

**ASSESSING THE BENEFITS, CHALLENGES, AND SCIENTIFIC VALUE OF
COMMUNITY SCIENCE PROGRAMS:
A CASE STUDY USING BUMBLE BEE WATCH**

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Abstract

We are experiencing a biodiversity crisis but resources to help species are limited. Scientists are turning to community science to complement traditional scientific methods. Bumble bees (*Bombus* spp.) are important pollinators in temperate regions, but many are in decline, and more information is needed to conserve them. The Bumble Bee Watch (BBW) program collects this information through photos submitted by volunteers and identified by experts. Yet many community science programs struggle. Chapter 2 reviews common successes and challenges, offering best practices for developing and running programs.

To determine whether BBW is filling knowledge gaps, Chapter 3 compares its data to the Bumble Bees of North America database (BBNA) over all years and 2010-2020. BBW recorded 41 species (BBNA had 48) from all parts of the continental US and Canada, confirmed persistence, and provided novel locations for species outside of and within the known extent of occurrence. BBW showed its greatest impact from 2010-2020 by contributing 25% of all records, 28% of all unique locations, and 32% new plant forage genera.

BBW does not replace traditional surveys, but does complement them. Chapter 4 shows that *B. pensylvanicus* is critically endangered in Canada according to IUCN Red List criteria. BBW provided 20% of all *B. pensylvanicus* records and 36% of its sites over the 2007-2016 period assessed, and thus provided important information on its current abundance and distribution.

No experience is required to participate in BBW, but having participants able to accurately identify species is beneficial. Chapter 5 explores the percent agreement and veracity of

participant species identifications compared to experts, with the average being 53% and 56%, respectively. With better educational resources, participants may be better trained to identify species more accurately.

Understanding the motivations and insights of community science participants is important.

Chapter 6 discusses the results of a BBW user and expert survey: participants want to contribute to science and save the bees, and report an increase in knowledge and skills after participating.

Although areas for improvement are noted, BBW is an important tool for *Bombus* researchers, and demonstrates the value that community science has for species conservation.

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Bees have been a hot topic that the public is increasingly growing to love, and I have been fortunate to be able to share my love and knowledge of them with others through a variety of

interviews, presentations, workshops, and articles. Appearing on an episode of TVO's The Agenda, and being featured on CNN, CTV, CBC, the Toronto Star, Guelph Mercury, Guelph Today, and many other media has been thrilling! Thanks to everyone who reached out to ask for a story and for those who shared that I inspired them to take action. The bees thank you too!

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Chapter 1. Overall Introduction

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The ecological and economic importance of wild insect pollinators is becoming increasingly recognized due to their role in pollinating native plants and agricultural crops, about 85% of which rely on animal pollinators for reproduction (Buchmann and Nabhan 1996; Losey and Vaughan 2006; Klein et al. 2007; Potts et al. 2010; Ollerton et al. 2011). Recent studies have determined that some native bumble bee (Hymenoptera: Apidae: *Bombus*) species have suffered rapid declines in the wild while others remain common, but we do not have enough information to make a status assessment for all species in North America (Colla and Packer 2008; Colla et al. 2012b; Hatfield et al. 2015a; Cameron and Sadd 2020; IUCN 2020). There is evidence that habitat loss, pesticide use, pathogen spillover from managed bees, and climate change have contributed to the declines of some North American bumble bee species (Colla et al. 2006; Gixti et al. 2009; Cameron et al. 2011b; Meeus et al. 2011; Szabo et al. 2012; Kerr et al. 2015; McMahon et al. 2015; Colla and MacIvor 2017; Cameron and Sadd 2020; Martinet et al. 2020) but proposed hypotheses are difficult to investigate due to low detectability and the previously mentioned lack of data. This, along with a lack of awareness by the public and policy makers, prevents appropriate recovery actions and policy from being implemented to stop the declines (Colla 2016). Community science is a growing field that can potentially help with both the data gap and lack of awareness.

Community science projects use volunteers to provide and/or analyze baseline, point, or monitoring data; ask and/or answer research questions; increase stewardship and awareness;

influence conservation actions and policies; allow for public engagement in science; and create social capital and public support for conservation (Bonney et al. 2009b; Silvertown 2009; Conrad and Hilchey 2011; Wiggins and Crowston 2011; Danielson et al. 2014; Follett and Strezov 2015; Jordan et al. 2016; Thomas 2016; Lepczyk et al. 2020). The data collected can be similar to or identical to that collected by experts (Hoyer et al. 2012; Starr et al. 2014; Danielson et al. 2014; Thomas 2016; van der Velde et al. 2017) although this depends on the level of skills needed (Kremen et al. 2011; Jordan et al. 2012), and the program design (Jordan et al. 2012; Trautmann et al. 2012; Acorn 2017).

Most insect taxa require specimen collection for accurate identification (Kremen et al. 2011), but bumble bees can often be reliably identified to the species level by field photos (Lye et al. 2011; Suzuki-Ohno et al. 2017; The Xerces Society for Invertebrate Conservation et al. 2017; Falk et al. 2019). This makes bumble bees an excellent target taxa for use in community science programs, where data could then be collected on everything from their phenology to distribution.

Bumble Bee Watch (BBW) is a community science web-based program where participants photograph bumble bees anywhere in the United States or Canada, upload the photos and relevant site information to a website (www.bumblebeewatch.org) or through an app (free download from <https://apps.apple.com/us/app/bumble-bee-watch/id1112626392> or <https://play.google.com/store/apps/details?id=com.birdseyebirding.birdseye.bumblebeewatch>). They can optionally then use an interactive identification key based on the bees' colour patterns, and limited by location, to assign a tentative species identification, with all records then verified by a regional expert (The Xerces Society for Invertebrate Conservation et al. 2017). Participation

is free and no experience is required. A collaborative effort amongst several different institutions, primarily administered by the Xerces Society for Invertebrate Conservation, Wildlife Preservation Canada, and York University, its stated goal is “to track and conserve North America’s bumble bees” (The Xerces Society for Invertebrate Conservation et al. 2017).

I have been involved with the Bumble Bee Watch program from the later stages of its initial development in 2012, through its website launch in January 2014, iOS and Android apps for smart phones and tablets in July 2017 and July 2018, respectively, through to present. Maintaining a high quality dataset that can be used to consider local and landscape level research questions and inform policy is critical. I have thus spent large amounts of time administering the program and database through Quality Assurance/Quality Control (QA/QC) work (e.g. looking for records in wrong provinces/states, probable wrong dates of observations, etc.), beta testing (website and two apps, and updates of those), creating a tutorial for the app, and other tasks. I have also been a regional expert, verifying records primarily from Ontario east through Newfoundland and Labrador, in addition to other regions of Canada and the US. This has been in addition to outreach and education activities, from bumble bee workshops and survey events through to presentations at naturalist clubs through professional conferences and written articles and interviews.

Having seen the enthusiasm that participants and experts have for Bumble Bee Watch, and the type of data being submitted, I am interested in how this program, in conjunction with researcher-collected data, answers ecological questions and increase awareness and conservation actions. I investigate these topics in a series of chapters as outlined below.

Chapter 2 explores the field of community science, from its history to range of applications today. It includes an investigation into the types of projects and designs, use and value of the data, reasons for and outcomes of volunteer participation, and provide best practices on how to improve programs.

Chapter 3 evaluates the type and value of biological data being gathered from the Bumble Bee Watch program by comparing it with the largest source of data on *Bombus* in North America: the Bumble Bees of North America database (BBNA). This includes determining if the BBW program has gathered information that can increase our natural history knowledge related to species biology, and distribution. I also evaluate the data to determine if there are new locations of rare species, changes in known species ranges, and/or observations from under-surveyed areas being reported.

Chapter 4 tests the idea that community science data can aid in species conservation status assessments. I combine data from BBW with museum specimen data and more recent field work data to assess the extinction risk for the American bumble bee (*Bombus pensylvanicus*) in Canada using IUCN criteria.

Chapter 5 investigates the accuracy of the initial species identifications by participants as compared to the verified identifications by experts. This will help to identify species that are commonly mis-identified, as well as the potential user bias and over-reporting of species. These results may suggest areas for improvement, both in the program and in training resources. I also

compare the self-evaluated ease of identification per species by both users and expert, and relate that to the level of misidentifications.

Chapter 6 investigates the demographics of BBW participants, the effects and perceived value of participation, as well as the perceived pros and cons of the program by participants and experts. Suggestions as to how to increase the success of the program will also be discussed.

Chapter 7 summarizes the findings from all these investigations and discuss the next steps for the conservation of pollinators using community science, and for the value and potential use of these programs in general.

Note that the field of community science has had different names and meanings since it was first proposed, and is currently still unsettled (Irwin 1995; Bonney 1996; Eitzel et al. 2017; Auerbach et al. 2019; Heigl et al. 2019a; Cooper et al. 2021)(see also discussion in Chapter 2). In an effort to be more inclusive, researchers with the Bumble Bee Watch program transitioned from using the previously more common term “citizen science” to “community science”: while I generally use “community science” throughout this thesis, in chapters previously published prior to the transition, I use “citizen science”.

Chapter 2. Power of the People: A Review of Citizen Science Programs for Conservation

Victoria J. MacPhail and Sheila R. Colla

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Abstract

Citizen science is a rapidly growing field whereby volunteers can collect and/or analyze data to contribute to research and gain an appreciation for the environment. There are countless programs currently underway around the world: some have clear scientific hypotheses being tested and others are simple data gathering; some are designed and led at the grass-roots level while others are done by academics. This literature review focusses on best practices for the development and running of citizen science projects to make them successful. It includes discussion around different methods of experimental design, data collection, and analyses; how participants are recruited, engaged, and rewarded (including who participates and why); the effect of participation on the volunteer's knowledge and actions; and the impact programs have on policy and other conservation actions. While there are several challenges that projects face, and more research is needed in various areas, the many benefits support the continued expansion of citizen science projects.

Introduction

While humans have been sharing observations of the world around them for millennia (Silvertown 2009; Miller-Rushing et al. 2012; Pastor 2018), the domain of citizen science is a relatively new area of research and discovery. Dating to the early 1990s (Irwin 1995; Follett and

Strezov 2015; Hannibal 2016), citizen science is a fast-growing field covering a wide range of topics, from human microbiota (del Savio et al. 2016) to distant galaxies (Edwards and Gaber 2014). As a newer science that is being practiced globally in different forms, with different definitions, frameworks, and protocols, it has not yet settled into a cohesive whole. Yet to fully realize the potential of citizen science, it is necessary to identify what works well and what does not, and where more research is needed to develop new techniques.

Although still young, the field of citizen science has received review articles on a wide variety of subjects. For example, new technologies (Newman et al. 2012; Ceccaroni et al. 2019), methods of data analysis (Cooper et al. 2012; Kelling et al. 2015a; Zipkin and Saunders 2018), assessments of data credibility and quality (Freitag et al. 2016; Kosmala et al. 2016; Aceves-Bueno et al. 2017), impacts on policy (Greenwood 2012; Hecker et al. 2018, 2019), economic implications (Sauermann and Franzoni 2015; Theobald et al. 2015) and impacts on and by volunteers (Firehock and West 1995; Bell et al. 2008; Shirk et al. 2012; Lewandowski and Specht 2015; NAESM, 2018; Schuttler et al. 2018) and on and by stakeholders (Sterling et al. 2017). Additionally, there have been several reviews on the impacts of citizen science on conservation efforts (Silvertown et al. 2013; Chandler et al. 2016; Ballard et al. 2017; Newman et al. 2017; McKinley et al. 2017; Poisson et al. 2020). Other reviews have been conducted on additional aspects of citizen science programs (Sullivan et al. 2009, 2017; Conrad and Hilchey 2011; Wiggins and Crowston 2011; Danielson et al. 2014; Pocock et al. 2015; Aceves-Bueno et al. 2017).

Governments, universities, and non-profit organizations are now coming together to support the development of common frameworks and guides (Bonney et al. 2009a; Strasser et al. 2012; Tweddle et al. 2012; Socientize Consortium 2013; Wiggins et al. 2013; Blaney et al. 2016; NEIWPC, 2016; Citizen Science Association 2020; CitizenScience.gov 2020). To maximize project resources, common challenges should be noted and avoided or addressed.

The purpose of this review paper is to provide an expanded, cohesive overview of what citizen science is, who it involves, and the reasons to use it. It covers small, in-person projects to large, online ones. It focusses on best practices for developing and running citizen science projects through the identification of common challenges faced and solutions to them, and includes suggestions on how to make projects more successful. These include areas such as experimental design, data analysis and quality control; volunteer recruitment, training, and retention; motivations for and effects of participation; data management and security; data sharing and project overlap; obtaining funding and other resources; economic, social and political controversies; project assessment and evaluation; and new technologies.

Methods

To locate relevant sources, searches were conducted through Google Scholar using key words such as “citizen science” and “community science” with additional qualifiers including “challenges”, “techniques”, “review” and “research”. The titles and abstracts of the resultant papers were read and evaluated and if they appeared relevant, the paper was given a full review. Relevant references cited within this first group of papers were then obtained, and their content and references evaluated, with more papers being targeted for review. This process was ongoing,

with the main searches occurring from January to June 2018. Additional searches were also conducted via Google Scholar and the York University library system during the writing of this article to locate information on specific topics not adequately captured using those original search terms.

Results and Discussion

Using the snowball approach described above, over 300 papers were selected for a deeper review. These included original research through review articles, on scales from local city or regional based studies through national and international ones. While most of the research was based in North America and Western Europe, others were from Africa, Asia, South America, and other parts of Europe. Many were focused on ecological topics, from systems to species, and covered a range of taxonomic groups, from insects to mammals and plants. Projects were generally led by professional scientists, but citizen scientists also contributed to project design in some cases.

What is citizen science?

Definition

There is no consistent definition for citizen science (Eitzel et al. 2017; McKinley et al. 2017; NASEM, 2018; Auerbach et al. 2019; Heigl et al. 2019b), although a spectrum of concepts and terminologies exists (Table 2.1). It commonly refers to a scientific program, overseen by professional scientists, where non-professional volunteers collect and/or analyse data that are then used to advance scientific knowledge (Eitzel et al. 2017; McKinley et al. 2017; NASEM, 2018; Auerbach et al. 2019; Heigl et al. 2019b). These projects can provide baseline or monitoring data, answer research questions, increase stewardship and awareness, and influence conservation actions and policies (Bonney et al. 2009b; Conrad and Hilchey 2011; Wiggins and

Crowston 2011; Follett and Strezov 2015; Jordan et al. 2016; Thomas 2016; Le Féon et al. 2016; Acorn 2017; McKinley et al. 2017; Ryan et al. 2018).

Citizen science may include certain types of games (Khatib et al. 2011; Kawrykow et al. 2012; Ponti et al. 2018) although some authors disagree as the players do not always understand the science behind the game (NASEM, 2018; Ponti et al. 2018). In Europe, the term can also relate to engaging the public in science discussions and policy making (Irwin 1995). Projects that are focused on public relations or science/environmental education (Russell 2014), or that do not produce or share new knowledge (Miller-Rushing et al. 2012; Acorn 2017; Ballard et al. 2017; NASEM 2018), do not fall into the definition of citizen science that is used here.

Topics covered by Citizen Science projects

Many projects involve a natural science topic (see broad discussions in e.g. Griffin Burns and Harasimowicz, 2012; Hannibal, 2016; Russell, 2014; Theobald et al. 2015), ranging from aligning DNA sequences (Kawrykow et al. 2012) and folding proteins (Khatib et al., 2011) to capturing information on a single taxa (e.g. Sullivan et al. 2017) or all taxa (e.g. van Horn et al. 2018). Other projects are found in medical fields, informational sciences, and traffic management (Gonzalez et al. 2011; Wiggins and Crowston 2011; Shirk et al. 2012; Follett and Strezov 2015; Den Broeder et al. 2018).

Classifications of Citizen Science projects

Projects can be classified according to the level of participant involvement or the focus of project. Participants may only collect data or may be involved in the whole process of devising

questions, collecting data, conducting analyses, and sharing results (Conrad and Hilchey 2011; Gonzalez et al. 2011; Miller-Rushing et al. 2012; Silvertown et al. 2013; McKinley et al. 2017; Irwin 2018; NASEM, 2018). Bonney et al. (2009a) defined three categories of citizen science based on the level of participation: contributory, collaborative, and co-created. Shirk et al. (2012) defined five models also based on this: contractual, contributory, collaborative, co-created, and collegial. Lawrence (2006) in (Conrad and Hilchey 2011) organized participation into four forms: consultative, functional, collaborative, and transformative. The definitions for many of these are similar and overlap, but there can also be differences, so it is important to establish the meaning of these terms in publications or when comparing projects.

Wiggins and Crowston (2011) identified five categories which relate to the type of project: socio-political action on local environmental issues; conservation projects, stewardship, and monitoring; real-world scientific investigation of particular questions; virtual scientific investigation of particular questions; and education and outreach. Bell et al. (2008) present the four categories proposed by McKelvey (1975), which relate to the type of organization: participatory environmental tourism; virtual network organisations; national non-governmental organisations; and local associations (Bell et al. 2008). Silvertown (2009) proposed categories of hypothesis-driven research, volunteer mapping and monitoring, and tools, guidance, and resources. Follet and Strezov (2015) initially divided projects into contributory, collaborative, and co-created, and then divided them based on their stated goals, including action, conservation, investigation, virtual and education.

There are pros and cons to all of these classifications, and no one is better overall than another (Conrad and Hilchey 2011; Shirk et al. 2012). Certain styles of projects may suit some project types or scales better than others. For example, consultative and functional styles work better in large-scale projects that are “top-down” directed, while collaborative and transformative projects work better at smaller scales that are often “bottom-up” directed (Conrad and Hilchey 2011; Shirk et al. 2012).

Why have citizen science?

There are many benefits of citizen science to science, participants, policy and management. They are summarized in Figure 2.1 and discussed below.

Value to Science

Citizen science programs can provide ecological data, answer research questions, increase learning, stewardship and awareness, introduce new epistemologies, and influence conservation actions and policies (Conrad and Hilchey 2011; Wiggins and Crowston 2011; Gonzalez et al. 2011; Follett and Strezov 2015; Jordan et al. 2016; Thomas 2016; Peters et al. 2017; Reynolds et al. 2017; McKinley et al. 2017; Irwin 2018; NASEM, 2018). In particular, they help answer questions related to the abundance, distribution, behaviour, and changes in species, habitats, and ecosystems (including agricultural systems)(Aceves-Bueno et al. 2017; Acorn 2017; Eaton et al. 2017; Sullivan et al. 2017; Ryan et al. 2018).

This power comes as volunteers can increase the temporal and spatial scope and intensity of a project, often beyond anything professional scientists could accomplish alone (Bell et al. 2008;

Conrad and Hilchey 2011; Cooper et al. 2012; Hoyer et al. 2012; Miller-Rushing et al. 2012; Danielson et al. 2014; van der Wal et al. 2015; Acorn 2017; Parker and Thomson 2018). These data can be of high quality, similar to or identical to that collected by experts (Hoyer et al. 2012; Trautmann et al. 2012; Starr et al. 2014; Danielson et al. 2014; Thomas 2016; van der Velde et al. 2017), although it depends on the program design and level of skills needed (Kremen et al. 2011; Jordan et al. 2012; Trautmann et al. 2012; Acorn 2017).

Citizen science data can be added to professional data to fill in gaps and/or expand total knowledge (Bonter et al. 2012; Zuckerberg and McGarigal 2012; Gonsamo et al. 2013; Silvertown et al. 2013; Zapponi et al. 2017; Soroye et al. 2018; MacPhail et al. 2019). It can be used to validate models (Gonsamo et al. 2013; Pimm et al. 2014) and ground-truth remote sensing data (Cooper et al. 2012; Pimm et al. 2014; Hannibal 2016). Other projects are concerned with issues of economic, social, and environmental importance (Conrad and Hilchey 2011; Gonzalez et al. 2011). Other data sets (e.g. environmental, demographic) can be combined with citizen science data to further explore trends and answer questions (Hames et al. 2012; Acorn 2017).

Projects have the potential to answer questions from changes in range and climate (Bonney and Dickinson 2012; Bonter et al. 2012; Cooper et al. 2012; Miller-Rushing et al. 2012; Gonsamo et al. 2013; Sullivan et al. 2017) to habitat loss and landscape level analyses (Dickinson and Bonney 2012; Miller-Rushing et al. 2012; Zuckerberg and McGarigal 2012) and evaluation of ecosystem goods and services (Birkin and Goulson 2015). They can track changes in populations over time, including declines of rare species and spread of invasive ones (Dickinson et al. 2012;

Acorn 2017; Sullivan et al. 2017; Zapponi et al. 2017; McKinley et al. 2017; Soroye et al. 2018; MacPhail et al. 2019), as well as migration rates or impacts of predators, disease, pollution, infrastructure, effects of livestock, environmental events, and other human activities (Conrad and Hilchey 2011; Bonter et al. 2012; Cooper et al. 2012; Greenwood 2012; Tidball and Krasny 2012; Bonney et al. 2014; Danielson et al. 2014; Acorn 2017; Eaton et al. 2017).

Studies can be designed to replicate historic research to evaluate changes over time (Miller-Rushing et al. 2012; Worthington et al. 2012) or provide necessary monitoring to back up claims or evaluate actions (Danielson et al. 2014). They can act as a “crisis response network” (Hannibal 2016), reacting quickly to monitor changes (e.g. in water or air quality, distribution of pathogens or invasive species) (Cooper et al. 2012; Shirk et al. 2012; Bonney et al. 2014; Hannibal 2016), while also connecting local people to each other, governments, and the environment, and helping them recover their own livelihoods and landscapes (Dickinson and Bonney 2012; Tidball and Krasny 2012; Owen and Parker 2019).

New technologies provide options to the traditional approach of in-person observations or collections that are shared on paper. For example, images, videos, and other data (e.g. radiation counts) can be obtained by individuals via data loggers, tablets, smartphones, wildlife cameras, satellites, telescopes, and drones and shared over the internet (Bonney et al. 2014; Acorn 2017; Eaton et al. 2017; Austen et al. 2018; Frigerio et al. 2018; Odenwald 2019). Data processing can be done by humans and computers, with new techniques evolving all the time (Shirk et al. 2012; Russell 2014; Wäldchen and Mäder 2018; Ceccaroni et al. 2019; Terry et al. 2020).

There can be an economic incentive to using citizen science. While there are costs, such as technology needs and staff salaries (Blaney et al. 2016), and recruiting, training, and retaining volunteers (Silvertown et al. 2013; Blaney et al. 2016; McKinley et al. 2017), overall costs are lower than hiring an equivalent number of staff (Joint Nature Conservation Committee 2017). For example, 100,386 users participated in the first 180 days of seven projects on the broad Zooniverse platform, contributing 129,540 hours estimated at \$1.6 million USD (Sauermann and Franzoni 2015). Theobald et al. (2015) estimated that about 1.3 million citizen scientists contributed \$2.5 billion USD in-kind annually over 388 projects. Investments can therefore bring high returns. Indeed, the Joint Nature Conservation Committee (nd, cited in MacKechnie et al. 2011) estimated that a £7 million government investment into volunteer monitoring in 2007-2008 facilitated an in-kind outcome of about £20 million from volunteers. However, citizen science should not entirely replace research by academic or government organizations, particularly as many governments require data to enact parts of their environmental legislation and thus should bear responsibility for the cost and commitment to collect the data (Silvertown 2009; Conrad and Hilchey 2011; MacKechnie et al. 2011; Hoyer et al. 2012; Birkin and Goulson 2015; Le Féon et al. 2016; Owen and Parker 2019).

Value to Participants

Citizen science can increase awareness, knowledge, and skills, as well as conservation and advocacy efforts among participants and the public (Bubela et al. 2009; Conrad and Hilchey 2011; Miller-Rushing et al. 2012; Socientize Consortium 2013; Toomey and Domroese 2013; Le Féon et al. 2016; McKinley et al. 2017; NASEM 2018). As we are in an age of increasing environmental degradation and disconnect from nature, public engagement and nature based

experiences are key (Conrad and Hilchey 2011; Socientize Consortium 2013; Hannibal 2016; Acorn 2017; Schuttler et al. 2018).

A person's attitude towards, and knowledge about, the environment can predict and influence their behaviours related to conservation (Bickford et al. 2012; Jordan et al. 2012; Toomey and Domroese 2013). Participation in citizen science projects can lead to a closer relationship to nature and a greater appreciation of species and their environment (Bickford et al. 2012; Wells and Lekies 2012; Silvertown et al. 2013; Acorn 2017; Schuttler et al. 2018). It can also lead to participants becoming experts in the field in the future (Trautmann et al. 2012; Hannibal 2016; Ballard et al. 2017). But impacts of participation can be short or long lasting (Jordan et al. 2012; Wells and Lekies 2012), and not all participants report changes in behaviours or actions (Toomey and Domroese 2013; Ellwood et al. 2017), just as data collection alone does not trigger understanding of scientific processes (Trautmann et al. 2012). Learning is not always an outcome of participation (Bonney et al. 2009a, b; Fitzpatrick 2012; Jordan et al. 2012; Phillips et al. 2012; Jordan et al. 2016), and knowledge does not always lead to an increase in actions (Bickford et al. 2012). Participants may volunteer to enjoy time in nature or with like-minded people, rather than specifically for nature conservation (Bell et al. 2008). However, some participants have expressed major changes in how they act (Bonter et al. 2012; Toomey and Domroese 2013; Jordan et al. 2016), and any positive change is better than no change (Silvertown et al. 2013).

