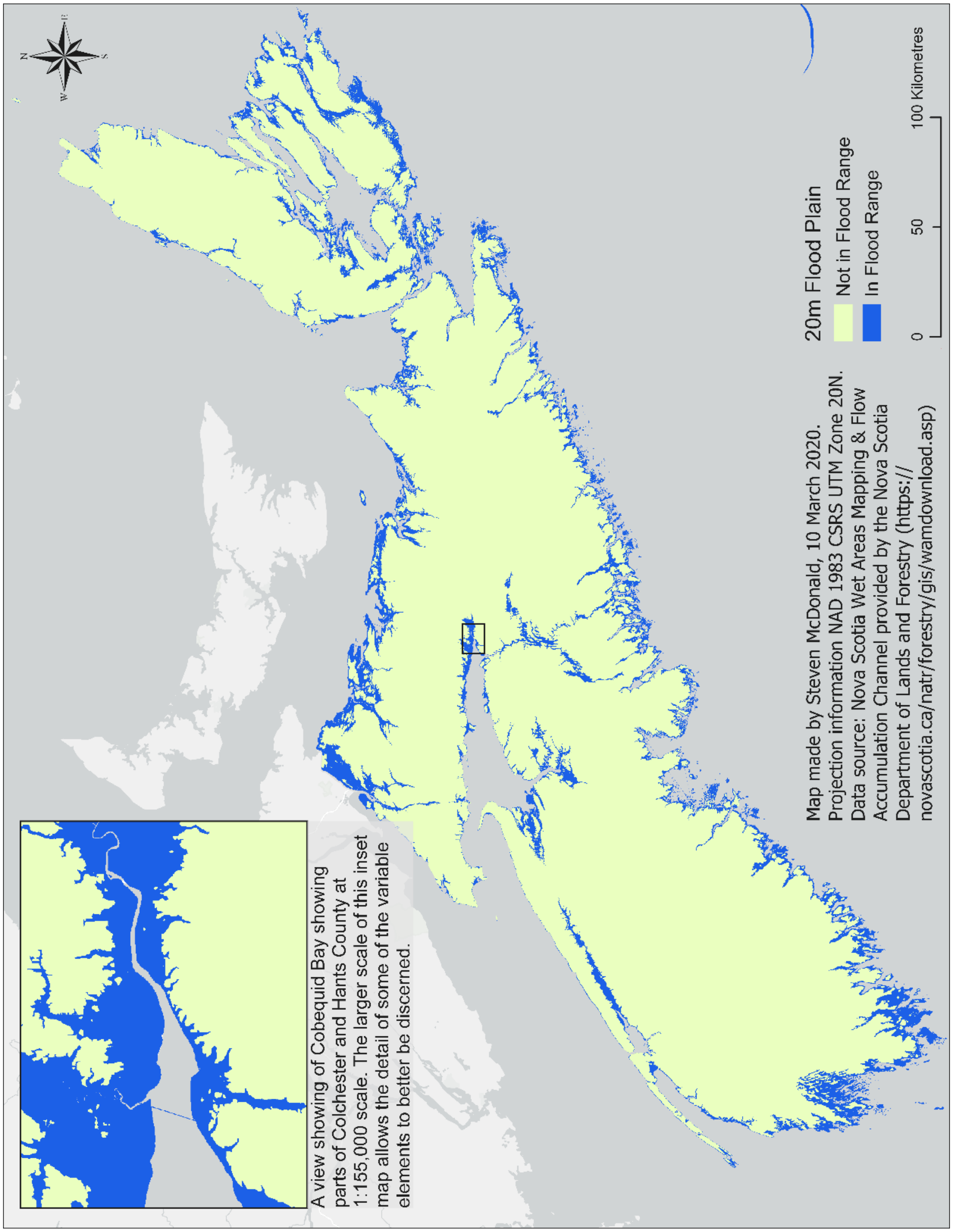


Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Wet Areas Mapping & Flow Accumulation Channel provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/forestry/gis/wamdownload.asp)