Value to Policy and Management

Citizen science can influence policy and management actions (Firehock and West 1995; Conrad and Hilchey 2011; Dickinson et al. 2012; Greenwood 2012; Hoyer et al. 2012; Shirk et al. 2012;

Socientize Consortium 2013; Acorn 2017; Peters et al. 2017; McKinley et al. 2017). However, the impacts of specific projects are often unknown (Collins and Evans 2002; Conrad and Hilchey 2011; Toomey and Domroese 2013; Acorn 2017). More research is needed into the design of projects so that desired outcomes occur (Socientize Consortium 2013; Toomey and Domroese 2013; Bonney et al. 2014; Ballard et al. 2017).

Where can citizen science occur?

Projects can occur anywhere in the world, although the United States and Canada have the fastest growing number of programs (Lawrence 2006 in (Conrad and Hilchey 2011)). Urban environments are well suited (Davies et al. 2011; van der Wal et al. 2015) but activities can happen anywhere: backyards, urban parks, conservation areas, other natural and agricultural areas, or anywhere there is a computer or smart device and internet access (Khatib et al. 2011; Bonter et al. 2012; Griffin Burns and Harasimowicz 2012; Russell 2014; Hannibal 2016; EarthWatch 2018; Ryan et al. 2018). Projects may be local, provincial/state/territorial, national, or international in scope.

Who are citizen scientists?

Just as there is no one definition for citizen science, there is no consensus for what a participant is called. There is debate over the term to use, as the language has implications for both volunteer management and knowledge generation (Eitzel et al. 2017). The original use of the term “citizen scientist” has been credited to Rick Bonney at Cornell University in the United States in the mid-1990s (Hannibal 2016), although Alan Irwin used the term in Europe in 1994 (Irwin 1995; Follett and Strezov 2015; Hannibal 2016).

The very first naturalists can be considered citizen scientists (Silvertown 2009; Bonter et al. 2012; Dickinson and Bonney 2012; Miller-Rushing et al. 2012; Russell 2014). Phenological records date back over three thousand years in China (Bonter et al. 2012; Russell 2014). Many early naturalists were not professional scientists and conducted their explorations on the side (Silvertown 2009; Bonter et al. 2012; Dickinson and Bonney 2012; Russell 2014). Over time, more individuals were hired as professional researchers, and those who pursued their work as a hobby began to be considered as amateurs (Silvertown 2009; Miller-Rushing et al. 2012). However, “amateurs” may be well educated, have skills in the area, and even be leading experts in the field (Collins and Evans 2002; Bell et al. 2008; Bonter et al. 2012; Miller-Rushing et al. 2012; Shirk et al. 2012).

Citizen scientists today are people who generally volunteer on their own time with scientific projects (Dickinson and Bonney 2012); they range in their level of expertise, although most projects do not require formal training, credentials, or experience (Danielson et al. 2014; Hannibal 2016; Acorn 2017). People of all ages, sexes, and abilities can participate. Age generally does not have an effect on volunteer ability or rate of participation (Silvertown et al. 2013; Ballard et al. 2017; MacPhail et al. 2020a), but different ages may be better suited for certain activities (Griffin Burns and Harasimowicz 2012; Silvertown et al. 2013; van der Velde et al. 2017). Participants can volunteer individually, with their family, school, or with a group of similar or mixed ages (Bonter et al. 2012; Griffin Burns and Harasimowicz 2012; Trautmann et al. 2012; Ballard et al. 2017; van der Velde et al. 2017; Frigerio et al. 2018). However, individuals who are the subject or focus of the research project are not citizen scientists (NASEM, 2018).

Generally program participants are not as diverse as they could be, with most being middle-aged or older (Purcell et al. 2012; Toomey and Domroese 2013; MacPhail et al. 2020a), female (Toomey and Domroese 2013), upper-middle class and white (Purcell et al. 2012; NASEM, 2018). Programs also tend to target and involve groups of avid participants/hobbyists and not the general public (Fitzpatrick 2012). However technology is allowing citizen science projects to cross cultural, language, literacy, and physical barriers (Khatib et al. 2011; Kawrykow et al. 2012; Bonney et al. 2014; Russell 2014; Danielson et al. 2014; Hannibal 2016; Liebenberg et al. 2017).

Why do citizen scientists participate?

Participants participate for many reasons. Some enjoy the competition to find rare species or more species than others, the ability to survey in areas lacking in data, or to add to their life lists of species (Sullivan et al. 2009; Russell 2014; van der Wal et al. 2015; Hannibal 2016; Acorn 2017; Prudic et al. 2017). Others want to learn about the world around them (Bonter et al. 2012; Shirk et al. 2012; Trautmann et al. 2012; van der Wal et al. 2015; Voss et al. 2017), contribute to our overall knowledge (Dickinson and Bonney 2012; Shirk et al. 2012; Trautmann et al. 2012), help with conservation efforts (Shirk et al. 2012; van der Wal et al. 2015; Lewandowski and Oberhauser 2017; MacPhail et al. 2020a), gain local knowledge related to a concern in the community (Firehock and West 1995; Conrad and Hilchey 2011; Greenwood 2012; Miller-Rushing et al. 2012; Shirk et al. 2012; Russell 2014; Hannibal 2016; Roy and Edwards 2019) or influence decision making (Conrad and Hilchey 2011; Shirk et al. 2012).

Many love the social aspect of participating (Bell et al. 2008; Shirk et al. 2012; van der Wal et al. 2015; NASEM 2018) while others appreciate being alone in nature (Bell et al. 2008). Some participate through school projects (Oberhauser and Lebuhn 2012; Worthington et al. 2012; Russell 2014) or to protect their livelihoods ((Danielsen et al. 2007) in (Shirk et al. 2012)). Improving personal skills and abilities is important (Bell et al. 2008; Bonter et al. 2012; Dickinson and Bonney 2012; Shirk et al. 2012; van der Wal et al. 2015) but so is having fun (Khatib et al. 2011; Kawrykow et al. 2012; Hannibal 2016; Ponti et al. 2018), and improving their health (Bell et al. 2008; Wells and Lekies 2012).

Experimental design, data collection, quality control, and analyses

A variety of experimental designs exist, from one-off collections or incidental observations to formal atlas squares or assigned routes (Bonter et al. 2012; Zuckerberg and McGarigal 2012; Acorn 2017; Sullivan et al. 2017; McKinley et al. 2017). Resources for guiding citizen science projects are compiled by the US government (CitizenScience.gov 2020), Citizen Science Association (2020), California Academy of Sciences (2019), and other organizations (Tweddle et al. 2012; Pocock et al. 2014). There are also specific resources for data management, including ensuring data validation and quality and control assurances are in place (USEPA, 2002; Kelling 2012; Strasser et al. 2012; Wiggins et al. 2013; NEIWPCC, 2016).

Projects can be designed to answer specific questions or to collect data broadly (Cooper et al. 2012; Hannibal 2016), but study design must be considered in order for the project's results to be accepted and its impacts measured (Bonney et al. 2009b; Conrad and Hilchey 2011; Bonney and Dickinson 2012; Shirk et al. 2012; Strasser et al. 2012; Wiggins et al. 2013; Hannibal 2016;

Acorn 2017). Project designers must consider the potential participants and their skill levels, and develop training materials and methods to suit (Dickinson and Bonney 2012; Frigerio et al. 2018).

Project design is often done by professional researchers but can also include, or even be led by, members of the public, stakeholders, and other professionals (Conrad and Hilchey 2011; Bonter et al. 2012; Cooper et al. 2012; Dickinson and Bonney 2012; Shirk et al. 2012). Additional members can include individuals experienced in statistics (Bonney and Dickinson 2012; Cooper et al. 2012; Hannibal 2016); data management and analyses (Bonney and Dickinson 2012; Kelling 2012); computer programming (Jordan et al. 2012; Frigerio et al. 2018; Wäldchen and Mäder 2018; Ceccaroni et al. 2019; Terry et al. 2020); volunteer management; collective action; and social networking theory (Jordan et al. 2012; Purcell et al. 2012; Triezenberg et al. 2012; Wells and Lekies 2012).

New statistical and computational techniques are being developed that better compile and analyze complex and unstructured data sets (Cooper et al. 2012; Dickinson and Bonney 2012; Fink and Hochachka 2012; Gonsamo et al. 2013; Bonney et al. 2014; Pocock et al. 2015; Acorn 2017). They can handle “sampling bias, detection, measurement error, identification, and spatial clustering (Bird et al. 2013, Munson et al. 2010)” (Bonney et al. 2014), nonindependence (Cooper et al. 2012), false negatives (Kelling et al. 2015a), and various other errors or biases (Fink and Hochachka 2012; Gonsamo et al. 2013; Acorn 2017; Johnston et al. 2018). They can also be used for data mining (Fink and Hochachka 2012) and model validation (Fink and Hochachka 2012).

Historically, participants mailed paper records to researchers, although most now enter records digitally (Bonter et al. 2012; Purcell et al. 2012). Physical specimens may still be mailed to researchers (Hannibal 2016; Le Féon et al. 2016; Acorn 2017), viewed in person (Acorn 2017), or identified from photos (Blake et al. 2012; Acorn 2017; Soroye et al. 2018; Falk et al. 2019; MacPhail et al. 2020a). Some programs tag animals with the tags later viewed or recovered by other individuals, who then pass the information to the researchers (Acorn 2017).

Data may be collected in field notebooks (Acorn 2017), data sheets (Worthington et al. 2012), smart devices (Pimm et al. 2014; Frigerio et al. 2018), or transcribed from historic images or specimens (Cooper et al. 2012; Hannibal 2016; Acorn 2017). The information can be e-mailed to the researcher (Hannibal 2016; Le Féon et al. 2016; Acorn 2017), entered through an online portal (Blake et al. 2012; Worthington et al. 2012; Toomey and Domroese 2013; Pimm et al. 2014; Silvertown et al. 2015; MacPhail et al. 2020a), shared on and/or culled from social media (Russell 2014; Daume and Galaz 2016; Hannibal 2016; Acorn 2017; Smith et al. 2017), and photo sharing sites (Stafford et al. 2010; Hiller and Haelewaters 2019). New technology allows for some data to be automatically recorded and transferred to researchers (Cooper et al. 2012), or identified automatically (Wäldchen and Mäder 2018; Ceccaroni et al. 2019; Terry et al. 2020). Not all programs require confirmation of observations, although most have techniques to lower errors in the data (Bonter et al. 2012; Kelling et al. 2015b; Acorn 2017).

The classical citizen science paradigm has participants collecting the data, including identifying species, and sending it directly to the researchers, while in the expert-assisted paradigm, participants collect materials and send that to the researchers or other experts to identify (Le

Féon et al. 2016). Some species groups are well suited for the classical paradigm as they are easy for citizen scientists to identify but others are more difficult (Le Féon et al. 2016). Alternatives include accepting a higher taxonomic level of identification or involving experts, although having enough experts to do the identifications is a challenge (Kremen et al. 2011; Le Féon et al. 2016; Falk et al. 2019; MacPhail et al. 2020a). A further challenge is the quality and composition of the photos or specimens submitted (Austen et al. 2018).

The accuracy of participants as compared to experts needs to be considered, as volunteers may have less formal training and/or inherent biases (Trautmann et al. 2012; Danielson et al. 2014; Silvertown et al. 2015; Austen et al. 2016; Blaney et al. 2016; Johnston et al. 2018; Roy and Edwards 2019). Yet often their ability to identify species is not questioned, and their experience not quantified or accounted for (Austen et al. 2016; Acorn 2017). Some programs will accept identifications from anyone, others have developed a ranking system that takes into account the individual's skill, and others allow participants to suggest an identification that is verified by experts (Blake et al. 2012; Silvertown et al. 2015; Acorn 2017; Falk et al. 2019; MacPhail et al. 2020a). However, in many cases, citizen scientists can provide accurate data (Lovell et al. 2009; Kremen et al. 2011; Bonter et al. 2012; Hoyer et al. 2012; Danielson et al. 2014; Acorn 2017; Ballard et al. 2017; Austen et al. 2018). Although the accuracy of the expert is not often questioned, it can be variable (Suzuki-Ohno et al. 2017; Austen et al. 2018).

There can be serious repercussions for misidentifications, such as “the accidental culling of endangered species...(Hunt 2015), the incorrect monitoring of harmful algal blooms (Culverhouse et al. 2013), the unobserved decline in important fish stocks (Beerkircher et al.

2009), and wasted resources,(Solow et al 2012)” (Austen et al. 2016). It can also “affect assessments of population status and distribution and result in erroneous conservation decisions (Elphick 2008, Shea et al. 2011, Runge et al. 2007)” (Austen et al. 2016). It is therefore important to understand the level of potential error during study design and analysis, and when developing conservation actions (Austen et al. 2016). This is particularly true for programs that do not keep photos or specimens (Worthington et al. 2012; Acorn 2017).

Spatial biases are reflected in e.g. more data coming from densely populated areas than rural areas (van der Wal et al. 2015; Blaney et al. 2016), although this may be balanced by skilled naturalists focusing outside of urban areas and lay individuals inside (van der Wal et al. 2015). Species biases occur through selective reporting, over-reporting, or under-reporting of rare or enigmatic species (Stribling et al. 2008; Gardiner et al. 2012; Kelling et al. 2015b; van der Wal et al. 2015; Acorn 2017). Temporal biases result from observations occurring more at certain times of the day or year than others (van der Wal et al. 2015). Non-standard search efforts can be sensitive to these biases (Pocock et al. 2015; Acorn 2017).

Interpretation of data may need to consider the popularity of a program as compared to the number of submissions (e.g. is a species increasing or are more individuals participating)(van der Wal et al. 2015). Researchers also need to consider false positives (reporting a species that is not present) and false negatives (not reporting a species that is present) (Kelling et al. 2015b). Zero data (e.g. absence of a species) is often not collected but is very important (Cooper et al. 2012; Russell 2014).

Quality assurance and control, and data validation, are important aspects of all programs. Any project has the potential for errors (deliberate or accidental); researchers must attempt to recognize, control, and fix or remove them (USEPA, 2002; MacKechnie et al. 2011; Strasser et al. 2012; Worthington et al. 2012; Wiggins et al. 2013; NEIWPCC, 2016; Rasmussen 2019; Roy and Edwards 2019). Some programs may keep erroneous data in user profiles and online maps so as to not hurt the observers feelings; this is concerning and it is important for data users to obtain a good understanding of the data status and background before using (Bonter et al. 2012). Misconduct and incorrect information should be corrected immediately to prevent problems with credibility, data analyses, and funding (Rasmussen 2019; Roy and Edwards 2019).

Both current and historic data sets can cover a spectrum of data types, techniques, and levels of participation (Miller-Rushing et al. 2012; Worthington et al. 2012). It is important to review any program documentation to determine the value and quality of the data and how the details may affect analyses (Kelling 2012; Miller-Rushing et al. 2012; Wiggins et al. 2013).

Challenges with citizen science

Although there are many positive outcomes of citizen science, there are also challenges and drawbacks (Figure 2.2). These include issues involving participants, researchers, experimental design and data collection, data use, and the need for specialists. While they may not be unique to citizen science programs, they still should be identified and addressed. Some solutions are discussed below.

Barriers related to economics, social status, culture, accessibility, time, language, transportation, plus discrimination, lack of trust, or a perception of science being “boring”, may prevent individuals from participating (Conrad and Hilchey 2011; Bonter et al. 2012; Purcell et al. 2012; Worthington et al. 2012; Birkin and Goulson 2015; Acorn 2017). Designing and running a citizen science program can take time away from researcher’s professional work and potentially reduce their productivity (Dickinson and Bonney 2012; Silvertown et al. 2013); early career researchers may not be able to make the necessary commitment (Irwin 2018). Obtaining adequate funding to start and sustain projects can also be a challenge (Silvertown 2009; Conrad and Hilchey 2011; Bonter et al. 2012; Dickinson and Bonney 2012; Silvertown et al. 2013; Blaney et al. 2016; Frigerio et al. 2018).

Projects may not have a robust experimental design, such as an adequate sample size or a plan to analyze the data (Conrad and Hilchey 2011; Bonney and Dickinson 2012). They may collect the wrong type of data or be seen as monitoring for the sake of monitoring (Conrad and Hilchey 2011; Toomey and Domroese 2013). With the variation in the types and scope of data being collected, new computer programs and types of analyzes are needed (Conrad and Hilchey 2011; Bonney and Dickinson 2012; Cooper et al. 2012; Ceccaroni et al. 2019). Any delays in identifications or analyses can have a negative effect on participant involvement, as well as for end users such as policy makers and conservationists (van der Wal et al. 2015).

Unfortunately, due to concerns related to quality, validity, and consistency of the data and experimental design, results of citizen science programs are not always accepted or used by other researchers, peer-reviewed journals, or decision makers (Conrad and Hilchey 2011; Cooper et al.

2012; Hoyer et al. 2012; Silvertown et al. 2013; Burgess et al. 2017; Rasmussen 2019). While Burgess et al. (2017) found that data quality itself was not a strong barrier to researcher use of data, lack of awareness of the data and researcher bias were. These concerns can mean that much-needed data for species conservation status assessments may be excluded, targeted habitat conservation actions may not occur, ongoing environmental issues (e.g. pollution, noise) may not be addressed, models may not be validated correctly, and policy may not be developed. As well, funders of the program may be upset that there were “no” results and be reluctant to fund additional programs in the future, and volunteers may be disheartened by the impression their work was not useful and not participate in the future. Other programs may not be able to learn from or build off the excluded program(s) data. Finally, the discrediting of some citizen science data may put a pall over other programs, negatively influencing their success and impressions.

It is difficult to make broad statements about the impact of citizen science as there is no standardized method of assessment (Bonney et al. 2009a; Conrad and Hilchey 2011; Jordan et al. 2012; Phillips et al. 2012), although frameworks are being discussed (Bonney et al. 2009a; Jordan et al. 2012; Phillips et al. 2012; Wells and Lekies 2012; Toomey and Domroese 2013; Ellwood et al. 2017). Most frameworks are based on those that evaluate public participation in scientific research (Phillips et al. 2012; Blaney et al. 2016; Schröter et al. 2017), while some are specific to children and their environmental attitudes, behaviours, knowledge, and measure of fear (Wells and Lekies 2012), or specific to informal science education (Bonney et al. 2009a; Phillips et al. 2012). Current methods have trouble evaluating slight changes in knowledge or attitude, particularly when a participant already had experience in an area (Phillips et al. 2012), or to prove that learning was a result of participation (Phillips et al. 2012). It is still important to

take pre and post measures in order to evaluate impacts of participation, whether through workshops, online quizzes, or other methods (Phillips et al. 2012; Wells and Lekies 2012). Participants have different cultural, economic, social, ethnic, and geographic makeup, making analyses even more difficult (Phillips et al. 2012).

While much of science relies on comparison to a control group, it is hard to get unbiased groups for citizen science projects, particularly for randomized control trials (Phillips et al. 2012; Wells and Lekies 2012). This could potentially be accomplished by having a waiting list of people who may/will participate in the future, with individuals randomly assigned to the wait list and the participation groups (Wells and Lekies 2012).

There are also areas of research that can not be done by citizen scientists, where professionals are required due to specialized experience, equipment, or other project requirements (Fitzpatrick 2012; Tidball and Krasny 2012; Blaney et al. 2016). Professionals may be required to meet regulations, such as with animal handling or health and safety (Buesching and Slade 2012 in (Silvertown et al. 2013)), or site access concerns (Blaney et al. 2016). Finally, some argue that long-term monitoring should only be done by professionals rather than volunteers (Luzar et al. 2011 in (Danielson et al. 2014)).

[Economic, social, and political-economic controversy](#)

Citizen science can provide cost-effective ways for data collection (see discussion above). However, a social and political-economic controversy exists related to the reduction in funding many projects are experiencing or the unequal funding paid to new or high-profile projects

(Nestle 2001; Rosenstock and Lee 2002; Ancker and Flanagan 2007; Bozeman and Gaughan 2007; Bubela et al. 2009; Conrad and Hilchey 2011; Bonter et al. 2012; Silvertown et al. 2013; Godfray et al. 2015; Hannibal 2016).

One area of concern is that funding can be cut, only given in the short-term, and/or be vulnerable to loss. Monitoring projects in particular are often not seen to provide a lot of value (Silvertown et al. 2013; Hannibal 2016). Projects face problems if funding is reduced (Conrad and Hilchey 2011), as is common with funders that prefer to support new programs, even if longer-running programs produce more valuable data and other outcomes (Dickinson and Bonney 2012; Blaney et al. 2016). Even if funding is maintained, projects can struggle to meet deliverables and expand (Bonter et al. 2012). However, cutbacks in internal government funding can cause an increase in citizen science, as governments still want, and may even be required by law, to collect data and carry out monitoring (Conrad and Hilchey 2011; Owen and Parker 2019); in these cases, they should make funding citizen science a priority (Conrad and Hilchey 2011).

Funding may come with requirements, such as working with industry partners (Bozeman and Gaughan 2007). A dependency on private funding and bureaucracy can also limit or decrease public trust (Bubela et al. 2009). In the United States, federal funding is decreasing annually while industry funding is increasing, which brings potential concerns about directions of research and biases (Rosenstock and Lee 2002; Bozeman and Gaughan 2007). Funding may come from participants themselves via participation fees or material costs (Bell et al. 2008; Bonter et al. 2012; Chu et al. 2012; Silvertown et al. 2013; EarthWatch 2018).

Politics and legislation can encourage or discourage citizen science. For example, Wyoming passed a law in 2015 that permitted charging individuals who collect “resource data” on “open lands” as trespassers if they intend to submit that information to the government; the law was amended in 2016 but it is still a discouragement to citizen scientists (Pidot 2015; Opar 2017). Wyoming has also pushed to only allow water quality data to be collected by governmental entities or contractors, which would prohibit citizen science (Thuermer 2020; Wyoming Department of Environmental Quality 2020). However, the United States government passed legislation in 2017 that explicitly permitted the involvement of crowd sourcing and citizen science activities that furthered the missions of its federal science agencies (United States Government 2017). The US also assembled an online toolkit to facilitate citizen science (CitizenScience.gov 2020).

What is success and how can it be measured?

Individuals, science, and society all benefit from citizen science (Bonney et al. 2014; Sterling et al. 2017; Sullivan et al. 2017; McKinley et al. 2017; Irwin 2018; NASEM, 2018; Sharma et al. 2019). Outcomes vary depending on why the project was created, how it was designed and data used, and how the volunteers embraced it (Theobald et al. 2015; Bonney et al. 2016; Ballard et al. 2017; Ellwood et al. 2017; Forrester et al. 2017; NASEM 2018; Ponti et al. 2018).

Quantifiable outcomes include number of individuals involved, data records, website visits, publications, workshops and media articles, (Bonter et al. 2012; Phillips et al. 2012; Shirk et al. 2012; Gonsamo et al. 2013; Follett and Strezov 2015; Theobald et al. 2015; Aceves-Bueno et al. 2017; Irwin 2018). Qualitative outcomes include an increase in knowledge or the quality of volunteer involvement (Bonney and Dickinson 2012; Shirk et al. 2012).

Projects may have vastly different numbers for their metrics of success, often due to the type and longevity of the program, but all be considered equally successful by their organizers. For example, the stand alone, single city Neighbourhood Nestwatch program had at least 12 peer-reviewed publications after about a decade (Bonter et al. 2012), while at least 150 have come from the Cornell Lab of Ornithology, which has been involved in multiple projects globally for about a century (Cornell Lab of Ornithology 2018). Projects associated with the international Earthwatch organization averaged 6.5 publications and 5.2 contributions to management plans and policies each over a seven year period (Chandler et al. 2017). Other projects may not publish their results in peer-reviewed journals (Follett and Strezov 2015; Theobald et al. 2015; Sullivan et al. 2017) but in other areas like project newsletters (Follett and Strezov 2015).

The number of observations submitted to a program also varies. The online Zooniverse platform reports over 12 million daily observations across its programs (Sauermann and Franzoni 2015), while the international eBird program had more than 300 million observations submitted in the first twelve years of the program, with more than 70 million in 2015 alone (Sullivan et al. 2017). The North American eButterfly receives tens of thousands of observations per year (Prudic et al. 2017), while the UK BeeWatch had 10,000 records submitted and verified in its first three and a half years of operation (van der Wal et al. 2015). The Global Biodiversity Information Facility has estimated that “half of its billions of data points [come] from lay sources [and] that it has supplied data for more than 2,500 peer-reviewed papers in the past ten years” (Irwin 2018).

Generally only a small fraction of people who express interest in a project participate, and even fewer are high contributors (Wood et al. 2011; Worthington et al. 2012; Birkin and Goulson 2015; Sauermann and Franzoni 2015; Andow et al. 2016; Domroese and Johnson 2017;

MacPhail et al. 2020a); this seems to be particularly true for projects that are larger in size and/or online, although some projects do have high retention rates (McCaffrey 2005; Bonter et al. 2012; Sauermann and Franzoni 2015; Theobald et al. 2015). However, “super volunteers” help to offset overall lower participation rates (Wood et al. 2011; Hames et al. 2012; Sauermann and Franzoni 2015; Hannibal 2016; MacPhail et al. 2020a). Previous experience by participants may increase the success of data collection (Danielson et al. 2014; Birkin and Goulson 2015; Kelling et al. 2015b); over time, the learning curve decreases while accuracy and breadth of data increases (Danielson et al. 2014; Kelling et al. 2015b).

Participation can result in an increased understanding of and interest in science (Bonney and Dickinson 2012; McKinley et al. 2017). It can result in participants becoming resources to be approached by others (conservation professionals, school groups, etc.) (Bonter et al. 2012), or participants asking their own questions, which in turn could be answered by using citizen science data (Dickinson and Bonney 2012).

How can citizen science programs be improved?

Study design

As every project has different goals and outcomes, there is no one experimental design that will work for all projects. However, researchers can still use standardized techniques and obtain useable data (Cooper et al. 2012; Shirk et al. 2012). Programs based at regional citizen science societies and related organizations (e.g. citizenscience.gov, citizenscience.org, citizensciencealliance.org, ecsa.citizenscience.net, citizenscience.org.au, and citsci.org), in addition to the peer-reviewed journal on citizen science (theoryandpractice.citizenscienceassociation.org), provide resources to assist others, although

additional funding and collaboration with experts would improve them further (Bonney et al. 2014; Russell 2014; Ellwood et al. 2017).

Repeated sampling at a site is preferred versus one-off observations to better account for site or user effects, distinguish between false positives and negatives, and to evaluate changes over time (Cooper et al. 2012; Zuckerberg and McGarigal 2012; Hannibal 2016; Acorn 2017), although long-term repetition of point in time collections can still help to find new species, range extensions, and other data (Acorn 2017). A few ways to avoid non-random/unrepresentative data include using a stratified random sampling design or gridding the region of interest; non-random distribution of sampling points can be taken into account for analysis and interpretation (Cooper et al. 2012; Greenwood 2012). It is important that all areas that need to be surveyed are included in the study (e.g. to compare historically surveyed sites), rather than having an open survey process (Worthington et al. 2012; van der Wal et al. 2015). However, observations that are not from repeated survey sites, including those that are incidental, can still be used and can be quite valuable (Hochachka et al. 2012; Sullivan et al. 2017; Zapponi et al. 2017; Gazdic and Groom 2019; Mueller et al. 2019; MacPhail et al. 2019; Meiners et al. 2020; Wilson et al. 2020).

Projects must encourage the submission of zero data (Cooper et al. 2012; Russell 2014) and the recording of search effort, as this can help researchers identify undersampled or oversampled areas or quantify variability in data (Zuckerberg and McGarigal 2012). Where possible, the project should be set up so that data analyses can include observer skill as a factor (Kelling et al. 2015b). Researchers should choose the best species to monitor that will both fit with the research

question and be as easy as possible for participants to identify and engage with (Worthington et al. 2012; Danielson et al. 2014).

Pilot studies can help ensure training materials are understood, data are collected efficiently and accurately, participants are engaged in the program, feedback can be addressed, and data can be analyzed (Bonney and Dickinson 2012; Bonter et al. 2012; Greenwood 2012; Jordan et al. 2012; Shirk et al. 2012; Worthington et al. 2012; Birkin and Goulson 2015; Frigerio et al. 2018). It is important to allow for uncertainty to be acknowledged during data recording or verification (Purcell et al. 2012). Researchers need to determine how to verify records during project design, such as through the submission of photos and not just text (Worthington et al. 2012).

Standardized terminology, classification codes, and methods of recording and entering data can reduce many errors (Greenwood 2012; Kelling 2012; Wiggins et al. 2013). Multiple individuals can also assess the same record to ensure agreement (Russell 2014). Data can be flagged automatically if they fail pre-set criteria (e.g. spatial, temporal, numerical) or a quality assurance test (Bonter et al. 2012; Kelling 2012; Silvertown et al. 2013; Russell 2014), although this latter approach does not catch records that are plausible but incorrect (Bonter et al. 2012). It is best if information can be georeferenced to a precise area, whether it be through GPS units, geocoding based on street addresses, selection of a site through online mapping programs, or other methods, as this may allow for multiple uses of the data, including for habitat and landscape level analyses (Zuckerberg and McGarigal 2012).

Project leaders need to identify learning goals before starting, and design protocols that will result in them, realizing that different approaches may be needed for volunteers than traditional ones used with experts (Jordan et al. 2012; Strasser et al. 2012; Wiggins et al. 2013; NASEM, 2018). For retention to be high, projects should meet the needs of the participants and communities involved; researchers need to have someone who can relate to the community and understand their concerns/biases/strengths (Purcell et al. 2012; Trautmann et al. 2012).

It is important to assess the value and viability of projects at all stages. Blaney et al. (2016) discuss four methods, including Return On Investment (values based on financial aspects alone), Cost-Benefit Analysis (values to society, including monetary and non-monetary ones), Cost-Effectiveness Analysis (monetary costs of citizen science as compared to different options), and Multi-Criteria Analysis (comparing value of different options using monetary and non-monetary costs). As more organizations undertake these evaluations, more evidence can be gathered to support current and future investment in citizen science projects.

Volunteer recruitment, training, support, retention

Individuals react differently to recruitment materials depending on their age, national or cultural identity, societal class, and educational background (Silvertown et al. 2013). They also have different motivations for volunteering, from wanting to learn new skills to making a difference in their community to feeling a sense of power (Bonney and Dickinson 2012; Chu et al. 2012; Silvertown et al. 2013; Domroese and Johnson 2017; MacPhail et al. 2020a). Therefore programs must develop specific messages and use different communication channels, depending on the group(s) they wish to target, rather than one message for a general audience (Bonney and

Dickinson 2012; Chu et al. 2012; Worthington et al. 2012; Silvertown et al. 2013). Wymer (2003) in (Chu et al. 2012) suggests that volunteers be considered as customers, and similar principles considered and actions taken as done by businesses in finding and retaining new customers.

Communications should be made locally relevant, even if part of a broader project (Chu et al. 2012). Messaging should reinforce reasons for and positive outcomes of participation, such as by announcing a data gap in a specific region and the need for people to submit information (van der Wal et al. 2015), or by promoting the health and wellness benefits of participating (Chu et al. 2012), while also linking the scientific and conservation angles (Chu et al. 2012).

Communications can also tie into specific events (Worthington et al. 2012), and contests and promotions can increase media attention and recruit new people to a project (Chu et al. 2012).

Barriers to participation must be considered and avoided where possible. For example, a required payment for participation may be prohibitive (Bell et al. 2008; Bonter et al. 2012; Silvertown et al. 2013). Projects that have support and training materials in multiple languages, or heavily rely on graphics versus written text, can reach more people (Purcell et al. 2012; Worthington et al. 2012; Liebenberg et al. 2017). However projects may unconsciously exclude certain minority or underrepresented groups (Purcell et al. 2012; NASEM, 2018). Project organizers must ensure projects are inclusive, equitable, and diverse (NASEM, 2018). Partnerships with other organizations can help researchers reach niche communities or underserved audiences (Chu et al. 2012; Purcell et al. 2012; Silvertown et al. 2013).

Youth involvement is also encouraged as involvement as a youth translates into involvement as an adult, and there is a concern that the current majority of volunteers may soon no longer participate due to age (Wells and Lekies 2012). As well, there is a need to get more families and children out into the natural world “to know it and care for it” (Dickinson and Bonney 2012), and “build their capacity for future conservation actions” (Ballard et al. 2017).

Researchers should encourage people to recruit others with whom they rarely interact with in order to bring more people in and move away from a “preaching to the choir” approach (Triezenberg et al. 2012). These weak-tie relationships may help spread new information faster than close-tie/strong-tie relationships, although the latter can help to reinforce and foster adoptions of new behaviours (Triezenberg et al. 2012).

Creating tools of value to participants, like the ability to view their own data online and to explore data submitted by other participants, as well as customized data portals for specific projects or areas, can help lead to increased participant involvement (Chu et al. 2012; Acorn 2017; Prudic et al. 2017). However, more research is needed to understand why some people contribute to projects while others “free ride” on contributed data (Triezenberg et al. 2012).

Advertising can be done through a variety of channels, including social media (Chu et al. 2012; Birkin and Goulson 2015; Liberatore et al. 2018), blogs, YouTube, RSS feed (Chu et al. 2012), websites (Bell et al. 2008; Bonter et al. 2012; Toomey and Domroese 2013; Birkin and Goulson 2015), e-mail listservs (Bonter et al. 2012; Toomey and Domroese 2013), newsletters (Bonter et al. 2012; Birkin and Goulson 2015), presentations, flyers (Bonter et al. 2012; Chu et al. 2012),

special events (Toomey and Domroese 2013), conferences (Worthington et al. 2012), other organizations (Bonter et al. 2012; Jordan et al. 2012; Wells and Lekies 2012), and traditional print and broadcast media (Bell et al. 2008; Bonter et al. 2012; Chu et al. 2012; Worthington et al. 2012; Silvertown et al. 2013; Toomey and Domroese 2013; van der Wal et al. 2015).

However, while media can increase awareness of a project, it may not always result in large numbers of volunteers (Silvertown et al. 2013) or it can recruit too many people, overwhelming the program organizers (Bell et al. 2008). It may be necessary to target publicity to groups that are more likely to participate in order to increase recruitment (Worthington et al. 2012).

Volunteers can be trained in program protocols through a variety of methods. Static training and support documents can be mailed out physically or electronically (Firehock and West 1995; Bonter et al. 2012; Shirk et al. 2012; Birkin and Goulson 2015) or resources can be made available online (Bonter et al. 2012; Purcell et al. 2012; Shirk et al. 2012; Worthington et al. 2012; Toomey and Domroese 2013; Birkin and Goulson 2015). Participants can carry out simulations of data collection tasks and get feedback, helping them to improve their skills (Bonney and Dickinson 2012; Jordan et al. 2012; Worthington et al. 2012) while giving researchers the opportunity to evaluate their skill level and potential biases (Dickinson et al. 2010 in (Dickinson and Bonney 2012)).

Workshops or trainings are often held in-person, varying from a few hours to several days in length (Kremen et al. 2011; Bonney and Dickinson 2012; Bonter et al. 2012; Hames et al. 2012; Jordan et al. 2012; Silvertown et al. 2013; Toomey and Domroese 2013; Danielson et al. 2014; Hannibal 2016; Le Féon et al. 2016). Volunteer accuracy has been shown to increase if training

is provided in-person with an expert as compared to just online or mailed materials (Silvertown et al. 2013). Multiple trainings held over time can allow for people to process instructions, build on knowledge, gain experience with the protocols, and avoid information overload (Jordan et al. 2012; Trautmann et al. 2012; Silvertown et al. 2013). Training should be provided on recognizing and avoiding biases, and the consequences of not doing so (Jordan et al. 2012; Silvertown et al. 2013).

It is important that participants can connect with project leaders. Some programs provide a phone number for participants to call with questions or problems (Firehock and West 1995; Bonter et al. 2012; Purcell et al. 2012; Shirk et al. 2012; Birkin and Goulson 2015), while others regularly correspond by e-mail (Bonter et al. 2012; Chu et al. 2012; Purcell et al. 2012; Toomey and Domroese 2013), and others have participants and researchers meet up periodically during the year (Bonter et al. 2012; Hames et al. 2012; Danielson et al. 2014; Hannibal 2016). Support and information sharing can come from both researchers and participants through online discussion forums, blogs, and social networking tools (Bonney and Dickinson 2012; Bonter et al. 2012; Triezenberg et al. 2012; Toomey and Domroese 2013; Daume and Galaz 2016; Liberatore et al. 2018). Small programs with more interactions with researchers, particularly in-person, may yield more impact on participants and greater change in their behaviour, knowledge, and actions than programs with solely online training or single workshops (Bonter et al. 2012). More research is needed to understand how virtual communications and trainings work to connect people and create a sense of community (Triezenberg et al. 2012; Liberatore et al. 2018).

An important aspect of project management involves participant retention, as this decreases initial training and recruitment costs, builds expertise, and increases data quality (Bonter et al. 2012). In addition to regular communications, volunteers want to receive feedback on and be recognized for their efforts, have their motivations for participating met, and have a rewarding experience (Conrad and Hilchey 2011; Chu et al. 2012; Fitzpatrick 2012; Greenwood 2012; Purcell et al. 2012; Silvertown et al. 2013; Acorn 2017; Prudic et al. 2017; NASEM 2018). Too often programs are just about getting the data, leaving the participants feeling undesired and unappreciated (Silvertown 2009).

Feedback can be automatically sent to volunteers after data are submitted or verified (Silvertown 2009; Worthington et al. 2012; Russell 2014; van der Wal et al. 2015, 2016), while interactive websites can display their data live and compare it to other data on maps or to past records by the participant (Sullivan et al. 2009; Bonney and Dickinson 2012; Bonter et al. 2012; Chu et al. 2012; Dickinson and Bonney 2012). Participant spotlights can be placed online or in newsletters (Chu et al. 2012). A general acknowledgement of volunteers can occur in the media directly, and by sharing results showing the value of their work (Bell et al. 2008; Silvertown et al. 2013; van der Wal et al. 2015).

Social interactions and a feeling of community with other volunteers and project leaders, whether done in person or electronically, are important to keep people interested and engaged (Bell et al. 2008; Bonter et al. 2012; Hames et al. 2012; Shirk et al. 2012; Triezenberg et al. 2012; Silvertown et al. 2013; Hannibal 2016; NASEM, 2018). Some programs are small and locally based or have regional branches that can provide a more local connection and targeted

information to participants (Bell et al. 2008; Greenwood 2012). Informal mentorship between more experienced and inexperienced participants can be quite valuable, even with larger programs (Bell et al. 2008). Concerted efforts to communicate with past and present participants and targeted groups can help to regain and increase participation over time even after the initial wave of enthusiasm for a project has passed (Chu et al. 2012).

It is important for citizen science programs to capture the interest of “super volunteers” and engage and support them (Silvertown et al. 2013; Hannibal 2016). They could be encouraged to write articles about their participation to be published in newsletters or online (Trautmann et al. 2012), recruited for more in-depth research projects (Cooper et al. 2012; Hames et al. 2012), and encouraged to present at program events or scientific conferences (Trautmann et al. 2012).

Monitoring can be boring and repetitive, leading to carelessness and lower quality data (Silvertown et al. 2013; Russell 2014; Hannibal 2016). The best participants are those who are dedicated to a particular site and are attuned to small changes (Purcell et al. 2012; Russell 2014; Hannibal 2016). Successful programs may tie into the participants main interests and skills (Conrad and Hilchey 2011), livelihoods, regular routines, or to their cultural or spiritual values (Danielson et al. 2014) or their motivations (Chu et al. 2012; NASEM, 2018).

Projects vary in the type of equipment required. Some projects are only online, requiring users to have a computer and internet access to participate (Khatib et al. 2011; Russell 2014; van der Wal et al. 2015; Hannibal 2016). Others have the user collect data in the field and then enter it online (Bonter et al. 2012; Jordan et al. 2012; Gonsamo et al. 2013; Starr et al. 2014; Birkin and

Goulson 2015), although sometimes the data are mailed back to the researchers (Acorn 2017). Participants may be provided with specific items, (Jordan et al. 2012; Birkin and Goulson 2015; Le Féon et al. 2016) although participants may still need to supply some items (Birkin and Goulson 2015). The creation and use of localized species lists and field guides can make identifications easier for novices as compared to the more traditional regional or continental guides (Silvertown 2009).

Data management, security, longevity

Thought must be given to the life cycle of data, particularly for the long term use, reuse, and preservation of the data (USEPA, 2002; Kelling 2012; Strasser et al. 2012; Wiggins et al. 2013). Funders are increasingly requiring data management plans (Kelling 2012) and as citizen science data are essentially public data, they should be housed in a permanent collection (Kelling 2012). It is important to be able to combine project data with other data sets, and plan for their use in the future (Greenwood 2012; Wiggins et al. 2013; Hannibal 2016), showing the need for common frameworks and data standards (McKinley et al. 2017).

Data should be stored in a database management system as this allows access to multiple individuals at once and can link and analyze large quantities of related information in a systematic way (Cooper et al. 2012; Kelling 2012). This system is different from a spreadsheet program, which is prone to increasing errors or loss of data due to researcher error (Kelling 2012). Database programs can be tied to GIS applications (Cooper et al. 2012), and can be handle data from single or multiple projects (Kelling 2012). Citizen science programs could often support a common database structure (Bonney and Dickinson 2012; Kelling 2012; Worthington et al. 2012), although some program databases will still need to be custom built

(Worthington et al. 2012), and success relates to the quality of the database cyber-architecture itself (Newman et al. 2011 in (Acorn 2017), (Bonney and Dickinson 2012)).

Metadata, or information about the methods used to gather the data, must be developed and associated with the data (Kelling 2012; Strasser et al. 2012; Wiggins et al. 2013). It is usually in a standardized format, with two interchangeable standards recommended for citizen science: the Biological Data Profile, developed by the Federal Geographic Data Committee (FGDC), and the Ecological Markup Language, developed by the ecological community based on the FGDC standard (Kelling 2012).

Data must be protected through multiple secure backups (Bonney and Dickinson 2012; Wiggins et al. 2013; Acorn 2017). It should also be archived, which is the process of storing data together with the metadata in a long-term storage device (Kelling 2012; Wiggins et al. 2013). It is important to maintain access to the database, even if or after the project has ended (Acorn 2017). The Cornell Lab of Ornithology has a comprehensive backup and archival process for their data (Kelling 2012):

“First, every month each database is backed up in its entirety, initially to locally running disks and then off-site to a tape/disk backup system. Any and all changes made to the database are also simultaneously written locally to “change logs” on two different disk volumes. The logs are copied to the off-site system every four hours, and because they grow quickly (currently more than 13 GB/day), once or twice each week they are packaged into “incremental backups” and copied off-site. Therefore even if the database machine suffered a complete loss, only the most recent four hours of user data activity

would be irretrievable. Finally, we perform database restoration exercises several times each year to simulate total loss of the database machine. These exercises prove the viability of the backups, improve our restore procedures, and prepare us for an actual restore.” (Kelling 2012)

Prior to a program starting, policies should be developed about data sharing and management, on topics like intellectual property and open access of data, and to outline any legal or liability considerations (Strasser et al. 2012; Wiggins et al. 2013; Sullivan et al. 2017; McKinley et al. 2017; Heigl et al. 2019b). Finally, data privacy and confidentiality must be maintained, especially when data are being shared or presented (Wiggins et al. 2013; McKinley et al. 2017; Heigl et al. 2019b). This can range from anonymizing data to using locked or password protected storage devices (Wiggins et al. 2013).

Data awareness, sharing and project overlap

Visibility of citizen science programs, and the existence of their data, needs to be increased amongst scientists to increase the data usage; data should be made widely available, and be frequently shared with national or international repositories (Strasser et al. 2012; Hochachka et al. 2012; Wiggins et al. 2013; van der Wal et al. 2015; Acorn 2017; Burgess et al. 2017; Sullivan et al. 2017; McKinley et al. 2017; Heigl et al. 2019b; MacPhail et al. 2020a). Projects should be evaluated and the outcomes (both positive and negative) shared to allow others to use it as a model or to improve similar projects; to add to our knowledge of ecosystem function; and to contribute to socio-ecological topics (Conrad and Hilchey 2011; Bonney and Dickinson 2012; Gonsamo et al. 2013; Blaney et al. 2016).

It is important to keep participants informed as to the study's progress and results (MacKechnie et al. 2011; Bonney and Dickinson 2012). However, participants should be informed from the outset that some questions may take multiple years of data to understand/analyze (Bonney and Dickinson 2012; Frigerio et al. 2018). Updates and results should be shared with other target audiences, such as landowners, conservation partners, and managers (Bonney and Dickinson 2012; Bonney et al. 2014; Frigerio et al. 2018). While results should be published in academic, peer-reviewed papers, they must also be provided in formats that participants and other stakeholders can access and understand (Bonney and Dickinson 2012). Online availability makes it easy for others to access and analyze the data and further increase its reach and value (Silvertown 2009; Bonter et al. 2012; Trautmann et al. 2012; Follett and Strezov 2015; van der Wal et al. 2015; Hannibal 2016). It can also help move citizen science projects along the spectrum from having participants just collecting data to them analyzing the patterns (Hannibal 2016).

There are pros and cons to the collecting of data or projects under a larger group's umbrella. For example, some smaller grass-roots projects may be best left on their own while others may be taken over by a larger program, particularly if they have more support/resources (Acorn 2017). If data from one project are fed into another, participants need to decide what program to submit their data to, and may decide to bypass the smaller program in favor of going directly to the larger one (Acorn 2017). But by one group supporting smaller groups, they may be able to recruit and support the participants and researchers (Acorn 2017).

It is also important to avoid duplication of efforts. There can be multiple programs in the same area collecting similar data, which can confuse potential participants and/or result in patchy data (Bonter et al. 2012; Bonney et al. 2014; Russell 2014). Data collection should be standardized across programs, even if there are additional specific questions, and incorporated into one database (Bonter et al. 2012; Bonney et al. 2014; Russell 2014).

Increased funding and paid staff

Even with the use of volunteers, programs often struggle with getting enough funds to manage their project. But it is important to consider human resources costs for projects; a paid project leader and/or assistants can greatly increase program success (Bonter et al. 2012; Chu et al. 2012; Greenwood 2012; Worthington et al. 2012). Assistants can help with project planning, recruitment, promotion, mediation, analyses, and evaluation; respond to participant questions and comments; allow for more projects to be launched; and generally take pressure off the main project leaders (Bonter et al. 2012; Chu et al. 2012; Greenwood 2012; Worthington et al. 2012). Additionally, the cost to hire or provide honoraria to experts (e.g. for identification services) must be considered in budgets (Le Féon et al. 2016). As discussed earlier, it is important to evaluate the monetary and non-monetary values of projects at all stages (Blaney et al. 2016), which by necessity will take into account expenses in addition to outcomes.

Conclusion

While scientific research has been carried out by unpaid individuals for centuries, citizen science as a field is relatively new, increasing in popularity over the last few decades. It allows individuals of various backgrounds and skill levels to develop and/or participate in programs collecting information about the world around them, increasing their knowledge, and potentially

changing their behaviours related to conservation. Vast quantities of data are now available to help address research questions that would not otherwise be possible without these participants, which in turn help to inform policy and management decisions. The development of new technologies, particularly computers, smart phones, and high-speed internet, are increasing the depth and breadth of data being collected, and the diversity of volunteers who can participate. New experimental designs, databases, and statistical analyses, and common definitions, frameworks and data standards, are being developed to help collect and process new data alone and in conjunction with historic data, as well as store it securely and allow for sharing amongst participants, stakeholders, and other interested parties.

However, challenges do exist. It can be difficult to recruit and retain a diverse group of participants. Projects must be carefully and frequently evaluated and adapted as necessary. Researchers may need to gain experience in new disciplines of work, while juggling volunteer management and communication and their basic research, although having dedicated individuals to assist can help. As with any project, but especially with those using large numbers of volunteers, data collection can be patchy, incomplete, or include errors. Similarly, funding can be difficult to obtain, particularly for longer-term studies, and has a high potential for social-economic or political controversy. In some cases, citizen science data are not recognized or used by other researchers or decision makers, and it can be hard to truly evaluate the outcomes and impacts of a project. Additionally, small-scale programs, or larger-scale programs with patchy participation, may not generate the information needed to answer pressing questions, particularly related to conservation in changing times.

There are still areas where more research is needed, technological through social, and interdisciplinary teams must be put together when developing and running citizen science programs. Insights need to be shared and results (both positive and negative) communicated widely through the citizen science community, the broader scientific ones, and the public. But the potential is there for even further involvement and growth of citizen science programs, to the value of human societies and healthy ecosystems around the world.

Tables and Figures

Table 2.1. Other terminologies used for citizen science.

Term	Reference
Community science	Conrad and Hilchey, 2011
Community-based management	Conrad and Hilchey, 2011
Community-based monitoring	Conrad and Hilchey, 2011
Community and citizen science (Ballard et al. 2017)	Ballard et al., 2017
Crowd-sourcing*	Eitzel et al., 2017 (but see e.g. McKinley et al., 2017)
Participatory monitoring networks	Bell et al., 2008
Participatory research	Hannibal, 2016
Public participation in organized research efforts	Dickinson and Bonney, 2012
Public participation in scientific research	Shirk et al., 2012
Voluntary biological monitoring	Conrad and Hilchey, 2011

*Some authors explicitly include crowd sourcing in with citizen science, where the term involves large numbers of volunteers collecting data often with small specific tasks to accomplish. Others do not include crowd sourcing, where participants are only involved in basic data processing and analysis with no connection to the underlying science.