A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Figure A3.7

20-metre flood range in Nova Scotia

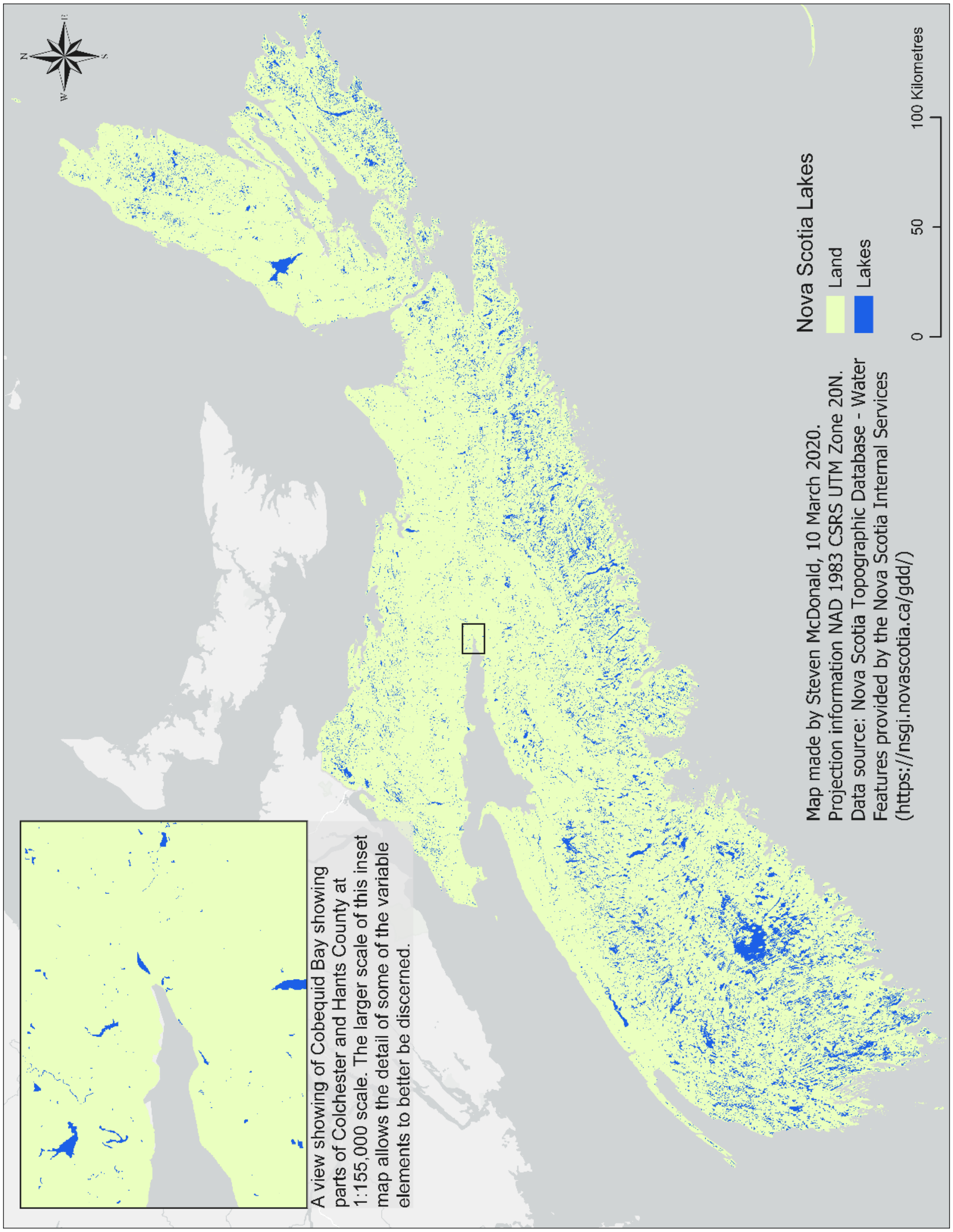


A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Wet Areas Mapping & Flow Accumulation Channel provided by the Nova Scotia Department of Lands and Forestry (https://novascotia.ca/natr/forestry/gis/wamdownload.asp)