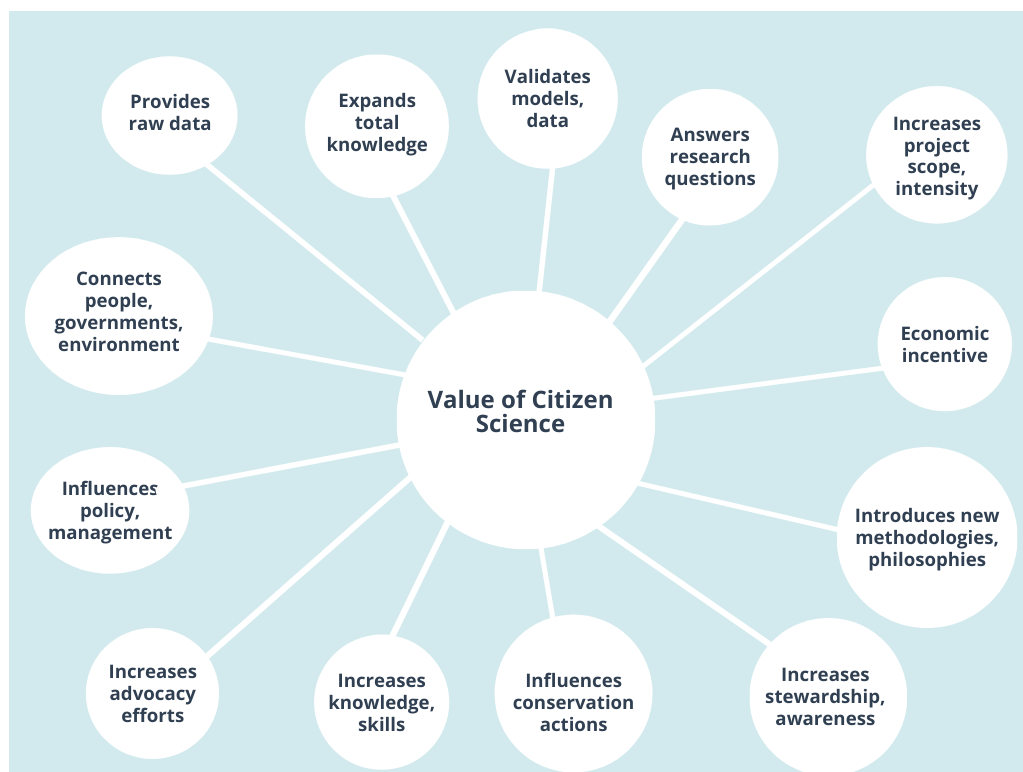


Figure 2.1. Example values of citizen science.



Figure 2.2. Example challenges of citizen science.

Chapter 3. A Community Science program worth buzzing about: Bumble Bee Watch increases ecological understanding and range coverage of an important pollinator group across the continent

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Abstract

In a time of increasing threats to bumble bees (Hymenoptera: Apidae: *Bombus*), and with some species at risk of extinction, it is important to understand their ecology and distribution. As experts are limited in their available time and finances to conduct surveys, there is potential for community scientists to help collect some of the data. The Bumble Bee Watch (BBW) community science program involves volunteers taking photos of bumble bees in Canada and the United States of America and submitting them, along with geographic and optional plant visitation information, to a website or through an app. Taxon experts then verify or edit the species identification. Here we compared the contributions of the BBW program to the knowledge collected by more traditional scientific methods and stored in the Bumble Bees of North America database (BBNA).

We found that BBW had similar geographic and species coverage as BBNA. It had records from all 63 provinces, states, and territories where bumble bees occur, including four more provinces and states than BBNA 2010-2020, and represented 41 of the 48 species in the BBNA all years dataset, with ten more species than the BBNA 2010-2020 dataset. While BBW contributed only

8.50% of records in the all years combined dataset, it contributed a full quarter (25.06%) of all records in the 2010-2020 only combined dataset. BBW confirmed the persistence of species and identified new locations of species, both inside and outside of the previously known extent of occurrence. BBW also contributed ecological information; for example, it uniquely contributed plant genera and species data for almost all the bee species in its database. Thus, while BBW had fewer bee records than the BBNA database overall, it helped to fill in data gaps and provided novel information, complementing the traditional methods of data collection. This community science data is valuable in helping to conserve bumble bee species across North America.

Introduction

Bumble bees (Hymenoptera: Apidae: *Bombus*) are a relatively recognizable genus of bees, with their often hairy bodies, large size, and frequent visits to flowers throughout the growing season. Found across the Northern Hemisphere and in South America (Williams et al. 2014), they are important pollinators of agricultural crops and wild plants (Buchmann and Nabhan 1996; Klein et al. 2007; Ollerton et al. 2011; Potts et al. 2016). While we know that approximately a quarter to a third of our bumble bees in North America are in decline, knowledge gaps on stressors, ranges, population dynamics and basic natural history remain (Bartomeus et al. 2013; Arbetman et al. 2017; IUCN 2020; Portman et al. 2020).

One impediment to wildlife conservation is the lack of knowledge about their natural history (such as habitat needs and species associations) and current status (such as current distribution and changes in their population size and range over time) (Mace et al. 2008; McKinley et al. 2017; IUCN Standards and Petitions Committee 2019; Didham et al. 2020; Williams et al. 2020; Albani Rocchetti et al. 2021). Conservation scientists often lack the resources (funding, staff

time, expertise) to adequately gather this information, particularly for species with broad distributions (Gardiner et al. 2012; Colla 2016; Ellwood et al. 2017; Flockhart et al. 2019; MacPhail and Colla 2020; Portman et al. 2020). This is particularly an issue with invertebrates, which are largely unstudied, particularly compared to vertebrates (Cardoso et al. 2011; Collen et al. 2012; Dicks et al. 2013; Wagner et al. 2021).

Community science (aka citizen science, participatory-based science) (Eitzel et al. 2017) involves volunteers designing, collecting, analyzing and/or interpreting scientific data to answer a research question (Bonney et al. 2009b; Silvertown 2009; Conrad and Hilchey 2011; Follett and Strezov 2015; Aceves-Bueno et al. 2017; MacPhail and Colla 2020). Volunteers can collect data similarly to experts (depending on skill level, training provided), often with greater coverage than researchers could cover alone and with a lower cost (Bonney et al. 2009a; Garibaldi et al. 2011; Dickinson and Bonney 2012; van der Velde et al. 2017; Zapponi et al. 2017; MacPhail and Colla 2020) (but see (Stribling et al. 2008; Kremen et al. 2011; McDonough MacKenzie et al. 2017; Falk et al. 2019)). Participants benefit in a variety of ways including increasing their knowledge of species and field techniques and becoming more environmentally aware and engaged (Conrad and Hilchey 2011; Bonter et al. 2012; Jordan et al. 2016; McKinley et al. 2017; MacPhail and Colla 2020). The data can be used independently, or combined with other programs and data sources, to increase knowledge about wildlife or habitat, create policies, aid in conservation management, and even help achieve United Nations Sustainable Development Goals (Theobald et al. 2015; Ballard et al. 2017; McKinley et al. 2017; Flockhart et al. 2019; MacPhail and Colla 2020; Koffler et al. 2021).

The Bumble Bee Watch community science program (herein “BBW”) (The Xerces Society for Invertebrate Conservation 2020) was launched on January 22, 2014 in an effort to collect information on bumble bees across North America (specifically the continental United States (including Alaska) and Canada), in a non-lethal survey method. Participants take photos of bumble bees and submit them through a web-interface or app (free for iOS and Android smart devices) along with other information such as the date observed, the geographic coordinates, and optionally, the plant it was observed foraging on. Regional experts then verify the bee identifications (MacPhail et al. 2020b). Records have now been submitted from every province, state, and territory, including remote, rural, suburban, and urban areas (MacPhail et al. 2020a). While previous work has been done on the accuracy and breadth of the BBW data (MacPhail et al. 2020b), and the impacts on and demographics of its participants (MacPhail et al. 2020a), it is valuable to see if BBW is contributing new or additional information than that collected by researchers. Previous research has done comparisons of other community science programs to more traditional programs (Sullivan et al. 2009; Lye et al. 2011; Losey et al. 2012; Beckham and Atkinson 2017; Dennis et al. 2017; Suzuki-Ohno et al. 2017; Zapponi et al. 2017; Soroye et al. 2018). In many cases, the studies discovered important information on topics such as range expansions and abundances from the community science data, and could learn more about changes over time using these data.

The Bumble Bees of North America database (herein “BBNA”) (Richardson 2020) was initially created to collate known information about bumble bees for the Bumble Bees of North America Identification Guide (Williams et al. 2014). It is now maintained by Dr. Leif Richardson, and is used by different organizations and individuals for research and conservation purposes. As of

April 2019, it had more than 587,000 observations across the United States and Canada, contributed by over 250 individuals or institutions, for locations, with records dating back to 1805; see <https://www.leifrichardson.org/bbna.html> for a full description of the contributors. While not all bumble bee researchers submit their data to this database (or to the Global Biodiversity Information Facility (GBIF), which is an international portal for data on all species that BBNA also contributes to and pulls data from), it is the single most populated database for bumble bees in North America.

Here we ask the following questions of the BBW dataset as compared to the BBNA dataset to determine the amount of novel information a new community science program can generate as compared to the long-term professional data set:

1. Does BBW show a higher number of species records, richness, or diversity?
2. Does BBW show examples of points outside a species known Extent Of Occurrence?
3. Does BBW show increases in species range sizes?
4. Does BBW show examples of species range infill?
5. Does BBW confirm species presence or recent persistence?
6. Does BBW provide new forage plant information per species?

Materials and Methods

We obtained an export of all BBNA records (individual bee observations or specimens) (excluding those with permissions prohibiting sharing) on May 28, 2020 (Richardson 2020) and BBW on August 19, 2020 (both nest and bee records, including those marked private). A second

copy of the BBNA data set was then made that only contained records recorded from 2010-2020. The data were cleaned to remove any records that were not verified by experts (i.e. still pending identification or determined to be non-*Bombus*) (BBW) or that were flagged as having identification problems (BBNA).

While the current primary identification guide for bumble bees in North America north of Mexico lists 46 species (Williams et al. 2014), new species have been described and other taxonomies changed or challenged since that book was published, with no consensus for the new number of species (Table A.S1). It was outside the scope of this paper to update species names, particularly given the limitations with reidentifying a species without a physical specimen or photo to refer to; this consideration applies to BBNA in particular where many records, particularly in the last decade, are not vouchered specimens but are instead from field observations. We thus use the species names as provided in the data obtained.

While BBNA only contained identifications at the species level, some BBW records were only determined to genus (i.e. *Bombus* sp., unknown bumble bee species) or were considered as one of two types of species groups: "*vagans*, *sandersoni* or *perplexus*" (two-striped yellow group) and "*vosnesenskii* or *caliginosus*" (yellow-faced group). While some authors removed records from their analyses that were not identified to a specific species (e.g. (Losey et al. 2012)), we felt that there was still value in including these data points. For example, it shows that at least one of the species in the "group" were present in the area (e.g. for the "two-striped yellow group", at least one of *B. perplexus*, *B. sandersoni*, or *B. vagans* was present), which is more information than omitting the record completely. Similarly, an unidentified bumble bee record still shows

that someone was at that site and saw at least one bee species at that time. Hereafter these species groups will be referred to simply as species, unless otherwise noted.

Finally, although some authors removed records of species that did not have the same corresponding species in the comparison dataset (e.g. (Soroye et al. 2018)), we again kept the points in and used them where applicable. Table A.S2 contains a list of all the species found in this study, their taxonomic authorities, and conservation statuses.

We obtained shapefiles of US and Canada federal jurisdiction boundaries (Statistics Canada 2016a; US National Weather Service 2016) merged them into one file, removed any regions from outside the study area, and merged the two Maryland polygons, resulting in 63 total provinces, territories, and states (including District of Columbia but excluding Hawaii, which has no bumble bees).

We removed all bee records that had missing or imprecise geographic coordinates. For BBNA, we removed records from community science efforts to concentrate the comparison on more traditional researcher data, and removed known duplicate records.

We imported BBW and BBNA data into ArcGIS (ESRI 2016) using the geographic projection GCS_NAD83, which we later projected to use GCS_ArcInfo and Sphere Azimunthal. (Note that the original records may have been collected using different projection systems; this information was not provided with the data). Records that fell at or within 5km of the US Canada boundary file were snapped to the nearest point of land; spot-checks using Google Maps and additional

data (e.g. site name, city name) confirmed that this seemed to be an appropriate process (records >5km away were removed). Some records had uncertainties noted regarding the exact location (often due to deliberate obscuring of coordinates for privacy or other restrictions), but records were left in when the uncertainty was <100km; however, this does mean that the actual location of some records may not be in the correct 10km x 10km or 100km x 100km grid for analyses in this study.

Various scales and methods have been used to determine the number of populations of insects in an area, and for comparisons between datasets, such as by ecoregion, province/state/territory, 100km x 100km grids, 50km x 50km grids, 10km x 10km grids, and 1km x 1km grids, as well as through population genomics (Williams et al. 2007; Cameron et al. 2011b; Colla et al. 2012a; Pocock et al. 2017; Zapponi et al. 2017; Kent et al. 2018; Soroye et al. 2018; United States Fish and Wildlife Service (USFWS) 2019a). We use here the definition provided in a US Fish and Wildlife Service report (2019a) that states “A population is a collection of tens to hundreds of colonies, and the health (long- term productivity) of populations is affected by the quantity and quality (a diversity of floral resources) of nectar and pollen available and the proximity of these resources to nesting sites. For monitoring the number of populations over time, a population is a single 10 x 10 kilometer (km) grid.”. The 10km x 10km grid is based on the average foraging and dispersal distances of a bumble bee colony that are usually less than 10 kilometers (although there are exceptions) and the expert knowledge that colonies are often densely concentrated (Stout and Goulson 2000; Osborne et al. 2008; Kraus et al. 2009; Lepais et al. 2010; Szymanski et al. 2016; Mola and Williams 2019; United States Fish and Wildlife Service (USFWS) 2019a).

We concentrated our analyses on the 100km x 100km grid cell to facilitate analyses on the broader North American scale while trying to avoid spatial biases, but also on the 10km x 10km grid cell to capture new populations. Continental wide grids of 10km x 10km and 100km x 100km in size were created using the fishnet polygon option in ArcGIS, and all species records were spatially joined with the relevant boundary files to associate province/state/territory name and 10km x 10km and 100km x 100km grid numbers.

One way to determine the outer limits of a species geographic distribution is through the application of minimum convex polygons (mcp) around all records in ArcGIS: this area is known as the species Extent of Occurrence (EOO)(Bachman et al. 2011; Soroye et al. 2018; IUCN Standards and Petitions Committee 2019). After creating the EOO layers, we then investigated the number of BBW points outside the BBNA all years and BBNA 2010-2020 EOOs by first selecting all BBW points that fell within the BBNA EOO, and then doing an inverse selection: these points show extensions of species geographic range limits due to BBW. The total area of each EOO was also calculated in ArcGIS and the difference between the datasets recorded using MS Excel. Another method of looking at range size per species was calculated by counting the number of 100km x 100km occupied grids in each individual and combined datasets.

The percent infill (i.e. new locations or occurrences within a species geographic range) contributed by BBW was calculated by dividing the number of unique or novel 10km x 10km and 100km x 100km grids contributed by BBW by the total number of grids in the BBNA all years and BBW combined datasets, and the BBNA 2010-2020 and BBW combined datasets, for each species.

To investigate if BBW confirms the presence of a species found by researchers, we looked at the proportion of all 100km x 100km grid cells in the BBNA all years dataset that also had at least one BBW record. For confirmation of recent species persistence (i.e. occurrences in last decade vs historical), we looked at the proportion of 100km x 100km grid cells in the BBNA all years dataset that were not in the BBNA 2010-2020 dataset but had at least one BBW record (i.e. proportion of all BBNA grids with observations in the last decade contributed solely by BBW).

To compare plant forage information, we collated, cleaned, and standardized the information provided in each data set. For example, we converted common plant names to scientific ones to most detailed level possible when scientific names were not provided, fixed spelling errors, and updated synonyms where new ones were known (e.g. joe pye weed, *Eupatorium maculatum* (old) vs *Eutrochium maculatum* (new); crown vetch, *Coronilla varia* (old) vs *Securigera varia* (new)). Taxonomic authorities were generally not provided with the plant names so interpretations involved the most common usages of the names.

Summary statistics (e.g. totals, means $\pm$ se), species richness (standard and Menhinick's index), species diversity (Shannon-Weiner), and unique values (e.g. number of species, records) were calculated using MS Excel (Microsoft Office 365) on a per species, province/state/territory, 100km x 100km grid and 10km x 10km grid basis. Species richness is the total number of species but does not consider sample size/sampling effort; Menhinick's index for species richness helps to take into account sampling effort and sample size, and is calculated as the number of species divided by the square-root of the total number of individuals. Species diversity was measured using the Shannon-Weiner Index (H) is calculated as $H = -$

$1 * \sum(p_i * \ln p_i)$, where p_i is the proportional abundance of each species. Note that these statistics excluded zero values/missing species where applicable (i.e. averages and range of numbers of plant genera, plant species, and total grids per species).

Statistical comparisons were carried out using JASP Version 0.14.1 (JASP Team 2020).

Independent student t-tests (statistic abbreviated as T), or the non-parametric Mann-Whitney U-tests (U) when assumptions of normality and equal variances could not be met, were used to compare differences in the mean numbers of bee species records, richness, and diversity, and the number of plant genera and plant species, between BBW and BBNA datasets on various scales. One-sample t-tests, or the non-parametric Wilcoxon signed rank test (W) when the assumption of normality was not met, were used to determine if the mean numbers of BBW points outside of the EOO of species in both BBNA datasets, or the mean numbers of unique 10km x 10km and 100km x 100km grids contributed by BBW per species in both BBNA datasets, were significantly different than zero (i.e. contributed significantly more points or grids overall than zero). Chi-square (χ^2) goodness-of-fit tests compared the observed BBW frequency of occupied grids vs the expected BBNA all years or BBNA 2010-2020 occupied grids to see if number of BBW grids was significantly different between the datasets being compared. Statistical tests are significant when $p < 0.05$.

Results

Does BBW show a difference in species records, richness or diversity?

BBW contributed 8.50% of all records (individual bee observations or specimens) in the BBW and BBNA all years combined dataset and 25.06% of all records in the BBW and BBNA 2010-2020 dataset. The average number of records per species per dataset ranged from $9,899.15 \pm 1675.14$ for BBNA all years, $2,933.36 \pm 796.86$ for BBNA 2010-2020, and $1,003.05 \pm 205.88$ for BBW (Table 3.1).

BBW had 41 full species and 3 species groups of the 51 total species represented across the combined dataset (Tables 3.1, A.S2), with the 3 species groups not in either BBNA all years or BBNA 2010-2020. BBW had more records for 3 species than BBNA all years and 13 species than BBNA 2010-2020.

All 63 provinces, territories, and states were represented in both the BBNA all years dataset and the BBW dataset; however, BBW had four more provinces and states represented than BBNA 2010-2020 (Fig. 3.1, Tables A.S3, A.S4). BBW provided observations of at least one unique species for 60 provinces and states vs BBNA all years and 63 vs BBNA 2010-2020 (Table A.S3), and more records for one province or state vs BBNA all years and 19 vs BBNA 2010-2020 (Table A.S3).

Mean values of number of bee records, species richness, and species diversity, were significantly greater in BBNA all years than BBW for all comparisons, except for number of bee records and

Menhinick's Index on the province/state basis, where BBW was greater, and species diversity, where there was no significant difference (Table A.S6-S8). Mean values of BBW were significantly greater than BBNA 2010-2020 for all comparisons except the number of bee records per province/state and 10km x 10km grid basis, where BBNA 2010-2020 was greater, and Menhinick's Index or species richness on the 100km x 100km grid and province/state basis, respectively, where there was no significant difference (Tables A.S5-S8).

Does BBW show examples of points outside a species known Extent Of Occurrence?

On a per species basis, 23 of the 41 species had records (individual bee observations) in BBW outside of the corresponding BBNA all years species EOO, ranging from 1 record (several spp.) to 121 records (*B. impatiens*) (Fig. A.S1, Table 3.2). When compared to the BBNA 2010-2020 data, 39 of 41 species had records in BBW outside of the corresponding species EOO, ranging from one record (several spp.) to 456 records (*B. vosnesenskii*) (Fig. A.S1, Table 3.2). The mean number of BBW records outside of each species EOO is significantly different than 0 for BBNA all years ($n=41$, $\text{mean}=9.439 \pm 3.716 \text{ SE}$, $W=276.000$, $p<0.001$; 2010-2020) and BBNA 2010-2020 ($n=41$, $\text{mean}=48.366 \pm 13.787 \text{ SE}$, $W=780.000$, $p<0.001$).

Does BBW show increase in species range sizes?

BBW never had a greater EOO than BBNA all years, but did have a greater EOO than BBNA 2010-2020 for 15 species. The total EOO values for each species in each dataset, and the difference between them, can be found in Table A.S9.

The average number of 100km x 100km grids with records per species, per dataset, when zeros are excluded, was 224.38 ± 21.22 , 74.40 ± 8.32 , and 98.66 ± 14.13 for BBNA all years, BBNA

2010-2020, and BBW, respectively. BBW did not meet the expected frequency distribution of grids per species as compared to BBNA all years ($\chi^2 = 1249.579$, $df=40$, $p<0.001$) or BBNA 2010-2020 ($\chi^2 = 857.386$, $df=40$, $p<0.001$) on the 100km x 100km grid scale.

The approximate range size per species, based on occupied 100km x 100km grids, can be calculated from Table A.S10 (total number of grids need to be multiplied by 10,000km² to get the area). While the BBNA all years dataset always provided larger range sizes (i.e. more occupied grids) than BBW (except for the three species groups only in BBW), BBW did provide a larger range size for 24 species (plus three species groups) as compared to BBNA 2010-2020 (Table A.S10).

Does BBW show examples of range infill?

We found multiple examples of BBW infilling the known range of up to 44 species, both on the 10km x 10km and 100km x 100km grid square bases, and especially when compared to the BBNA 2010-2020 dataset (Tables 3.4, A.S10; Fig. 3.2). While it was variable on a per species basis, the maximum number of unique grids contributed by BBW ranged from 1447 and 1524 10km x 10km grids when compared to BBNA all years and BBNA 2010-2020, respectively, and 419 100km x 100km grids when compared to each of the two BBNA datasets (Tables 3.4, A.S10; Fig. 3.2). The mean number of unique grids contributed by BBW per species ($n=51$) was significantly greater than 0 for both scales and dataset comparisons (Table 3.3).

Does BBW confirm species presence or recent persistence?

BBW confirmed the presence of at least one species in 717 of the 1434 100km x 100km grid cells that had records in BBNA all years (50.00%), with an average of $26.65\% \pm 2.72\%$ of the grids containing records on a per species basis (Fig. 3.3, Table A.S10). It uniquely confirmed the recent persistence of a species (i.e. found in BBNA all years but not BBNA 2010-2020) in 543 of the 1434 100km x 100km grids (37.87%), with an average of $15.34\% \pm 1.55\%$ of the grids with records per species (Fig. 3.3, Table A.S10). The mean number of these 100km x 100km grids is significantly different than zero, even when species with no new grids are included (presence mean= 58.078 ± 9.358 , $W=820.000$, $p<0.001$; persistence mean= 32.431 ± 5.135 , $W=820.000$, $p<0.001$).

Does BBW provides new forage plant information?

Although BBW had much fewer records than BBNA all years or BBNA 2010-2020 (Table 3.1), it provided more total plant genera (Table 3.4) and plant species (Table 3.5) than either of the BBNA datasets. While this was not significant on the all years comparison using the total numbers per bee species (plant genera: $U=1194.500$, $p=0.480$; plant species: $U=1235.000$, $p=0.663$), it was on the 2010-2020 comparison (plant genera: $U=864.500$, $p=0.003$; plant species: $U=894.500$, $p=0.007$). Indeed, 26.24% and 31.56% of the plant genera (Table 4), and 36.84% and 56.56% of the plant species (Table 3.5) were only provided by BBW records when compared to the BBNA all years and BBNA 2010-2020 datasets, respectively. The numbers of total and unique records per plant genera and plant species varied per bee species, but 42 bee species in the BBW and BBNA all years and 43 bee species in the BBW and BBNA 2010-2020 datasets had unique plant information provided by BBW (Tables 3.4, 3.5, Figs. A.S2, A.S3). A

full list of all plant species names per bee species, and numbers of bee records for each, is available in Table A.S11 for all datasets combined.

Discussion

Community science programs have immense potential to contribute to scientific understanding and wildlife conservation efforts. After just six years of operation, Bumble Bee Watch (BBW) has demonstrated its value for bumble bee conservation. While the total number of bee records and species contributed by community scientists is not higher than those of researchers to the BBNA database, the records are still filling knowledge gaps, particularly in recent years.

Species richness and diversity were often higher in BBW for most analyses. While the overall BBW range sizes for species were usually smaller than from BBNA, often BBW records were found outside of the BBNA range. BBW also increased the number of known populations for species inside of their ranges and vastly increased the number of plant genera and species known to be visited. These records all represent unique occurrences in space and time that will never occur again and cannot be recreated. Not only can they be used to help answer questions now when there is an urgent need for pollinator data (Potts et al. 2010), the data can be used indefinitely into the future, as new questions are always developed.

Species Richness

With the increase in photo quality and widespread use of digital cameras, the identification of species by photo is becoming more common in both community science and in the greater academic fields. The usage ranges from photos confirming an observation, as with BBW, through to using photos in lieu of the traditional physical “type” specimen (although the latter is currently accepted only in certain specific rare situations) (Krell and Marshall 2017). The

validity of this use does depend on the species being identified (such as visibility of key identifying features), the angles shown in the photo(s), and the quality of the photo(s) (e.g. lighting, focus) (Lye et al. 2011; Acorn 2017; Krell and Marshall 2017; Austen et al. 2018; MacPhail et al. 2020b).

Many of the recent species changes in the genus *Bombus* are a result of DNA barcoding and re-examination of morphological characters, particularly for cryptic species (Williams et al. 2014, 2016; Sheffield et al. 2019, 2020; Sikes and Rykken 2020). Some of these new species do appear in the BBNA datasets (e.g. *B. kluanensis* and *B. natvigi*), but not all (e.g. *B. johanseni*). A challenge with the BBW program is that some of these cryptic species cannot be identified from photos alone, particularly the type and quality submitted by community scientists (e.g. from a distance on a flower vs under a dissecting microscope). It is likely that some of these species, particularly those in the *Alpinobombus* sub-genus, have been submitted to BBW but are still pending verification or verified as an unknown species due to the difficulty in assigning an identification (MacPhail et al. 2020b). It may be useful for BBW administrators to follow up with the submitters of these records to gain a physical voucher specimen or portion thereof (e.g. antenna or tarsal (final segment in the leg of the insect) clip) for a researcher to identify in person or through DNA barcoding, and/or add in more species groups to account for these northern cryptic bees. In addition to the northern bees that are both difficult to identify and found in areas with fewer participants, other species missing from BBW but present in BBNA (e.g. *B. franklini*, *B. variabilis*) are those that are likely extirpated or very uncommon (Williams et al. 2014; MacPhail et al. 2020b). Therefore, BBW generally has captured all of the confirmed and extant species for North America.

Our results were consistent with previous findings that while the total numbers of community science records may or may not be lower than those from expert databases, it often makes up for it with more species per 1,000 observations (Losey et al. 2012) and/or observations in areas unique only to the community science databases, in some cases in areas unexpected by researchers (Losey et al. 2012; Zapponi et al. 2017; Soroye et al. 2018). Indeed, opportunistic observations can help to document new species, locations of species and/or changes in range, whether through natural or human-mediated causes (Dickinson et al. 2012; Losey et al. 2012; Acorn 2017; Pocock et al. 2017; Sullivan et al. 2017; Zapponi et al. 2017; Soroye et al. 2018). As climate change is a major component, affecting range expansion and contraction for many species, including bumble bees (Kerr et al. 2015; Pyke et al. 2016; Sirois-Delisle and Kerr 2018; Soroye et al. 2020; Suzuki-Ohno et al. 2020), this information will be increasingly important.

Rare Species

The BBW dataset provided observations and unique populations (unique presence in 10km x 10km grids versus BBNA) for 11 at-risk and 5 data-deficient species over both the BBNA all years and 2010-2020 datasets. One notable example was the discovery of *B. bohemicus* in eastern Canada in 2020 by a BBW participant at two areas in Rimouski, Quebec. This species is considered to be Endangered in Canada by COSEWIC (2014), Endangered in Ontario by COSSARO (Committee on the Status of Species at Risk in Ontario and COSSARO 2014), and Critically Imperiled across most of its range but Possibly Extirpated in Quebec by NatureServe (NatureServe 2021). Previously, the last observations of this species in Ontario and Quebec, as represented in the BBNA all years dataset, were in 2008 despite extensive surveys by researchers. Without community science programs, these occurrences may have gone

unrecorded and the species moved closer to being considered extirpated in these regions. There have been observations of *B. bohemicus* in the western part of Canada and Alaska in BBNA (127 records since 2010) and BBW (7 records).

Geographic Range Expansion, Infill, Presence, Persistence

Community science has documented species distributions, including changes in range, similar to or beyond that of traditionally collected data (Munson et al. 2010; Losey et al. 2012; Dennis et al. 2017; Zapponi et al. 2017; Soroye et al. 2018; Flockhart et al. 2019) (but also see (Snäll et al. 2011)). For example, the geographic coverage (range size estimations) of three saproxylic beetle species resulting from two years of records by community scientists in the European LIFE Project was approximately equal to ten years of a formal national inventory data (Zapponi et al. 2017), and new distribution information was provided for over 80% of the butterfly species in Canada by community scientists with eButterfly (Soroye et al. 2018).

BBW did not have any species not also documented in BBNA; this is not surprising due to the greater number of records and geographic coverage in the BBNA all years dataset, and the necessity for genetic characters to identify some cryptic species. However, BBW did have more records for 13 species than BBNA 2010-2020, and BBW reported observations in 50 and 398 unique 100km x 100km grids not in BBNA all years and 2010-2020, respectively. BBW also provided records for 23 species outside of their known distribution as calculated through the BBNA records. These examples confirm the value of community science data for determining species presence and persistence, particularly in areas that may not be known to or surveyed by

researchers, as was also seen in other projects (Zapponi et al. 2017; Soroye et al. 2018; MacPhail et al. 2019).

Biases in Data

Biases exist in the data, such as uneven geographical distribution (e.g. urban centres or along roadsides), overrepresentation of particular species (e.g. a focus on documenting rare or unusual species), variation in detectability of species (e.g. influenced by skill of the observer, quality of habitat, weather conditions, time of day, size of population, period of colony growth cycle), resulting again in an overrepresentation of certain species in the data (Guralnick and Van Cleve 2005; Snäll et al. 2011; Hochachka et al. 2012; Flockhart et al. 2019; Johnston et al. 2019, 2020; Didham et al. 2020; MacPhail et al. 2020b). These biases, and differing patterns of data collection between different surveyors, can occur in both community science data and in other data (e.g. museum collections, researcher surveys), and should be controlled when possible; results should be treated with care and evaluated for an effect of the bias(es) (Guralnick and Van Cleve 2005; Phillips et al. 2009; Snäll et al. 2011; Yackulic et al. 2013; Bartomeus et al. 2013; Flockhart et al. 2019; Didham et al. 2020; Johnston et al. 2020). However, biased data can still be used to complement more traditional, less biased data; indeed, the strengths of one can offset the weaknesses of others (Guralnick and Van Cleve 2005; Snäll et al. 2011; Cooper et al. 2012; Giraud et al. 2016; Flockhart et al. 2019; Johnston et al. 2020).

Comparing different types of data

BBW is composed primarily of incidental independent observations, which provides presence-only data, rather than a checklist-based set of observations, from which absences are easier to determine (i.e. if a species isn't recorded on a checklist it means it wasn't seen vs if there is no

record of a species from a particular site or day with incidental data, it is not clear if it wasn't seen or just wasn't reported). (While The Xerces Society for Invertebrate Conservation and various partner organizations now have atlas-based checklists for a few regions with data being contributed to BBW (The Xerces Society for Invertebrate Conservation 2021), those data have been lumped in with the incidental observations for these analyses). There is no standardized time or search effort required or reported for BBW, although most users submit only one record per site (MacPhail et al. 2020a). The use of photos allows for non-lethal sampling of the bees.

BBNA is composed of data from multiple sources, each with their own methods (e.g. netting, pan traps, blue vane traps, visual observations) and type of data collection (incidental observations, standardized surveys) (Ascher et al. 2020; Richardson 2020). It also includes many museum and collection-based records, which themselves likely are a result of both incidental captures and standardized surveys. Search effort is also not recorded and can be variable. In future, it is encouraged that researchers in particular record their search effort time and share those values with their data.

Both of the BBW and BBNA datasets may contain biases related from the recording/collecting (or non-recording/collecting) of rare species vs common species, as well as biases related to geography, the expertise of identifiers, ease of differentiation of species, etc. (see discussion above and (Ascher et al. 2020; Didham et al. 2020)). Findings often need to be interpreted with care, and indeed, data sources and methods reviewed prior to use. Soroye et al. (2018) cautions that, when other more suitable data exists, it may be better to not use opportunistic data in analyses related to species or regions, especially when it makes the analyses more complex. As

well, more data does not always mean more power for analyses, and are not always better if they introduce more uncertainty into analyses or obscure results (Soroye et al. 2018). In some cases, only part of the data may not be suitable for use; for instance, Graves et al. (2020) excluded BBW data from the BBNA dataset used in their models as the former database is generally composed of incidental or opportunistic observations as compared to complete inventories.

Opportunistic data can be used in many analyses, and indeed, in some cases (with particular species, regions, and/or methods) can provide more reliable results than other types of formal surveys, such as with bumble bees in areas where the study area is small and historical baseline data are available for comparisons (Simon 2020). At the very least these data can confirm historic observations and yield new locations or other novel information, as well as complementary and confirmatory data (Dennis et al. 2017; Zapponi et al. 2017; Soroye et al. 2018).

[Ability to effect policy and recovery actions](#)

By adding together existing datasets, such as BBNA and BBW, and by carefully designing both traditional research methods and community science programs, researchers and conservationists can potentially achieve a greater understanding and closer approximation of “real” conditions (Dennis et al. 2017; Sullivan et al. 2017; McKinley et al. 2017; Soroye et al. 2018; Didham et al. 2020; Graves et al. 2020). BBW data can be viewed in real-time via the website or app platforms, and exports can be requested via the program’s data request form. The data are also routinely accepted into the BBNA database and the USGS BISON (Biodiversity Information

Serving Our Nation) database (<https://bison.usgs.gov>), and has been added to other national and regional databases, so the data are increasingly becoming available to researchers.

BBW data has already been used by researchers for species conservation assessments (Szymanski et al. 2016; Committee on the Status of Endangered Wildlife in Canada 2018; MacPhail et al. 2019) and regional checklists (Gibbs et al. 2017), and by land managers and conservation professionals to identify sites for habitat conservation, restoration, and linkage efforts, or for further research or advocacy efforts (Gibson et al. 2019; MacPhail et al. 2019, 2020b; Liczner and Colla 2020). Similarly, data from other community science programs have helped assess the distribution and diversity of bumble bees and other bee species to occur (Lye et al. 2011; Le Féon et al. 2016; Beckham and Atkinson 2017; Richardson et al. 2019). As these data sets grow and join with others, many more future uses will be likely. As stated in McKinley et al (2017): “The best science does not necessarily come from the best peer-reviewed scientific publications with the most robust designs and inferences; rather, it is the best scientific information available to answer a specific question”.

Community science participation benefit the public and the environment

For effective wildlife conservation, we need to consider the whole spectrum of actions and tasks, from understanding the current status of a species population or conservation target to identifying and understanding the underlying drivers of the issues to describing the actions needed to support the species and testing the impacts and responses of those actions (Cardoso et al. 2011; Williams et al. 2020; Albani Rocchetti et al. 2021). We also need to raise public awareness of these species or targets and their interest in supporting and meeting them, as this

increases the probability of actions actually happening by the public, conservation groups, and governments (Bickford et al. 2012; Colla and MacIvor 2017; Underwood et al. 2017; Cardoso and Gonçalves 2018; Hall and Steiner 2019; Hall and Martins 2020; Requier et al. 2020; Vierssen Trip et al. 2020; Althaus et al. 2021; Albani Rocchetti et al. 2021).

Community science programs can help with these needs, as their participants are involved in collecting data and/or answering questions with that data, learning about how science works to answer questions and about the specific study focus, while gaining more awareness of the current status, threats, and needed actions, often getting reconnected with nature in the process (Conrad and Hilchey 2011; Acorn 2017; Dennis et al. 2017; Zapponi et al. 2017; McKinley et al. 2017; MacPhail and Colla 2020). This awareness and connectedness is achieved not only through hands on experiences but also through education components associated with the program; indeed, other members of the public also gain exposure to these topics through general media coverage and program outreach activities, even if they are not participants themselves (Bonney et al. 2009a; Federal Provincial and Territorial Governments of Canada 2014; Acorn 2017; Zapponi et al. 2017; McKinley et al. 2017; MacPhail and Colla 2020). Participants and the public in turn provide feedback to community science organizations and conservation professionals about their priorities and understandings (Cooper et al. 2007; Shirk et al. 2012; Acorn 2017; McKinley et al. 2017; NASEM 2018; MacPhail and Colla 2020). Past Bumble Bee Watch participants have noted the positive impacts the program has had on them, including their increased knowledge and willingness to take action (MacPhail et al. 2020a), and this may lead to more public support for broader actions in the future.

In conclusion, our findings show the incredible potential for community scientists to contribute to scientific knowledge and conservation management. As noted by Ellwood et al (2017), the intersections of community science and conservation can help address the large challenges we face. In this example, Bumble Bee Watch benefits from the public's desire to learn more about and protect pollinators, and researchers gain valuable data that would not have been possible otherwise. Coupled with the widespread availability of technology provided by digital cameras, smart devices, and the internet, the potential for this and other community science data to help mitigate species decline and other environmental challenges will grow in the future.

Tables and Figures

Table 3.1. Total number of bumble bee (*Bombus* spp.) records per species from BBNA all years, BBNA 2010-2020, and BBW datasets, and from the BBW + BBNA all years and BBW + 2010-2020 combined data sets.

<i>Bombus</i> species	#BBNA records all years	#BBNA records 2010-2020	#BBW records	total # records BBNA all years + BBW	total # records BBNA 2010- 2020 + BBW
<i>affinis</i> ¹	8,712	188	725	9,437	913
<i>appositus</i>	4,377	404	408	4,785	812
<i>auricomus</i>	3,200	128	269	3,469	397
<i>bifarius</i>	33,727	5,736	3,460	37,187	9,196
<i>bimaculatus</i>	19,255	8,129	2,326	21,581	10,455
<i>bohemicus</i> ^{2,4}	2,797	127	7	2,804	134
<i>borealis</i>	4,966	2,641	623	5,589	3,264
<i>caliginosus</i> ¹	2,552	89	101	2,653	190
<i>centralis</i>	7,685	1,202	1,009	8,694	2,211
<i>citrinus</i>	3,995	575	160	4,155	735
<i>cockerelli</i> ¹	120	6	0	120	6
<i>crotchii</i> ¹	1,837	14	17	1,854	31
<i>cryptarum</i> ²	2,462	1,087	152	2,614	1,239
<i>distinguendus</i> ²	6	0	0	6	0
<i>fervidus</i> ¹	20,033	1,900	1,158	21,191	3,058
<i>flavidus</i> ²	2,759	678	244	3,003	922
<i>flavifrons</i>	17,836	4,069	1,719	19,555	5,788
<i>franklini</i> ¹	324	0	0	324	0
<i>fraternus</i> ¹	1,846	69	98	1,944	167
<i>frigidus</i>	8,182	2,689	30	8,212	2,719
<i>griseocollis</i>	21,604	7,039	3,474	25,078	10,513
<i>huntii</i>	9,483	1,972	1,248	10,731	3,220
<i>impatiens</i>	59,991	31,694	7,755	67,746	39,449
<i>insularis</i>	6,050	759	505	6,555	1,264
<i>jonellus</i> ²	5,101	2,466	1	5,102	2,467
<i>kirbiellus</i> ²	2,424	616	12	2,436	628
<i>kluanensis</i> ¹	20	14	0	20	14
<i>melanopygus</i>	14,725	1,665	1,326	16,051	2,991
<i>mixtus</i>	18,307	8,306	1,460	19,767	9,766
<i>morrisoni</i> ¹	4,626	73	88	4,714	161
<i>natvigi</i> ^{1,2}	312	44	0	312	44

<i>Bombus</i> species	#BBNA records all years	#BBNA records 2010-2020	#BBW records	total # records BBNA all years + BBW	total # records BBNA 2010- 2020 + BBW
<i>neoboreus</i> ²	521	63	0	521	63
<i>nevadensis</i>	3,004	696	805	3,809	1,501
<i>occidentalis</i> ¹	22,572	2,934	544	23,116	3,478
<i>pennsylvanicus</i> ¹	24,509	1,460	615	25,124	2,075
<i>perplexus</i>	9,552	3,439	541	10,093	3,980
<i>polaris</i> ²	1,204	242	1	1,205	243
<i>rufocinctus</i>	12,521	4,297	1,733	14,254	6,030
<i>sandersoni</i>	2,158	1,096	43	2,201	1,139
<i>sitkensis</i>	2,741	347	221	2,962	568
<i>sp.</i> ³	0	0	3,395	3,395	3,395
<i>suckleyi</i> ¹	1,952	26	2	1,954	28
<i>sylvicola</i>	10,372	4,950	79	10,451	5,029
<i>ternarius</i>	20,292	13,033	2,045	22,337	15,078
<i>terricola</i> ¹	19,606	1,721	625	20,231	2,346
<i>vagans</i>	24,090	11,251	974	25,064	12,225
<i>vagans</i> , <i>sandersoni</i> or <i>perplexus</i>	0	0	550	550	550
<i>vandykei</i>	963	96	139	1,102	235
<i>variabilis</i> ¹	956	0	0	956	0
<i>vosnesenskii</i>	28,832	1,971	2,608	31,440	4,579
<i>vosnesenskii</i> or <i>caliginosus</i> ³	0	0	839	839	839
total # records	475,159	132,001	44,134	519,293	176,135
total # individual species (excluding species groups)	48	45	41	48	45
total # species (including species groups)	48	45	44	51	48

¹ species considered to be at-risk of extinction, with an IUCN or NatureServe status of VU, EN, CR

² species that are considered to be data deficient (DD) and thus no determination of their at-risk status can be made (i.e. may be LC, VU, EN, or CR)

³ species group where the observed individuals may or may not be at-risk of extinction, depending on the actual identity of the species

⁴ species considered to be at-risk of extinction by a federal assessment organization despite overall IUCN rank of DD

Table 3.2. A comparison of the number of BBW records that fall outside of the Extent of Occurrence (EOO) for each bumble bee (*Bombus*) species in the BBNA all years and BBNA 2010-2020 datasets.

Species	# BBW records outside BBNA EOO	
	BBW vs BBNA all years	BBW vs BBNA 2010-2020
<i>affinis</i>	1	126
<i>appositus</i>	0	27
<i>auricomus</i>	1	13
<i>bifarius</i>	0	3
<i>bimaculatus</i>	88	262
<i>bohemicus</i>	0	2
<i>borealis</i>	10	43
<i>caliginosus</i>	1	87
<i>centralis</i>	0	2
<i>citrinus</i>	4	4
<i>cockerelli</i>	n/a	n/a
<i>crotchii</i>	0	15
<i>cryptarum</i>	17	23
<i>distinguendus</i>	n/a	n/a
<i>fervidus</i>	0	2
<i>flavidus</i>	0	1
<i>flavifrons</i>	0	3
<i>franklini</i>	n/a	n/a
<i>fraternus</i>	0	16
<i>frigidus</i>	1	3
<i>griseocollis</i>	14	128
<i>huntii</i>	2	51
<i>impatiens</i>	121	219
<i>insularis</i>	0	0
<i>jonellus</i>	0	0
<i>kirbiellus</i>	0	4
<i>kluanensis</i>	n/a	n/a
<i>melanopygus</i>	2	30
<i>mixtus</i>	0	3
<i>morrisoni</i>	1	53
<i>natvigi</i>	n/a	n/a
<i>neoboreus</i>	n/a	n/a
<i>nevadensis</i>	8	46
<i>occidentalis</i>	1	7
<i>pensylvanicus</i>	0	13

Species	# BBW records outside BBNA EOO	
	BBW vs BBNA all years	BBW vs BBNA 2010-2020
<i>perplexus</i>	1	9
<i>polaris</i>	0	1
<i>rufocinctus</i>	27	54
<i>sandersoni</i>	3	21
<i>sitkensis</i>	0	5
<i>sp.</i>	n/a	n/a
<i>suckleyi</i>	0	1
<i>sylvicola</i>	4	4
<i>ternarius</i>	11	39
<i>terricola</i>	20	34
<i>vagans</i>	5	156
<i>vagans, sandersoni or perplexus</i>	n/a	n/a
<i>vandykei</i>	0	17
<i>variabilis</i>	n/a	n/a
<i>vosnesenskii</i>	44	456
<i>vosnesenskii or caliginosus</i>	n/a	n/a
all species combined	21	131

Table 3.3. Comparison of the 10km x 10km and 100km x 100km grids that are unique to BBW as compared to BBNA all years and BBNA 2010-2020 datasets. n= number of grid cells per original uncombined dataset. “Species” includes both individual species and species groups (i.e. "sp", "vagans, sandersoni or perplexus", "vosnesenskii or caliginosus"). The first average presented is the average of all grids per species, calculated based on averages per species excluding grids with no unique records; the second average looks at the total number of grids per species, while including species with no unique grids. W = Wilcoxon signed rank test statistic.

Combined datasets for comparisons	10km x 10km grids		100km x 100km grids	
	BBNA all years (n=15,727) + BBW (n=6,169)	BBNA 2010-2020 (n=3,464) + BBW (n=6,169)	BBNA all years (n=1,434) + BBW (n=842)	BBNA 2010-2020 (n=619) + BBW (n=842)
Total # grids in combined data	19,314	8,922	1,484	1,016
Number (%) of completely unique grids from BBW	3,587 (18.57%)	5,458 (61.17%)	50 (3.37%)	398 (39.13%)
Number (%) of grids unique for at least one species from BBW	5,513 (28.54%)	5,948 (66.67%)	604 (40.70%)	764 (75.12%)
Number of species with at least one unique grid from BBW	44	44	40	44
Average number or percent $\pm$ SE unique grids over all individual species (without 0's)	275.32 $\pm$ 47.36 (20.36% $\pm$ 3.55%)	318.25 $\pm$ 52.98 (52.29% $\pm$ 3.94%)	34.48 $\pm$ 10.69 (13.72% $\pm$ 3.98%)	68.93 $\pm$ 11.14 (43.89% $\pm$ 3.51%)
Average number $\pm$ SE unique grids for all species overall (including 0's)	237.529 $\pm$ 42.939	274.569 $\pm$ 48.193	27.039 $\pm$ 8.597	59.741 $\pm$ 10.168
Statistical test result	W = 990.000, p<0.001	W = 990.000, p<0.001	W = 820.000, p<0.001	W = 990.000, p<0.001

Table 3.4. A comparison of the total number of plant genera per data set and data set comparison, and records for the same. Note: the number of plant genera include the total number of plants identified to the Genus level; when that was not possible, the next closest, higher, equivalent (e.g. family) were recorded. These numbers exclude non-plant forage visitation records (e.g. flying by, sitting on a leaf). Average and range values exclude plant genera where no records were present for each bee species.

Data evaluated	Calculation	BBNA all years	BBNA 2010-2020	BBW	BBNA all years + BBW	BBNA 2010-2020 + BBW
all bee species combined	# total plant genera	652	414	653	884	735
all bee species combined	# (%) unique plant genera from BBW	n/a	n/a	n/a	232 (26.24 %)	231 (31.56%)
all bee species combined	average # records per plant genera	127.81 ± 22.48	116.78 ± 19.72	55.05 ± 6.70	134.94 ± 19.88	114.69 ± 15.87
separate bee species	# bee species with plant genera information	46	43	43	49	46
separate bee species	# bee species with unique plant genera from BBW	n/a	n/a	n/a	42	43
separate bee species	range in # plant genera per bee species	2-312	1-228	1-330	2-449	1-391

Data evaluated	Calculation	BBNA all years	BBNA 2010-2020	BBW	BBNA all years + BBW	BBNA 2010-2020 + BBW
separate bee species	average # plant genera per bee species	82.57±10.16	48.58±7.60	109.35±12.55	133.27 ± 14.79	118.52 ±13.74
separate bee species	range in # unique plant genera from BBW	n/a	n/a	n/a	1-308	1-308
separate bee species	avg # unique plant genera from BBW	n/a	n/a	n/a	65.17 ± 8.73	78.21 ± 9.41

Table 3.5. A comparison of the total number of plant species per data set and data set comparison, and records for the same. Note: number of plant species include the total number of plants identified to the species level. When that was not possible, the next closest, higher, equivalent (e.g. Genus) were recorded. These numbers exclude non-plant forage visitation records (e.g. flying by, sitting on a leaf). Means ± SE and range values exclude plant species where no records were present for each bee species.