Figure A3.8

Map depicting the locations of Nova Scotia lakes

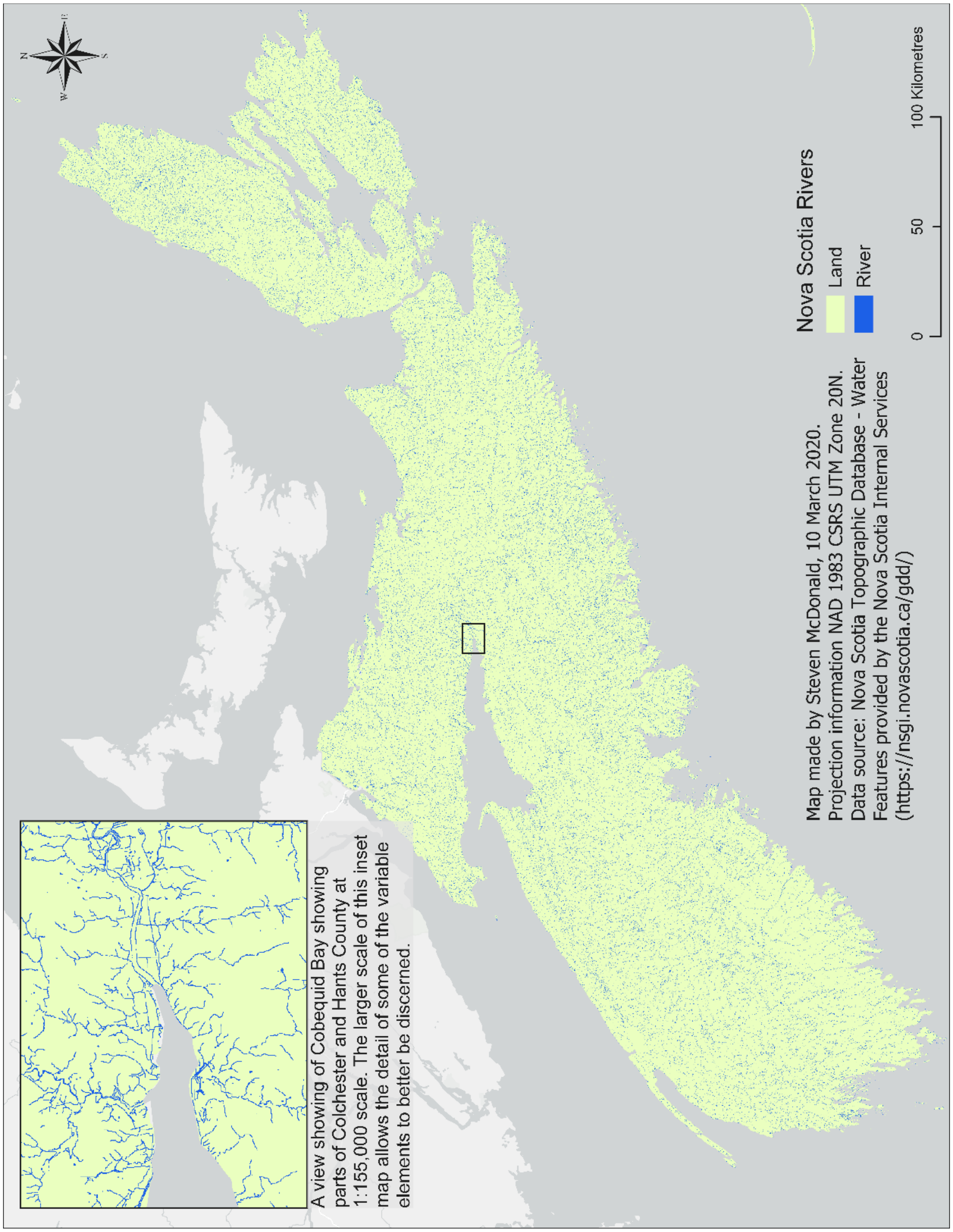


A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Topographic Database - Water Features provided by the Nova Scotia Internal Services (https://nsgi.novascotia.ca/gdd/)

Figure A3.9

Map depicting the locations of Nova Scotia rivers



A view showing of Cobequid Bay showing parts of Colchester and Hants County at 1:155,000 scale. The larger scale of this inset map allows the detail of some of the variable elements to better be discerned.

Map made by Steven McDonald, 10 March 2020.
Projection information NAD 1983 CSRS UTM Zone 20N.
Data source: Nova Scotia Topographic Database - Water
Features provided by the Nova Scotia Internal Services
(https://nsgi.novascotia.ca/gdd/)