Data evaluated	Calculation	BBNA all years	BBNA 2010-2020	BBW	BBNA all years + BBW	BBNA 2010-2020 + BBW
all bee species combined	# total plant species	1699	920	1755	2688	2117
all bee species combined	# (%) unique plant species from BBW	n/a	n/a	n/a	991 (36.84%)	1198 (56.56%)

Data evaluated	Calculation	BBNA all years	BBNA 2010-2020	BBW	BBNA all years + BBW	BBNA 2010-2020 + BBW
all bee species combined	mean # records per plant species	137.04 ± 18.87	72.72 ± 13.03	176.07 ± 22.93	240.41 ± 30.40	202.33 ± 26.83
separate bee species	# bee species with plant species information	46	43	43	49	46
separate bee species	# bee species with unique plant species from BBW	n/a	n/a	n/a	42	43
separate bee species	range in # plant species per bee species	2-599	1-413	1-592	2-936	1-788
separate bee species	mean # plant species per bee species	137.04 ± 18.87	72.72 ± 13.03	176.07 ± 22.93	240.41 ± 30.40	202.33 ± 26.83
separate bee species	mean # unique plant species from BBW	n/a	n/a	n/a	1-558	1-558
separate bee species	mean # unique plant species from BBW	n/a	n/a	n/a	130.45 ± 17.94	143.77 ± 19.05

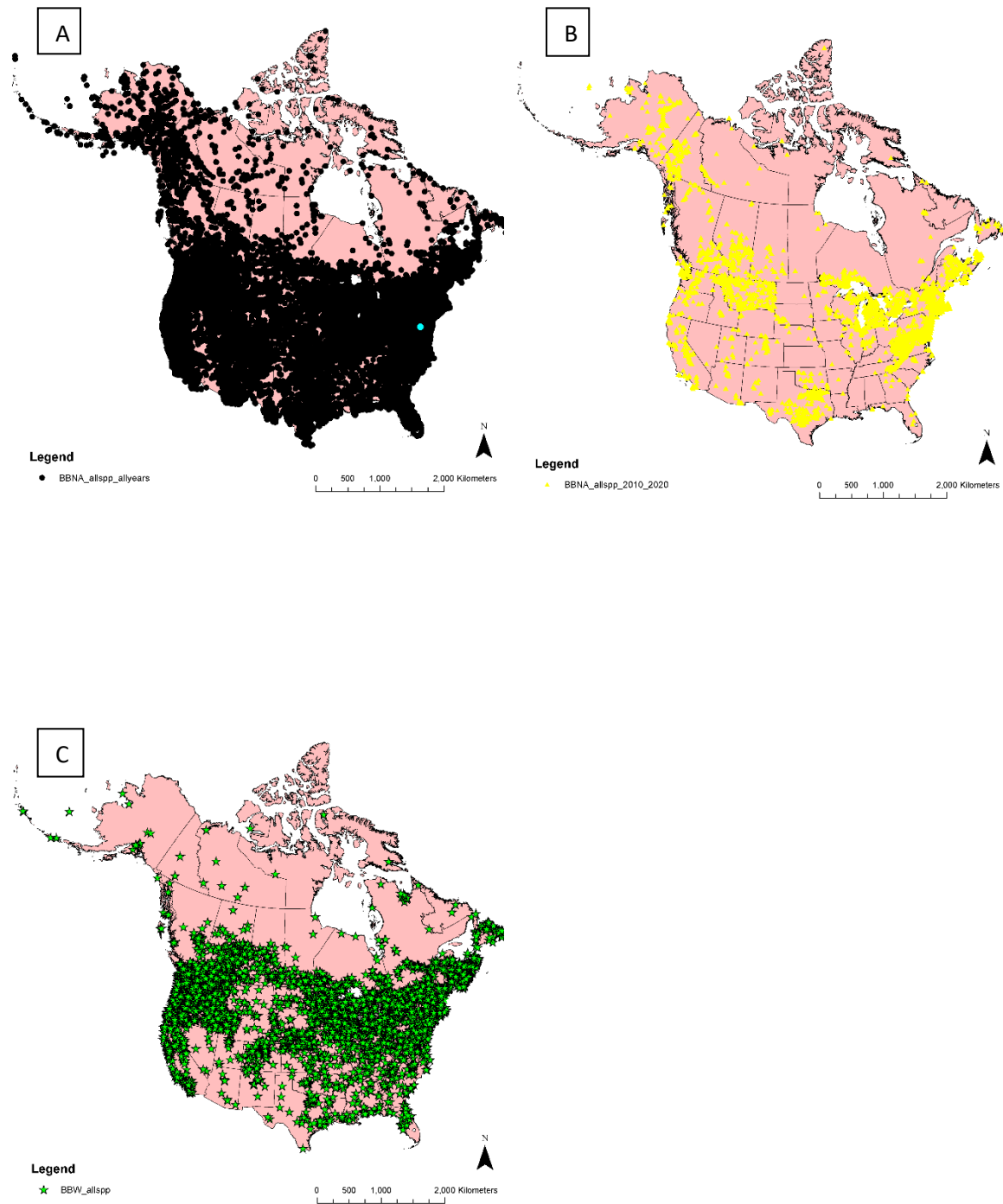


Figure 3.1. Distribution of bumble bee (*Bombus* spp.) records across North America from A) BBNA all years dataset, B) BBNA 2010-2020 dataset, and C) BBW dataset.

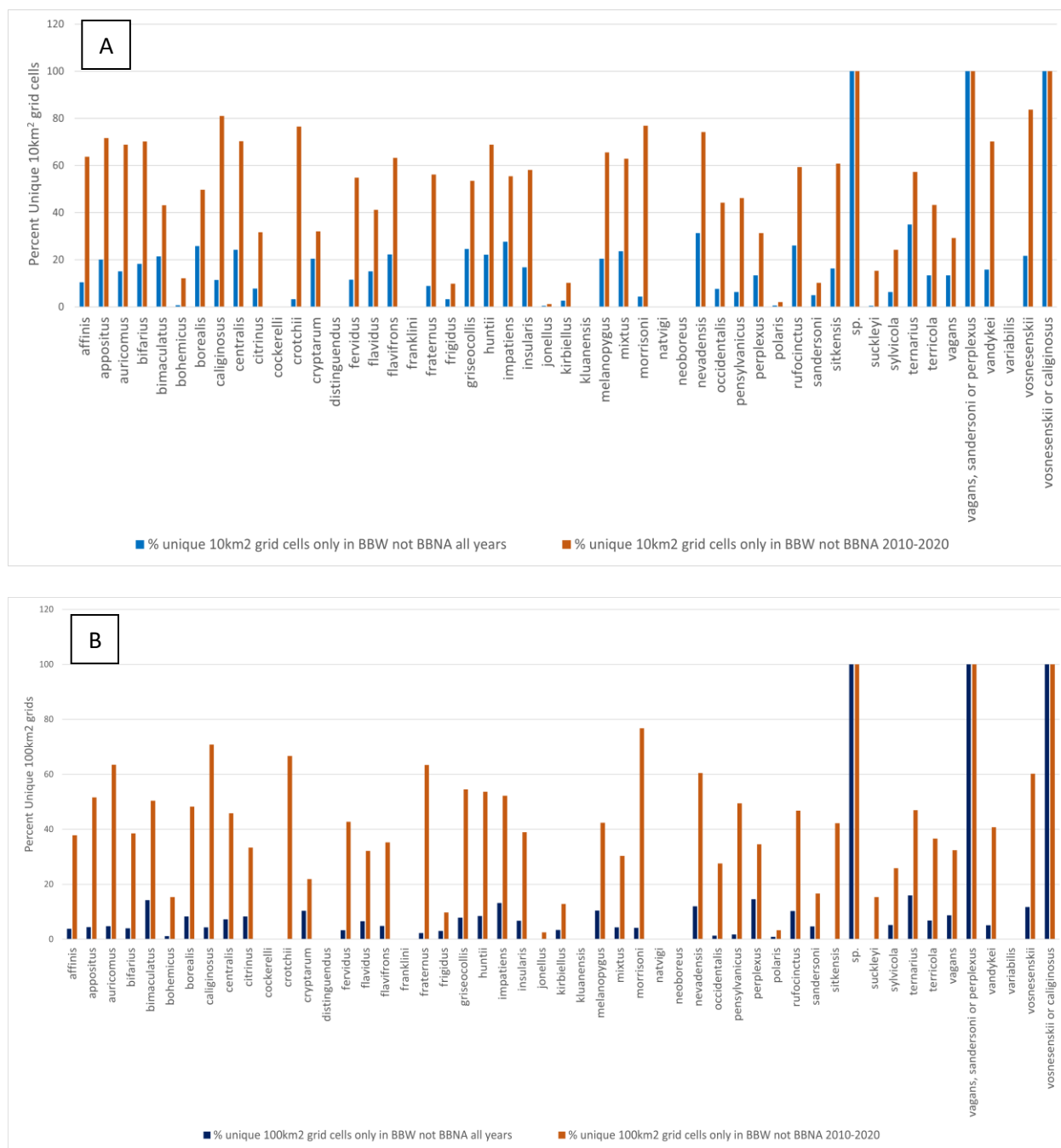


Figure 3.2. Percent unique A) 10km x 10km and B) 100km x 100km grid cells only found in BBW and not in BBNA all years (blue) or BBNA 2010-2020 (orange) datasets, per species.

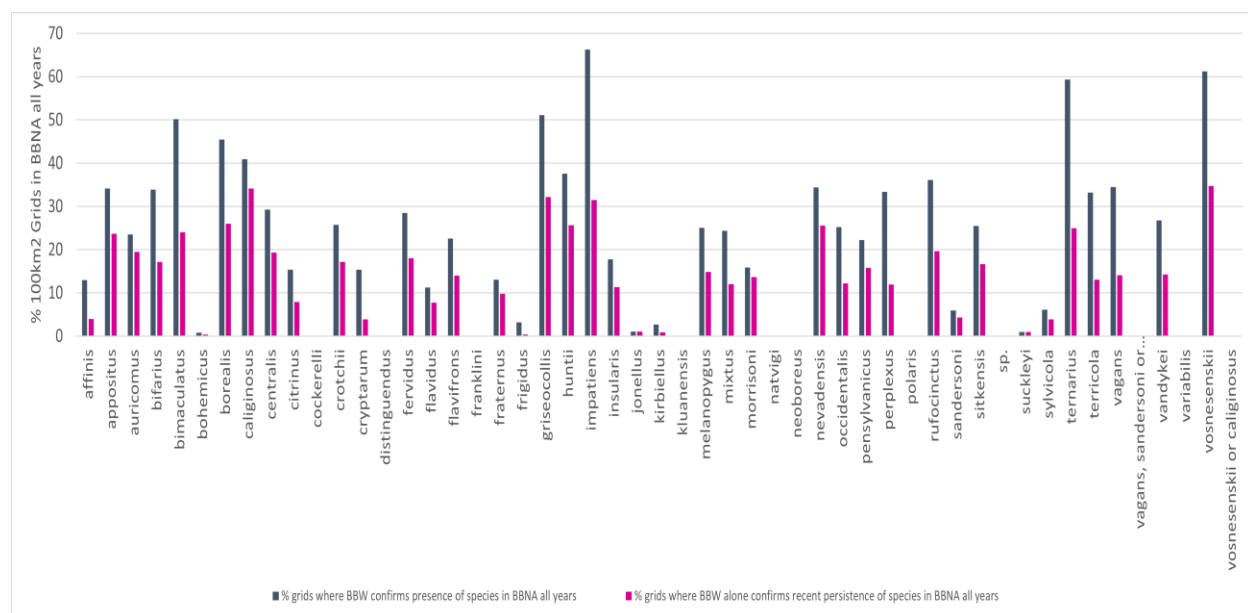


Figure 3.3. Percent of the BBNA all years occupied 100km x 100km grids where BBW shows confirmation of each species presence (dark blue bars) or unique persistence of each species in the last decade (light purple bars).

Chapter 4. Incorporating citizen science, museum specimens, and field work into the assessment of extinction risk of the American Bumble bee (*Bombus pensylvanicus* De Geer 1773) in Canada

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Abstract

Many bumble bee (*Bombus*) species are in decline and conservation efforts must be undertaken now to lessen or reverse the trend. For effective efforts to occur, the first step must be an accurate assessment of extinction risk. Yet only four of over forty Canadian *Bombus* species have been assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), despite evidence of decline for numerous species in this genus. Here, we evaluated the status of the American bumble bee, *B. pensylvanicus* De Geer 1773 in Canada.

A challenge with species assessments is obtaining adequate occurrence data temporally and spatially. Citizen science is a field where volunteers can collect data similar to that of experts over a broader coverage than researchers could often cover alone. We used data from the Bumble Bee Watch citizen science program, a database of North American *Bombus* records

representing field survey and collection records from the late-1800s, and our own field surveys to evaluate the status of *B. pensylvanicus* in Canada using the International Union for the Conservation of Nature (IUCN) Red List assessment criteria. We found that *B. pensylvanicus*' area of occurrence has decreased by 70%, its extent of occurrence by 37%, and its relative abundance by 89%, from 2007-2016 as compared to 1907-2006. These findings warrant an assessment of Critically Endangered using IUCN Red List criteria for *B. pensylvanicus* in Canada. Our findings will help inform management of *B. pensylvanicus* and exemplify the importance of citizen science programs for wildlife conservation.

Introduction

Effective conservation management of at-risk species requires the important first step of an accurate assessment of extinction risk (Rodrigues et al. 2006; Mace et al. 2008; Cardoso et al. 2011; Colla 2016). Currently in Canada, there are several federal and provincial policies considering pollinator conservation management (Parliament of Canada 2015; Ontario Ministry of Agriculture Food and Rural Affairs and Government of Ontario 2016; Agriculture and Agri-Food Canada 2017; Health Canada 2017). This is a considerable improvement since an earlier review found no real protection for pollinators in the legislation (Tang et al. 2007). In this paper, we focus on how, despite evidence of decline at various scales throughout its range and an assessment of Vulnerable by the IUCN Red List (Hatfield et al. 2015d), an assessment of extinction risk in Canada has not yet been completed for the American Bumble bee, *Bombus pensylvanicus* De Geer 1773.

Bombus pensylvanicus is widespread in eastern, central, and western US, and can be found in the several Mexican states (Williams et al. 2014). In Canada, it is known from southern Ontario and

Quebec (Williams et al. 2014); a previous record of it from Alberta as shown in Williams et al. (2014) was determined to be a misidentification (personal communication, C. Sheffield, Curator of Invertebrate Zoology, Royal Saskatchewan Museum). *Bombus p. sonorus* is found in the southwestern United States and has a lighter colour pattern than *B. pensylvanicus* in the east; the two groups appear to separate out in preliminary DNA barcoding analyses, but as there are potential intermediary groups not yet barcoded, we follow the treatment of Williams et al. (2014) by including *B. p. sonorus* as a subspecies of *B. pensylvanicus* (Williams et al. 2014).

Bombus pensylvanicus is a grassland species associated with open fields and farmlands (Colla and Dumesh 2010; Williams et al. 2014). In its Canadian range, it is a late-emerging species that tends to nest on the surface of the ground amidst long grasses, occasionally nests above ground, and only rarely nests underground (Wyatt 1970; MacFarlane 1974; Macfarlane et al. 1994; Colla and Dumesh 2010; Williams et al. 2014). This species tends to have smaller colonies (average of 33 new queens and 132 workers and males produced per colony) relative to congeners (Macfarlane et al. 1994). It is also more aggressive than those *Bombus* species that nest underground (Macfarlane et al. 1994), as has been seen in some but not all other surface-nesting *Bombus*, potentially because of the increased predation risk these nests face (Thorp et al. 1983; Macfarlane et al. 1994; Schweitzer et al. 2012). The aggression may also depend on the subgenera and location, with researchers indicating species such as *B. pensylvanicus* and others in the *Thoracobombus* subgenus being aggressive in North America but not in Britain (Cameron et al. 2001). In Ontario, queens first appear in mid to late May, with workers appearing within a month; males emerge in August and new queens emerge from late August to September, with the colonies finishing up by the end of September (Wyatt 1970; Macfarlane et al. 1994).

The Mixed-wood Plains Ecozone is contained primarily (73%) in the southern portion of Ontario, but also extends into the extreme southern portion of Quebec (ESTR Secretariat 2016). It represents approximately 8% of Ontario's landmass yet contains about 92% of its human population, which is reflected in the dense coverage (68%) of anthropogenic land uses types, particularly agricultural, in that Ecozone (Ontario Biodiversity Council 2010, 2011; Statistics Canada 2016b). While it is amongst the most species-rich regions of Canada, 73% of all Ontario species of conservation concern and 75% of its rare ecosystems are located in this Ecozone (Ontario Biodiversity Council 2010). Threats to species in this area include habitat loss, invasive alien species, human population growth, pollution, unsustainable land use, and climate change (Ontario Biodiversity Council 2010, 2011; ESTR Secretariat 2016).

Although bumble bees are known to live in patchy habitats (e.g. agricultural areas, urban areas), isolated or poor quality habitats may not be able to support bumble bee populations (Hatfield and LeBuhn 2007; Iles et al. 2018). Additional threats to bumble bees like *B. pensylvanicus* may include parasites and pathogens, such as the fungal pathogen *Nosema bombi*, including those spread from managed commercial bumble bee and honeybee colonies (Colla et al. 2006; Hoffmann et al. 2008; Otterstatter and Thomson 2008; Gillespie 2010; Cameron et al. 2011a, 2016; Szabo et al. 2012; Graystock et al. 2016). Pesticides have been and still are a threat to bees, from past use of organophosphorus and carbamate compounds (Kevan 1975; Kevan et al. 1984, 1997) to the current widespread use of systemic neonicotinoid insecticides and fungicides; neonicotinoids have been used increasingly since the 1990s with mounting evidence showing negative impacts on bumble bees, particularly sub-lethal effects (Gill et al. 2012; Szabo et al.

2012; Whitehorn et al. 2012; Godfray et al. 2014, 2015; Goulson 2015; Lundin et al. 2015; Wood and Goulson 2017).

Conservation assessments require occurrence data from all parts of a species' range, which can be a challenge for species with a large distribution. These assessments also require data coverage across time. Citizen science is a growing field that may help to increase data collection as volunteers can collect data similar or identical to that of experts, particularly as programs become more accessible through the use of the Internet and technology (websites, photos, smartphone apps, etc.) (Silvertown 2009; Conrad and Hilchey 2011; Follett and Strezov 2015). The success of the program and quality of data does depend on the complexity of information being collected and skills needed (Kremen et al. 2011).

Although most insect taxa require physical specimens to be collected in order for identifications to be made (Kremen et al. 2011), bumble bees can sometimes be identified to species by photos (van der Wal et al. 2015; Beckham and Atkinson 2017; The Xerces Society for Invertebrate Conservation et al. 2017). For example, 75% of the bumble bee observations submitted to the iNaturalist Vermont site were identified to species through photos (Mcfarland et al. 2016), and, as of January 31, 2018, 86% of all bumble bee observations that had been submitted to Bumble Bee Watch and reviewed by an expert were identified to species (those records that were assigned a tentative identification were considered to not be identified to species, and both pending and invalid submissions (those that were not actually bumble bees) were excluded from this analysis) (The Xerces Society for Invertebrate Conservation et al. 2018).

Previous work in the UK with the BeeWatch program (van der Wal et al. 2015), the Texas Bumblebees Facebook page, and the iNaturalist Bees and Wasps of Texas project (Beckham and Atkinson 2017) suggests that citizen science projects based on photo submissions of bees can capture data complementary to that collected by experts and assist in learning more about, and tracking changes to, species over time. Bumble Bee Watch is a web-based citizen science program where participants photograph bumble bees anywhere in North America, upload the photos and relevant site information to a website or through a hand held device, and work through an interactive identification key to arrive at a species name, which experts then verify (The Xerces Society for Invertebrate Conservation et al. 2017). We used this data set in conjunction with expert-collected data to aid in the assessment of conservation status for *B. pensylvanicus* in Canada using the IUCN Red List criteria.

Methods

Data Compilation

We obtained data from three sources for Ontario and Quebec, dating to the end of 2016: 1) The Bumble Bees of North America (BBNA) database; 2) Records from the Bumble Bee Watch citizen science program already verified by experts, particularly 2014-2016; and 3) Field surveys conducted by the authors dating to the early 2000s, particularly 2013-2016, excluding those records already incorporated into the BBNA database.

Bumble Bees of North America (BBNA) Database

LLR maintains a database of North American bumble bee species records assembled from numerous private, research, and other collections (see <http://www.leifrichardson.org/bbna.html>). This dataset was originally assembled to support the development and publication of the Bumble

Bees of North America (Williams et al. 2014), with new records added each year to support a variety of species status assessments (e.g. IUCN North American Red List *Bombus* Assessment (Hatfield et al. 2015d, e, c) and the United States Fish and Wildlife Service (USFWS) assessments (Defenders of Wildlife 2015; Szymanski et al. 2016)). An export was obtained from the database on May 12, 2016 for Ontario (18,986 records) and May 23, 2017 for Quebec (4,470 records); no further records for Ontario had been added between May 12, 2016 and May 23, 2017 so a newer export was not obtained.

We excluded duplicate occurrences found in the data set, as well as those found in other data sets used in the project, including some of SRC's research collections and Bumble Bee Watch data. Records with missing or incorrect geographic coordinates as determined by a visual review of the data were updated based on label data or removed. We further updated three records erroneously identified (as determined by SRC) as *B. pensylvanicus* from Grassy (Reed) Narrows (two records) and Thessalon (near Sault St. Marie) (one record) to be *Bombus* sp.

Bumble Bee Watch Data

All records submitted to the Bumble Bee Watch citizen science program that had been verified by experts to date were exported on May 12, 2017. This included 78 records from Quebec and 2,092 records for Ontario (2,170 total). Data was screened and corrected as described per the *BBNA* database.

MacPhail and Colla Field Surveys

Bumble bee surveys by the authors and colleagues were conducted at sites in southern and central Ontario and the extreme south of Quebec over the last decade (see Table B.S1 and Fig. B.S1). These included targeted surveys for known species at risk of extinction, such as at historic and extant *B. affinis* sites in 2007-2016, and known and potential *B. terricola* sites in 2014-2016, and *B. bohemicus* (= *B. ashtoni*) sites in 2016. Surveys generally took place between 7am and 7pm on precipitation-free days between 3 and 30°C from April to October, with the majority of surveys occurring during July and August. Bees were usually collected using sweep nets, identified, and released at the end of the survey period, although some were identified on the wing. Photos were also taken of some specimens for later review. Identification was based on keys in Lavery and Harder (1988) and Williams et al. (2014), as well as comparison to physical specimens in reference collections held at the University of Guelph and York University. Bumble bee data were also collected from pollinator surveys completed in 2010-2011 in Algonquin Provincial Park (Nardone 2013). Data collected by the authors previously incorporated into the BBNA database are not included in this source category.

Data Summary

After data compilation and cleaning, there were 34,221 *Bombus* records from 1907-2016 over all three data sets (Table 4.1). While the majority of *Bombus* records were from southern Ontario, southern Quebec and central Ontario also had fair representation, while the northern regions had few observations (Fig. 4.1). Despite the extensive data set and survey effort, *B. pensylvanicus* was only found from southern Ontario and extreme south-western Quebec (Fig. 4.1).

Data was limited and categorized into historic and recent time periods (Table 4.1). The 1907-2006 period was chosen to provide a one hundred year historic period (152 total *Bombus* records pre-1907 excluded, including 4 *B. pensylvanicus*), which provides an extensive baseline for comparison to modern times and evens out periods with varying levels of survey efforts. The 2007-2016 period meets the IUCN red list criterion A2 (population reduction) that required declines to have been observed over the last 10 years (IUCN 2012a; IUCN Standards and Petitions Subcommittee 2016).

Records that did not have a year associated with the observation but were known to occur pre-2007 (based on data associated with the record, such as the collector name or date the identification was determined) were included in the timeframe for analyses where possible. For example, these data were included for calculations of Extent of Occurrence and changes in relative abundance between the two main periods (as they were known to have occurred pre-2007), but not for calculations of relative abundances per decade (as they could not be assigned to a specific decade).

Limiting of all *Bombus* spp. Data to *B. pensylvanicus* Range Extent

We used ArcGIS 10.5 (ESRI 2016) to build a minimum convex polygon around the 1907-2016 Canadian observations of *B. pensylvanicus* (see Table B.S2 for a breakdown of records per data source), then clipped the full 1907-2016 *Bombus* dataset to this polygon to create a subset of the Ontario and Quebec *Bombus* observations (Fig. 4.2, Table 4.1). The resulting subset of data included 7,579 historic records and 11,895 recent records (Table 4.2), with the number of observations and relative abundance varying by decade (Table 4.3).

Analysis of Data

IUCN Criteria

We use the globally recognized, standardized, and comprehensive IUCN Red List Criteria (Rodrigues et al. 2006; Mace et al. 2008; IUCN 2012a; IUCN Standards and Petitions Subcommittee 2016) specifically their regional guidelines (IUCN 2012b) to calculate the conservation status or risk of extinction for *B. pensylvanicus*. As per the assessment process described in IUCN (2012b; 2016), each criterion (e.g. population reduction, small geographic area) was evaluated if possible, and the highest threat category (e.g. Endangered vs Vulnerable) from all of these evaluations was assigned to the species. We focused on IUCN Criterion A2, which relates to population reduction (measured over the last 10 years) observed, estimated, inferred, or suspected in the past where the causes of reduction may not have ceased or may not be understood or may not be reversible. A2b is an index of abundance appropriate to the taxon, for which we have used relative abundance relative to historic values to evaluate. A2c relates to a decline in Area of Occurrence, Extent of Occurrence, or habitat quality: we use both Area of Occurrence and Extent of Occurrence here. For each A2 category, population reduction must be $\geq 80\%$ to be Critically Endangered, $\geq 50\%$ to be Endangered, or $\geq 30\%$ to be Vulnerable.

To calculate changes in spatial distribution, we calculated the Area of Occurrence (AOO) and Extent of Occurrence (EOO) for each of the two *B. pensylvanicus* data sets as previously described (historic 1907-2006 and recent 2007-2016 periods). The EOO is measured as the area within the smallest boundary that can be drawn around the edge of all known or expected occurrences, while the AOO is a measurement of the space a species actually occupies, based on the number of 2km wide grid cells that it occupies within the EOO (IUCN 2012a). Each data set

was imported into the online GeoCAT geospatial conservation assessment tool (Bachman et al. 2011), which provided calculated values for AOO and EOO based on a minimum convex hull polygon. The GeoCat results do include portions of the Great Lakes, which are not habitat for bumble bees. The inclusion of these areas of unsuitable habitat in the calculations for EOO is encouraged by some authors (Gaston and Fuller 2009; Bachman et al. 2011) and in the GeoCAT program itself (Royal Botanic Gardens Kew 2017), which reference the discussion about the difference in EOO versus AOO (the AOO does not include any grid cells the species does not occur in so by default does not include areas of unsuitable habitat). While the IUCN indicates that either method is acceptable (IUCN 2012a), other authors, such as Hatfield et al. (2015b) indicate that these areas should be removed.

We therefore also calculated Extent of Occurrence in ArcGIS (ESRI 2016) using the minimum bounding geometry tool (with convex hull option) to calculate the area with and without the Great Lakes, to determine if the inclusion of these discontinuities or disjunctions affected the final status assessment. We found that the two ArcGIS approaches resulted in a similar final change in EOO and was also similar to the GeoCat approach (see Table B.S3). Thus, we will present results following the GeoCat approach in this paper.

Relative abundance can be used to compare data sets with unequal sample sizes, and to evaluate changes over time. To calculate changes in the relative abundance of *B. pensylvanicus* before and after 2007, the total number of *B. pensylvanicus* observations was divided by the total number of all *Bombus* observed in that period (1907-2006 and 2007-2016, and each individual decade). Linear regression was used to infer the rate of change in relative abundance over time.

Two-tailed z-tests of equal proportions were used to determine if the relative abundance differed significantly between the overall historic and recent periods, and between adjacent decades.

Microsoft Excel (Microsoft Office Professional Plus 2013) was used to calculate the relative abundances for each period, to plot the linear regression equation as calculated using SPSS (IBM SPSS Statistics ver. 24), and to plot other graphs in this chapter. SPSS was also used to calculate the z-test values.

To determine if immigration of *B. pensylvanicus* from outside of its Canadian range could occur and help lower its extinction risk (“rescue effect”(IUCN 2012b)), the ability of the species to move across the landscape must be considered. While the dispersal distances of *B. pensylvanicus* specifically and Ontario *Bombus* generally are unknown, it could be up to ten kilometers based on that of other *Bombus* species (Kraus et al. 2009; Colla 2017). Rescue must therefore be from US states adjacent to Canada and not from other parts of *B. pensylvanicus*’ North American range. However, the rescue effect also depends on how the species is doing in the adjacent areas: if it is declining there, it will not likely to be able to help rescue the Ontario and Quebec populations. We evaluated the nearest states and their NatureServe (2015) ranking of status for this section. If it is found that a rescue effect could occur, then the Red List assessment should be downlisted by one category (e.g. from critically endangered to endangered)(IUCN 2012b).

Natural History Information for *B. pennsylvanicus*

In addition to analyses related to declines, we also compiled information about *B. pennsylvanicus*' biology and natural history from this data set. This included emergence periods of each caste, flight periods, and forage plants: important information for conservation efforts.

Results

Change in Area Of Occurrence, Extent Of Occurrence

The Area of Occurrence for *B. pennsylvanicus* declined by over 204km² or 70% of its previous range (Table 4.4), and the Extent of Occurrence for *B. pennsylvanicus* declined by over 38,000 km² or about 37% of its previous range (Fig. 4.3, Table 4.4), between the historic 1907-2006 and recent 2007-2016 periods.

Relative Abundance

A statistically significant decline of over 89% in *B. pennsylvanicus* relative abundance within its Canadian range occurred between the historic (1907-2006) and recent (2007-2016) periods (Fig. 4.4, Table 4.5) ($Z = 17.215$; $p < 0.0001$). There was not a significant decline trend over the entire time period ($R^2 = 0.197$, $p = 0.172$)(Fig. 4.5). However, there were increases and decreases in relative abundance per decade overtime (Fig. 4.5). Indeed, there were significant differences in four pairs of decades: 1917 vs 1927 ($Z = 2.570$, $p = 0.001$), 1927 vs 1937 ($Z = 4.026$; $p < 0.0001$), 1947 vs 1957 ($Z = 2.462$; $p = 0.014$), and 1977 vs 1987 ($Z = 3.378$; $p = 0.001$)(see results for each set of decade comparisons in Table B.S4).

Rescue Effort

The nearest states to the Canadian range of *B. pensylvanicus*, and their NatureServe (2015) subnational (S-rank) status rankings are: Maine (SH - possibly extirpated (historical)), Vermont (S1 – critically imperiled), New York (S1 – critically imperiled), Pennsylvania (SNR – not ranked), Ohio (no NatureServe listing), Michigan (SNR – not ranked). *Bombus pensylvanicus* is therefore considered to be in severe declines (extirpated or critically imperiled) in all of the adjacent states that have been ranked. It is possible that the unranked (SNR) populations are also at risk as a query of the BBNA database for the adjacent states shows only 13 recent observations (since 2006) of *B. pensylvanicus* (personal communication, L. Richardson, Gund Institute for Environment, University of Vermont). As well, a recent continent-level status assessment for NatureServe found that *B. pensylvanicus* has been downgraded to G3 (personal communication, L. Richardson, Gund Institute for Environment, University of Vermont) from G3G4 (NatureServe 2015). The overall rescue effect from the United States is therefore believed to be limited, and thus no adjustment to the calculated IUCN Red List regional assessment needs to be made (i.e. no uplisting or downlisting of categories).

Application of IUCN Criteria

By applying the IUCN Red List Regional Guidelines to our assessment of this species, we find that it merits a status of Critically Endangered A2b due to a decline in relative abundance of over 80% (Table 4.6). Criteria A2c alone would merit a status of Vulnerable with a decline of over 30% in range size for EOO or Endangered for over 50% in range size for AOO (Table 4.6). While A2e also applies due to the suspected influence of introduced parasites and pathogens, including from commercial bumble bee colonies and honeybee colonies (Colla et al. 2006;

Otterstatter and Thomson 2008; Cameron et al. 2011b, 2016; Szabo et al. 2012; Graystock et al. 2016), this was not able to be quantified for the purposes of this study.

Other criteria were not applied as they were not relevant. For example, criterion B, C, and D were not relevant to *B. pensylvanicus* as the species has too great an EOO, population size, and number of locations, and E was not relevant as the criteria requires a 50% probability of extinction in the wild in the next 10 years, which is unlikely to happen based on current population size and trend.

Natural History Information

The earliest spring record of *B. pensylvanicus* was May 15 and the latest record was October 5, with the most records reported in August (avg 1.1 bees per month $\pm$ 0.34 SE) (Fig. BS2). Unsurprisingly, workers were the most common caste recorded (56% of records), followed by queens and males (Table B.S5). Queens begin to emerge in May and can be found through October (Fig. B.S3). Workers emerge in June and males begin to emerge in July, with both still being found through October (Fig. B.S3).

Very few records (9.2% or 32 of 329) actually had information about what plant the bee was collected off of so it is difficult to make any declarations about preferred host plants. The forage plant was only recorded for 31 observations, while 1 bee record was noted as flying by.

Although the most commonly visited species was *Vicia cracca* (cow vetch), this may be a site-specific finding as 19 of the 22 observations were from same the site.

Discussion

Many bumble bee species are currently in decline and conservation efforts must be undertaken now to lessen or reverse the trend. For effective efforts to take place, the first step must be an accurate assessment of extinction risk. *Bombus pensylvanicus* is just one species that has not yet been assessed by provincial or federal governments in Canada yet we found it to be Critically Endangered using the IUCN criteria. A global risk assessment (Hatfield et al. 2015d) for *Bombus pensylvanicus* previously found it be Vulnerable, according to the IUCN Red List criteria A2be based on a >30% reduction in population using relative abundance and persistence measurements, as well as a decrease in range and with the documented threat of pathogens. Hatfield et al. (2015d) had actually calculated a 51% reduction, which leads to an Endangered listing, but downlisted their assessment as they believed a Vulnerable listing was more representative of the true decline of the species. However, with *B. pensylvanicus*' smaller range in Canada, the rapid declines seen in other Canadian bumble bee species (e.g. *B. affinis* and *B. bohemicus*)(COSEWIC 2010, 2014a; Environment and Climate Change Canada 2016; Colla 2017), the knowledge that bumble bees at northern latitudes tend to have smaller colonies (Yalden 1982; Donovan and Wier 1984; Williams 1988; Macfarlane et al. 1994) and with climate change shown to be limiting rather than allowing a northward range expansion or elevational shift by bumble bees (Kerr et al. 2015; Pyke et al. 2016), a more protective stance needs to be taken here in order to prevent extirpation.

Our study was the first to combine citizen science data with expert-collected and historic data to examine the status of a bumble bee species across its Canadian range. The data from Bumble Bee Watch was particularly valuable as it represented 20% of the recent (2007-2016) records of

B. pensylvanicus (10/50 records) and 36% of the recent *B. pensylvanicus* locations (8/22 sites).

The inclusion of these data led to a better understanding of the species status, as the change in EOO between historic and recent times was found to be -37.12% with the data as compared to -53.65% without, and the decline in RA 88.6% with the data (and a 57% increase in sample size) as compared to an 89.2% decline in RA (and a 32% increase in sample size) without, again between historic and recent time periods. Considering the program did not start until 2014, and the Canadian range of *B. pensylvanicus* occurs in the most densely populated area of Canada and thus an area of many potential participants, there is a strong potential for an increase in records and locations to be found in the future. However, more records of other species will also be submitted, potentially keeping the relative abundance trends the same. As the species is likely already at the northern edge of its North American range, its range to the west in Ontario is interrupted at Lake Huron, and the south is at the Canada-US border, the extent of occurrence for its Canadian range is not likely to change drastically. An additional benefit of this program will be an increase in information about *B. pensylvanicus*' natural history, from activity times to forage plants being visited.

It is not yet clear why *B. pensylvanicus* is declining. It is suspected that different factors and interaction effects are involved: pesticides, habitat loss, climate change, parasites, diseases, non-native species, and low genetic diversity and effective population sizes may all play a role (Zayed and Packer 2005; Colla et al. 2006; Colla and Packer 2008; Hoffmann et al. 2008; Cameron et al. 2011b; Szabo et al. 2012; Burkle et al. 2013; Goulson et al. 2015; Hatfield et al. 2015d; Kerr et al. 2015; Pyke et al. 2016; Colla and MacIvor 2017). Indeed, these factors may effect species and populations differently or have synergistic or antagonistic effects.

Additionally, bumble bees with more specialized or narrower niches, as well as those at the edges of their ranges (thus including *B. pensylvanicus*), may be more vulnerable to decline than others (Williams et al. 2007; Arbetman et al. 2017), even without the stressor of climate change that is already causing bumble bee species ranges to contract from the south, not expand to the north, and to not shift in elevation (Kerr et al. 2015; Pyke et al. 2016). While it is not clear if this is the reason for the decline in *B. pensylvanicus* (particularly considering the fact that it's declining even in historically strong and central parts of its range), it does mean that conservation efforts must focus on supporting current populations and not anticipating immigration from the south.

Not all bumble bee species are declining in Canada and globally, and there are trends to suggest that certain phylogenies may be more susceptible than others (Arbetman et al. 2017). Globally, the *Thoracobombus* subgenus of bumble bees has been shown to have more species in decline than other subgenera (Arbetman et al. 2017). *Bombus pensylvanicus* is a member of the *Thoracobombus* subgenus, which also includes *B. fervidus* (Williams et al. 2014), another grassland species shown to be Vulnerable across its range in North America (Hatfield et al. 2015c) but not yet assessed in Canada (Hatfield et al. 2015c). In Canada, the *Bombus* subgenus has been noted to be strongly in decline. Currently four bumble bee species have been assessed by the Committee on the Status of Wildlife in Canada, and all have been found to be at risk of extinction. Three of these species, *B. affinis*, *B. occidentalis*, and *B. terricola*, are all from the *Bombus* subgenus (Williams et al. 2014), while the fourth species, *B. bohemicus* (from the *Psithyrus* subgenus) is a parasite of bees of that subgenus (COSEWIC 2010, 2014b, a, 2015).

This suggests that there are differences in the evolutionary history of bumble bees that are making some more vulnerable to stressors than others (Arbetman et al. 2017).

In Illinois, Lozier and Cameron (2009) found that *B. pensylvanicus* had lower genetic diversity than *B. impatiens*, as was found in later broader studies (Cameron et al. 2011b; Lozier et al. 2011). However, when a restriction site-associated DNA sequencing (RADseq) technique was used as compared to the previous microsatellite-based analyses, Lozier (2014) found little difference between these two species. Bees are known to experience rapid loss of diversity with a resulting increased risk of extinction with decreased population size and inbreeding due to the haplodiploidy system of sex determination Hymenoptera have (Zayed and Packer 2005). Thus their populations can crash quickly, and action must be taken sooner rather than later to recover them.

Cameron et al. (2011b) and Gillespie (2010) found that declining species of bumble bees, including *B. pensylvanicus*, had higher levels of the parasite *Nosema bombi* than stable species, although interestingly, Arbetman et al. (2017) found the opposite, that common species were more likely to carry parasite loads than declining ones. Gillespie (2010) found that there was no significant difference in conopid parasitism between rare species like *B. pensylvanicus* and common species, although there were significantly lower *Crithidia* parasitic infections in the rare species. It is possible that spill-over of *Nosema* from managed bumble bee pollinators in greenhouses to wild populations (Colla et al. 2006; Otterstatter and Thomson 2008) is causing declines, as the decline in *B. pensylvanicus* was correlated with high densities of vegetable greenhouses (Szabo et al. 2012). However, Gillespie (2010) noted that sites over three

kilometers from any potential managed bumble bee colony still showed high *Crithidia* and *Nosema* infection levels. A study in Southern Ontario and Quebec by Cheryomina (personal communication, M. Cheryomina (unpublished draft MSc thesis), York University) found no *Nosema* infection in six uncommon species, including *B. pensylvanicus*, while it was present in five common species; similarly, she found no tracheal mites in the uncommon species and only one individual of a declining species with conopid fly parasitism. It is possible that Cheryomina's and Gillespie's results were influenced by small sample size, with each study having less than ten individuals of each the uncommon species sampled (including *B. pensylvanicus*) found as compared to the range of 5-379 (Cheryomina) and 7-557 (Gillespie) individuals of each species investigated overall. It is also possible that common species have more resistance or tolerance to these parasites, thus carrying them while still foraging, while declining species may not survive the infection and thus infected workers would not be found (Arbetman et al. 2017). Therefore the connection between infection and species decline is still uncertain.

As *B. pensylvanicus* is a grassland species, the extensive loss of grasslands in Ontario may be one reason why this species is in decline (Colla and Dumesht 2010; Ontario Biodiversity Council 2010, 2011; Hatfield et al. 2015d). A visual assessment using Google Maps and Google Streetview (Google 2018) of the habitat around the recent sites documented in this study found that 73% were located in, or within 500m of, a grassland/old field area (including 1 pasture site), with an additional 18% of sites in, or within 200m of, a large city park and/or a large riparian area. The remaining 10% of sites were either in an intense agricultural area (1 site) or urban area (1 site), with the latter just over 600m from a riparian area. *Bombus pensylvanicus* was reported

to use many anthropogenic sites (e.g. edge of agricultural fields, sheds, lofts) when it was more common (MacFarlane 1974; Macfarlane et al. 1994), which suggests the lack of natural sites currently may not be a limiting factor, but this study suggests that the current Canadian populations seem to prefer open un-mowed areas.

In addition to general habitat needs, such as for nesting, sufficient foraging resources are critical for bumble bee species (Colla and Packer 2008; Potts et al. 2010; Burkle et al. 2013; Goulson et al. 2015; Colla 2016). Climate change can cause changes in phenology, or reduce the number of flowers or amount of flower provisions, in addition to effects of extreme weather events on plants and pollinators (Inouye 2008; Bartomeus et al. 2011; Kjohl et al. 2011; Goulson et al. 2015; Miller-Struttmann et al. 2015; Pyke et al. 2016). The loss of forage plants, particularly for specialist species, may result in a decline of the pollinator species (León-Cortés et al. 1999; Johnson and Steiner 2000; Memmott et al. 2007; Burkle et al. 2013). As a generalist species that has been known to feed on over 200 plant species (MacFarlane 1974; Colla and Dumes 2010; Williams et al. 2014), *B. pensylvanicus* could be thought resilient to the loss of some plant species, as a result of disturbances such as habitat loss or climate change. However, although *B. pensylvanicus* was the bee species with the most observed unique plant species interactions in an Illinois study in the late 1800s, it was only observed on one plant species a century later at the same area, despite an extensive survey effort and with many of the same plants being in existence (Burkle et al. 2013). In our study, we only had information on plant forage for 31 *B. pensylvanicus* observations, but 71% of those were on *Vicia cracca*, a non-native species; interestingly, another recent study in southern Ontario found that at-risk *Bombus*, including *B. pensylvanicus*, showed a preference for this species rather than native species in the same area as

more common *Bombus* did, presenting an interesting conservation dilemma relating to planting of non-native species (Gibson et al. 2019). More information about its plant preferences and nest sites will be important to gather to aid in conservation efforts.

Neonicotinoid pesticides are a class of pesticides that have increasingly been flagged as an area of concern in relationship to pollinator health, including bumble bees (although there is still debate as to their role in declines) (Gill et al. 2012; Szabo et al. 2012; Whitehorn et al. 2012; Godfray et al. 2014, 2015; Goulson 2015; Lundin et al. 2015; Wood and Goulson 2017). They have been used in Ontario since the 1990s in the agricultural industry in particular, with as much as 99% of all corn and 60% of all soybean seeds, representing about 4.9 million acres total, being treated with them annually (Government of Ontario 2014), although a regulation was introduced to try and limit the amount of crops treated starting in 2016 (Ontario Ministry of Agriculture Food and Rural Affairs and Government of Ontario 2016). The area of the province these crops are grown in highest concentration includes the main region of *B. pensylvanicus*' range (Agricorp 2016a, b).

Declines in populations of this species have been noted in other studies as well. For example, Giles and Ascher (2006) surveyed more than 1,200 *Bombus* in the Black Rock Forest of New York and found no *B. pensylvanicus*, while Grixti et al. (2009) found that its range had decreased in Illinois and only represented 4.4% of all recent observations compared to 28.1% historically. Cameron et al. (Cameron et al. 2011b) did not find it across its' historical northern and eastern range in the United States, estimating a 23% reduction. Bartomeus et al. (2013) also found it to be in significant decline in the northeastern United States, and Richardson et al. (2019) found it

to be in decline in Vermont. It was classified as data deficient in a recent 150 year evaluation of *Bombus* in New Hampshire as there were not enough recent records to be assessed (Jacobson et al. 2018). Colla and Packer (2008) intensively re-surveyed two areas of Ontario in 2004-2006 previously surveyed in 1971-1973, and found no *B. pensylvanicus* out of 1,195 *Bombus* specimens, despite the species previous abundance. Indeed when they expanded their analyses to all of Canada and the United States, Colla et al. (2012b) found *B. pensylvanicus* was still present in only 34% of historically occupied and re-sampled 50km x 50km grid cells. However, relative abundances do vary by site; for example, Macfarlane (1974) found values of 0%, 2.9%, 14%, and 19.9% for sites and regions in southern Ontario.

There are concerns with using relative abundance as a calculation to evaluate changes in populations, as it assumes the denominator (all *Bombus* spp.) does not change over time; i.e. only the species (*B. pensylvanicus*) being investigated should be changing (Bartomeus et al. 2013; Jacobson et al. 2018). However, we know with *Bombus* spp. in North America that this is not true, as some species like *B. impatiens* have actually increased over time, which would make everything else “rarer” compared to it, while other species, like *B. affinis*, have also decreased, further complicating the comparison (Colla and Packer 2008; Cameron et al. 2011b; Colla et al. 2012b; Jacobson et al. 2018). However, other approaches (e.g. using species richness or presence/absence data, comparing to stable species, modeling with all species weighted equally vs by percent or by number of individuals, standardizing survey effort, etc.) also have concerns, and relative abundance is still widely used by many authors (Cameron et al. 2011b; Colla et al. 2012b; Bartomeus et al. 2013; Jacobson et al. 2018).

Survey effort may also impact analyses. Area of Occurrence estimates, particularly at the IUCN recommended 2km cell width, can be underestimated if cells exist where sampling has not occurred but the species exists (Royal Botanic Gardens Kew 2017); as *B. pensylvanicus*' range may cover grid squares where no surveys have (re-)occurred, we also used additional methods of determining status.

Relative abundance is a method that can help account for unequal sample sizes, but low search effort or biased surveys may cause differences in results. In this study, the decades beginning in 1927 and 1937 were unusual ones for relative abundance, as the value for the 1927 decade was much lower than the previous one beginning in 1917, before an extreme jump in relative abundance occurred for the next decade starting in 1937. However, the number of unique survey events and average number of bees collected per survey event do not show similar trends (Figs. B.S4, B.S5). The number of survey events decreased over the first part of the century, from the 1907-1916 period to the 1937-1946 period (potentially relating to impacts from the two World Wars and the Great Depression), before rising each decade until 1987-1996 where there was a smaller drop, followed by a reversal in the 1997-2006 period and then drastic jump in the 2007-2016 period (Fig. B.S4). The average number of bees per survey event varied little on a per decade basis in the first $\frac{3}{4}$ of the century before dipping in the 1977-1986 period and then increasing linearly through the 2007-2016 period (Fig. B.S5). While the Bumble Bee Watch citizen science program greatly increased the number of total unique events in 2007-2016 as compared to prior decades, and lowered the average number of bees collected per survey event compared to that from the other data sources in the 2007-2016 period (Fig. B.S6, B.S7), this variation in effort is unlikely to have affected our analyses.

Regardless of the method used and variation in survey effort, the overall trend over time and comparison of the historic as compared to the recent data (particularly EOO and relative abundance) show that there has been declines in *B. pensylvanicus* that are cause for concern.

Additionally, this study focused on *B. pensylvanicus* in Canada, which is an arbitrarily delimited political area. Calculations using data from this region has value particularly for national conservation efforts and assessments. It is possible that the addition of observations from adjacent areas in the United States may change these results. As indicated above, this species has shown to be in decline over its entire geographic range and in studies evaluating its current status. However, further research in the adjacent areas, such as those that do not currently have a Nature Serve ranking (2015), should be conducted to investigate this angle.

As is clear from above, further research into *B. pensylvanicus*' biology and threats is required as there is much not yet known. While broad conservation actions for the recovery of bumble bees in general have been suggested (see e.g. Cameron et al. (2011b) for the final report of the 2010 North American Bumble Bee Species Conservation Planning Workshop, and the Ontario *Bombus* recovery strategies (Environment and Climate Change Canada 2016; Colla 2017)), specific needs for this species still need to be identified (Hatfield et al. 2015d).

Bombus affinis Cresson 1863 co-occurs with *B. pensylvanicus* in southern Ontario, and was listed as Endangered federally and provincially in 2010 (Committee on the Status of Species at Risk in Ontario 2010; COSEWIC 2010; Queen's Printer for Ontario 2016). However, no individuals have been observed throughout its Canadian range since 2009 (Colla and Taylor-

Pindar 2011; Government of Ontario 2017) indicating the listing and subsequent protection may have occurred at a date too late to conserve this species from extirpation in Canada. It is imperative that the status of *B. pensylvanicus* in Canada is determined in order to begin conservation management strategies to avoid the regional extirpation of this species.

Extreme declines in relative abundance and moderate declines in Extent of Occurrence were seen for *Bombus pensylvanicus* in its Canadian range, meriting it a suggested IUCN rank of Critically Endangered. Citizen science data provided valuable coverage and can be used in assessments of other species, particularly in conjunction with historic museum specimens and researcher-led field work. Promotion of citizen science programs should therefore occur in order to increase the number of submissions, our knowledge of species, and an interest by the public through government agencies in conserving them. Data from this study can be used to support provincial and federal assessments, encourage habitat restoration and management efforts, effect policy related to commercial pollinators, and guide further research.

Tables and Figures

Table 4.1. A comparison of the number of records of all *Bombus* spp. in Ontario and Quebec, all *Bombus* spp. found within the range of *B. pensylvanicus* in Ontario and Quebec, and all *B. pensylvanicus* found in Ontario and Quebec in each of three data sets sourced for the period 1907-2016. BBNA is the Bumble Bees of North America database maintained by LRR.

Data source	# of all <i>Bombus</i> spp. 1907-2016		# of <i>B. pensylvanicus</i> 1907-2016
	All ON, QC	<i>B. pensylvanicus</i> range only	All ON, QC
BBNA	20,182	9,949	287
Bumble Bee Watch	2,234	1,867	10
MacPhail and Colla	11,805	7,658	32
Total	34,221	19,474	329

Table 4.2. A comparison of the number of observations of all *Bombus* spp. (including *B. pensylvanicus*) and all *B. pensylvanicus* within the known range of *B. pensylvanicus* in Ontario and Quebec between historic (1907-2006) and recent (2007-2016) periods.

Period	# <i>Bombus</i> spp.	# <i>B. pensylvanicus</i>
Historic (1907-2006)	7,579	279
Recent (2007-2016)	11,895	50
Total	19,474	329

Table 4.3. A comparison by decade of the number of observations of all *Bombus*, all *B. pensylvanicus*, and the relative percent abundance of *B. pensylvanicus*, within the range of *B. pensylvanicus* in Ontario and Quebec. Data with no recorded year but that were known to have been recorded pre-2007 (based on data associated with the record, such as the collector name or date the identification was determined) are included in a separate row in the table.

Decade	# <i>Bombus</i>	# <i>B. pensylvanicus</i>	Relative Abundance <i>B. pensylvanicus</i> (%)
1907-1916	368	11	2.99
1917-1926	370	20	5.41
1927-1936	158	1	0.63
1937-1946	65	8	12.31
1947-1956	428	28	6.54
1957-1966	585	19	3.25
1967-1976	694	26	3.75
1977-1986	659	23	3.49
1987-1996	766	7	0.91
1997-2006	1,987	12	0.60
2007-2016	11,895	50	0.42
Total Records With Known Years	17,975	205	1.14
Unknown Years (But Pre-2007)	1,499	124	not valid comparison
Total Records All Years	19,474	329	1.69

Table 4.4. A comparison of the Area of Occurrence (AOO) and Extent of Occurrence (EOO) for *B. pensylvanicus* from historic (1907-2006) to recent (2007-2016) periods in Ontario and Quebec.

	Historic, 1907-2006 (279 records) (km²)	Recent, 2007-2016 (50 records) (km²)	Change between Historic and Recent periods (km²)	Change between Historic and Recent periods (%)	Amount of Historic range still occupied (%)
AOO	292	88	-204	-69.86	30.14
EOO	103,084.97	64,821.53	-38,263.45	-37.12	62.88

Table 4.5. Relative percent abundance of *B. pensylvanicus* as compared to all *Bombus* spp. recorded in its range across Ontario and Quebec in historic (1907-2006) as compared to recent (2007-2016) periods. A decline of over 89% was seen.

Period	# <i>Bombus</i>	# <i>B. pensylvanicus</i>	Relative percent abundance <i>B. pensylvanicus</i> to all <i>Bombus</i> spp.
Historic (1907-2006)	7,579	279	3.68
Recent (2007-2016)	11,895	50	0.42
Change Between Periods			-3.26
Change in <i>B. pensylvanicus</i> relative abundance Between Periods			-88.58

Table 4.6. Application of the relevant IUCN Red List Criteria to *Bombus pensylvanicus* in its Canadian range for the period 2007-2016 as compared to 1907-2006. A discussion of the criteria and assessment levels can be found in the text.

IUCN Criterion	Current Status Relative to Historic	Decrease Relative to Historic	IUCN Assessment
A2b Relative abundance relative to historic values	11.45%	88.58%	>80% decline = Critically Endangered
A2c Range size relative to historic range based on EOO	62.88%	37.12%	>30% decline = Vulnerable
A2c Range size relative to historic range based on AOO	30.14%	69.86%	>50% decline = Endangered

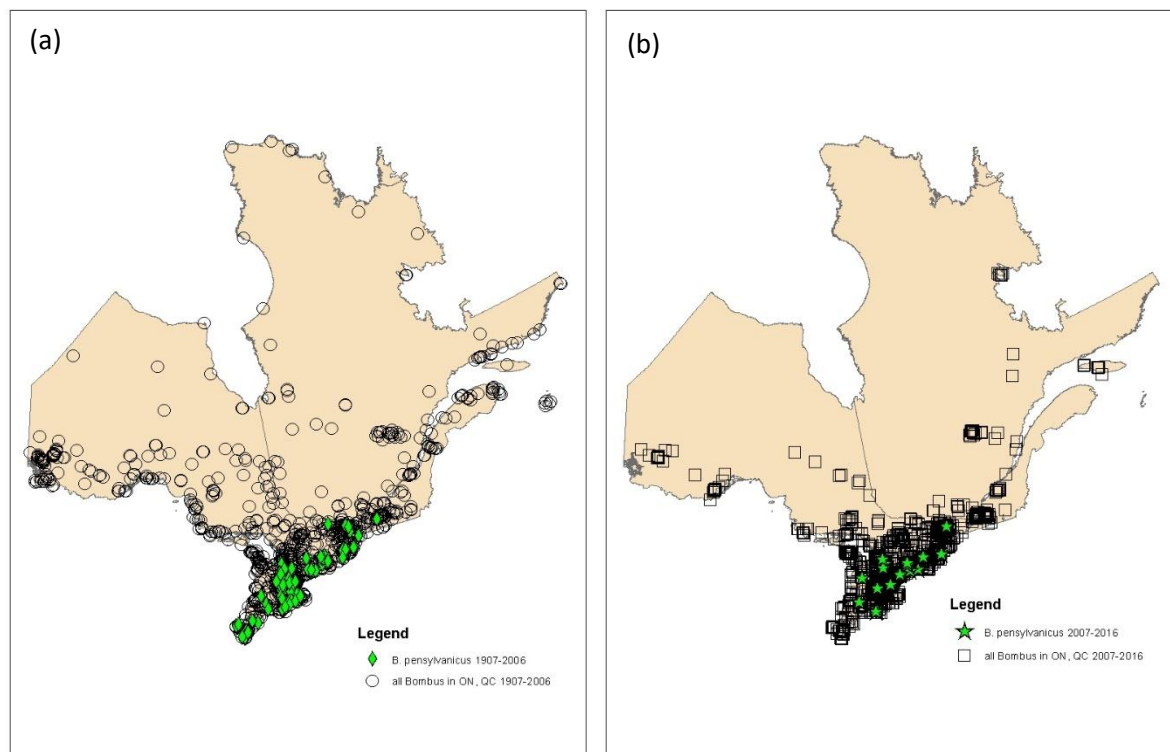


Figure 4.1. All *Bombus* observations in (a) historic (1907-2006) and (b) recent (2007-2016) period in Ontario and Quebec, based on the three data sources as described in the text (BBNA database, Bumble Bee Watch citizen science program, MacPhail and Colla surveys).

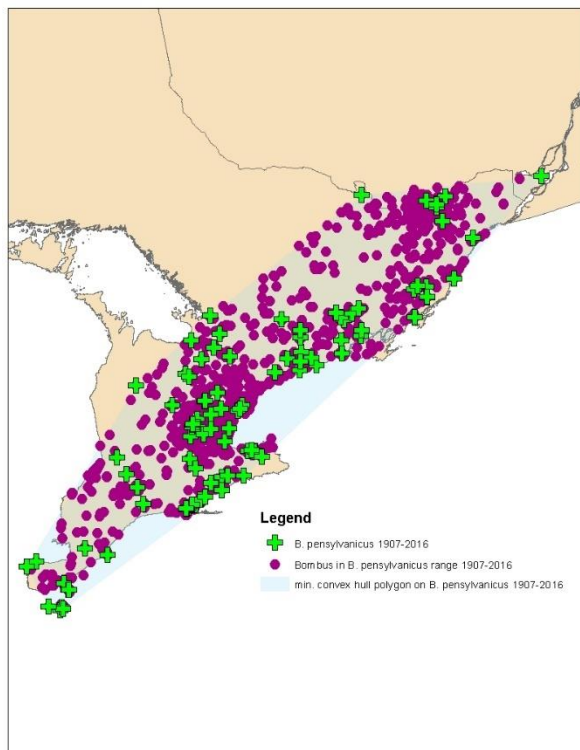


Figure 4.2. All *Bombus* spp. and *B. pensylvanicus* records observed in historic (1907-2006) and recent (2007-2016) periods in Ontario and Quebec, with all *Bombus* spp. records (1907-2016) as limited by a minimum convex hull polygon over all *B. pensylvanicus* observations (1907-2016).

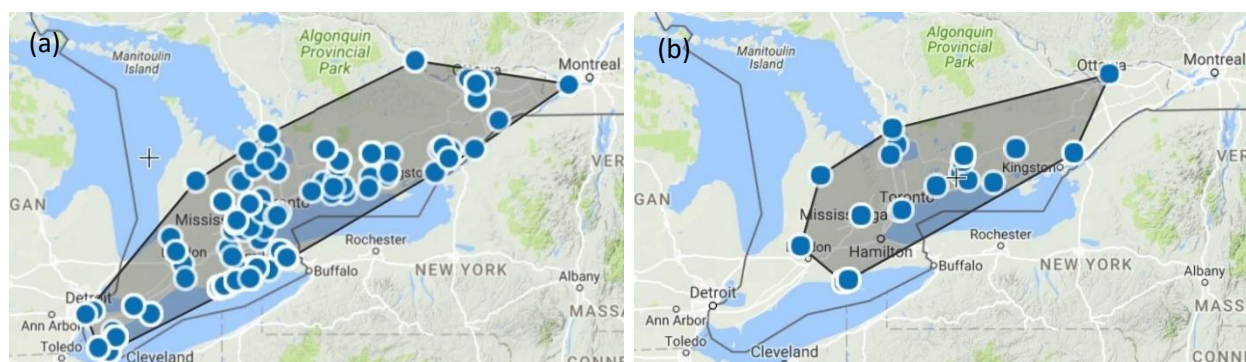


Figure 4.3. Extent of Occurrence (EOO) maps for *B. pensylvanicus* showing an over 37% reduction in EOO from (a) historic (1907-2006) to (b) recent (2007-2016) periods in Ontario and Quebec.

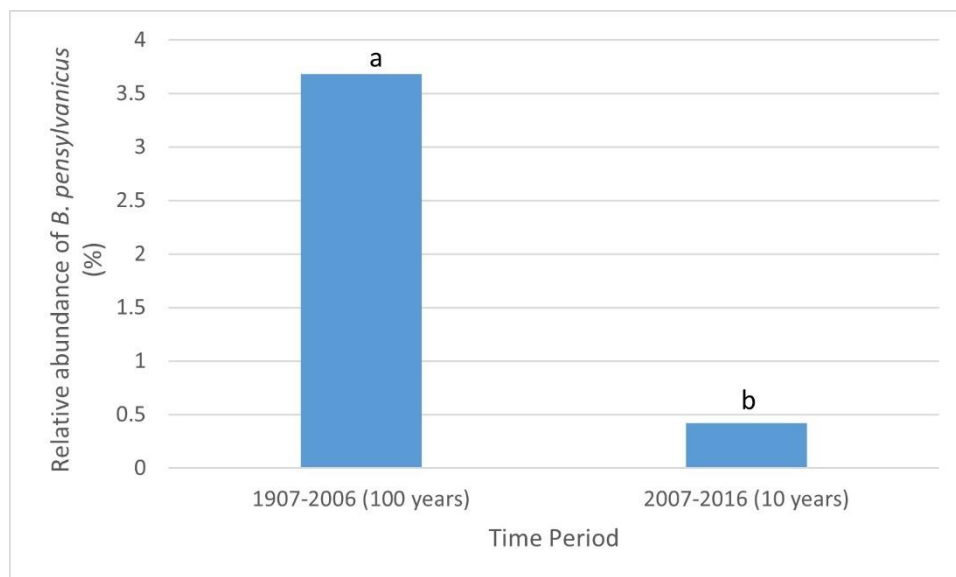


Figure 4.4. A comparison of the mean relative percent abundance of *B. pensylvanicus* as compared to all *Bombus* spp. recorded in its range across Ontario and Quebec in historic (1907-2006; n= 7,579) and recent (2007-2016; n= 11,895) periods (total n=19,474). There were significantly fewer *B. pensylvanicus* relative to all *Bombus* spp. in the recent period as compared to the historic period (z-value 17.2145 p-value < 0.0001). Different letters above the bars indicate significant differences.

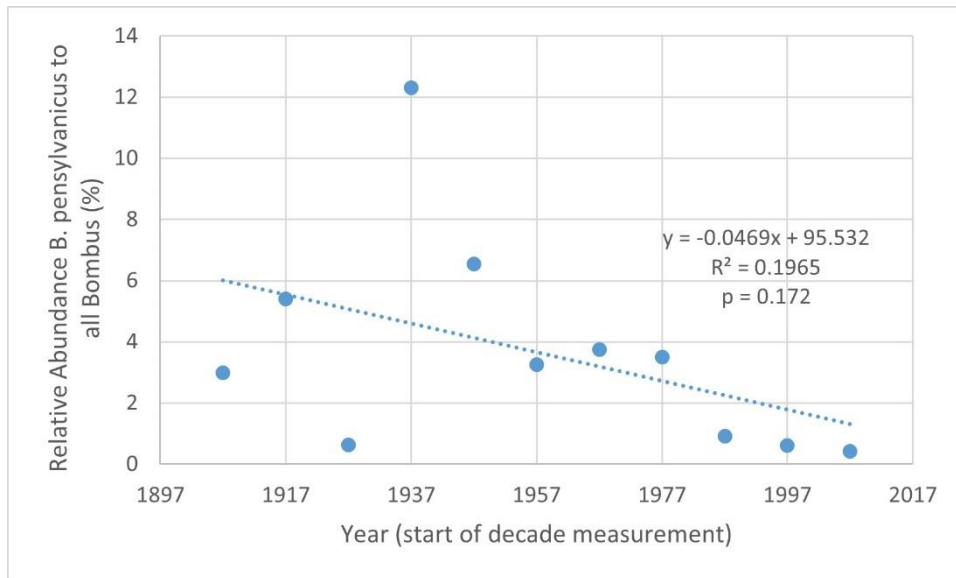


Figure 4.5. Relative percent abundance of *B. pennsylvanicus* as compared to all *Bombus* spp. recorded in its range across Ontario and Quebec, by decade, from 1907-2016 (n=19,474).

Chapter 5. Using Bumble Bee Watch to investigate the accuracy and perception of bumble bee (*Bombus* spp.) identification by community scientists

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*Accuracy of Initial Identification of Bumble Bees (*Bombus* spp.) to the Species-level by Citizen Scientists on Bumble Bee Watch. PeerJ, PeerJ 8:e9412 DOI 10.7717/peerj.9412*

Abstract

Community science programs provide an opportunity to gather scientific data to inform conservation policy and management. This study examines the accuracy of community science identifications submitted to the North American Bumble Bee Watch program on a per species level and as compared to each species' conservation status, as well as users (members of the public) and experts (those with expertise in the field of bumble bee biology) perceived ease of species identification. Photos of bumble bees (Hymenoptera: Apidae: *Bombus*) are submitted to the program by users and verified (species name corrected or assigned as necessary) by a bumble bee expert. Over 22,000 records from over 4,900 users were used in the analyses. Accuracy was measured in two ways: percent agreement (percent of all records submitted correctly by users) and veracity (percent of all verified records submitted correctly by the users). Users generally perceived it harder to identify species than experts. User perceptions were not significantly different from the observed percent agreement or veracity, while expert perceptions were significantly different (overly optimistic) from the observed percent agreement but not the veracity.

We compared user submitted names to final expert verified names and found that, for all species combined, the average percent agreement was 53.20% while the average veracity was 55.86%. There was a wide range in percent agreement values per species, although sample size and the role of chance did affect some species agreements. As the conservation status of species increased to higher levels of extinction risk, species were increasingly more likely to have a lower percent agreement but higher levels of veracity than species of least concern. For each species name submitted, the number of different species verified by experts varied from 1 to 32. Future research may investigate which factors relate to success in user identification through community science. These findings could play a role in informing the design of community science programs in the future, including for use in long-term and national-level monitoring of wild pollinators.

Introduction

Community science, which is also known as citizen science, is a popular tool in conservation biology that involves public participation in scientific data collection (Silvertown 2009; Crall et al. 2011; Kremen et al. 2011; Lye et al. 2011; Roy et al. 2012; Cooper et al. 2012; Dickinson et al. 2012; Lebuhn et al. 2013; Birkin and Goulson 2015; Kobori et al. 2016; Kosmala et al. 2016; Aceves-Bueno et al. 2017; McKinley et al. 2017). The main strengths of community science include increasing the spatial and temporal scale and magnitude of sampling efforts; reducing the cost of sampling; and creating educational and recreational benefits for participants (Bonney et al. 2009a; Kremen et al. 2011; Dickinson et al. 2012; Lebuhn et al. 2013; Birkin and Goulson 2015; McKinley et al. 2017; Falk et al. 2019).

Accurate species level identification is an important first step in conservation and is an essential pre-requisite for effective conservation management decisions (Kremen et al. 2011; Le Féon et al. 2016). Previous research has found that community scientist data, when unreviewed or unverified by experts, can contain errors that significantly influence the interpretation of results by experts (Gardiner et al. 2012; Comont and Ashbrook 2017). Problematic errors include the overestimation of rare or at-risk species, as well as underestimation of common species, inflated species richness, and significant increases in species diversity (Dickinson et al. 2010; Gardiner et al. 2012; Silvertown et al. 2013; Comont and Ashbrook 2017; Falk et al. 2019).

Verification is part of expert assisted community science programs where experts in the field review a submission to determine if the identification is correct or incorrect, which can increase data quality (Gardiner et al. 2012; Le Féon et al. 2016; Comont and Ashbrook 2017; Falk et al. 2019). As such, expert assisted community science projects have a higher scientific value, particularly for conservation management decisions (Dickinson et al. 2010; Crall et al. 2011; Gardiner et al. 2012; Falk et al. 2019).

Bumble bees (Hymenoptera: Apidae: *Bombus*) are native throughout the Northern Hemisphere and in South America with their diversity centered in temperate and mountainous regions (Williams et al. 2014). They are important pollinators in natural and agro-ecosystems (Corbet et al. 1991; Buchmann and Nabhan 1996). A portion of North America's bumble bee species have been found to be in decline in recent years (Colla and Packer 2008; Gixti et al. 2009; Cameron et al. 2011b; IUCN Standards and Petitions Committee 2019)(see Table 5.1). There are several factors that have been identified as drivers of bumble bee decline, including: pathogen

transmission from managed bees, habitat loss, pesticides, interspecific competition with non-native species, and climate change (Colla et al. 2006; Otterstatter and Thomson 2008; Cameron et al. 2011b; Szabo et al. 2012; Goulson et al. 2015; Kerr et al. 2015; McMahon et al. 2015; Papanikolaou et al. 2017; Cameron and Sadd 2020; Soroye et al. 2020). As *Bombus* is a genus of relatively large bees, sometimes with distinct physical features, experts are often able to provide a confident identification to species level from photos, although it does depend on the species and angle and quality of the photo (Lye et al. 2011; Suzuki-Ohno et al. 2017; Falk et al. 2019).

The community science program, Bumble Bee Watch, was launched as a website (www.bumblebeewatch.org) in March 2014. An iOS app (computer program for mobile devices such as phones and tablets) was added in July 2017, and an Android app was added in July 2018. Users (members of the public who participate in this program) submit photo observations of bumble bees with known dates and geographic locations throughout Canada and the United States. Users are not required to have any prior experience with or training in bumble bee identification to participate in the program, and can range in age, ability, and location (MacPhail et al. 2020a). Photo documentation reduces the need for traditional monitoring protocols and equipment, including physical collection and curation of collected specimens (Silvertown 2009; Lye et al. 2011; Lebuhn et al. 2013; Koberi et al. 2016), although photos are not always sufficient to identify some bumble bee species due to either the photo quality or the physical features of the specimen that need to be examined (Lye et al. 2011; Suzuki-Ohno et al. 2017; Falk et al. 2019).

Bumble Bee Watch is an example of expert assisted community science, where submissions from community scientists are reviewed by an expert in the field before entry into a species database (Gardiner et al. 2012; Le Féon et al. 2016). For Bumble Bee Watch, experts (aka verifiers) are individuals with significant expertise in the identification of bumble bees. Verifiers currently include some of the top bumble bee experts in North America, and all new verifiers must be referred to and vouched for by experts known to the current administrators (e.g. RH of the Xerces Society, SC of York University).

Community science monitoring projects benefit from accurate identifications by participants, which reduces verification time from experts, speeding up feedback to participants and enhancing educational value. Yet accuracy can vary amongst participants and programs. Examining accuracy in the Bumble Bee Watch program can be useful in assessing the over- and/or under-reporting of various bumble bee species compared to researcher collected data. These bumble bee records are highly valuable to conservation biologists who may use data for common species as a comparative background for looking at the status of at-risk species.

Assessing the accuracy of initial identification of both common (least concern) and at-risk (vulnerable through extinct) bumble bee species (as determined by the IUCN (2019)) is useful for Bumble Bee Watch to help assess the identification skill levels of participants, the need for expert verification, and the most common species misidentifications. Overall, a high accuracy of initial identification from users could suggest one or more of the following: 1) bumble bees are relatively easy to identify; 2) common bumble bee species are easy to identify; 3) experts and users make similar mistakes during identification; 4) users are taking advantage of the bumble

bee identification materials provided by the program to have a high matching ability; 5) the identification key on the website and smart filter on the app is intuitive and easy to use; 6) users are experienced in bumble bee identification (e.g. enthusiasts, researchers, participants in targeted outreach programs); and/or 7) education and outreach programs are increasing the skill and abilities of users. Low accuracy of initial identification rates could suggest that: 1) bumble bees are hard to identify by novices and that expert assisted community science is required; 2) there is a need for program changes and/or additional training materials; 3) there are potential bias(es) by users; and/or 4) photographs are not clear enough or do not provide enough detail for verification. Accuracy of identification data can also be used to assess user interest and bias (Dickinson et al. 2012). Therefore, understanding what influences user accuracy could aid in the development of a long-term monitoring protocol for bumble bees in North America.

Effective long-term pollinator conservation requires collection of continuous, broad-scale data on native pollinator communities (Gixti et al. 2009; Cameron et al. 2011b; Lebuhn et al. 2013; Goulson et al. 2015; Hatfield et al. 2015c, e; Strange and Tripodi 2019). Conservation biologists are dependent on accurate spatial and temporal data to determine the status and extinction risk of bumble bee species (Rodrigues et al. 2006; Mace et al. 2008; Cardoso et al. 2011; Colla et al. 2012a; Hatfield et al. 2015a; Colla 2016; MacPhail et al. 2019). Since community science increases the ability for long-term monitoring programs to be developed, and community science data have recently been used to help assess many species (Howard and Davis 2009; Kremen et al. 2011; Lye et al. 2011; United States Fish and Wildlife Service (USFWS) 2019d, 2021, 2016, 2017, 2019b, c; Suzuki-Ohno et al. 2017; Committee on the Status of Endangered Wildlife in Canada 2018; MacPhail et al. 2019), there is potential for Bumble Bee Watch data to contribute

to long-term monitoring and management decisions for at-risk species. Community science data can also be used to monitor all species for trends in abundance, potentially providing an early warning before catastrophic collapses occur, such as have been seen in several North American bumble bees (Colla and Packer 2008; Cameron et al. 2011b; Colla et al. 2012a; Bartomeus et al. 2013; Mathiasson and Rehan 2019; Richardson et al. 2019; MacPhail et al. 2019; Cameron and Sadd 2020).

A recent meta-analysis showed that no significant difference, a correlation greater than 0.5, or a minimum percent agreement of 80% between community scientists and professional scientists is considered acceptable in terms of equivalency (Aceves-Bueno et al. 2017), although this does not take into account repercussions such as misidentification of specific species (such as those that are rare, endangered or invasive) (Stribling et al. 2008; Austen et al. 2016). Here, we use the reviewed database available from Bumble Bee Watch to assess the accuracy rate of data submitted by community scientists as assessed by bumble bee experts (The Xerces Society for Invertebrate Conservation et al. 2019).

Experts and users may have different perceptions on the ease or difficulty in identifying specific bumble bee species. Identifying differences in these perceptions could help those conducting outreach and training target their efforts and resources appropriately. To accomplish this, we completed a user and expert online survey to investigate the perceived ease of identification for each species and compared that to the actual observed accuracy in the program.

As the users who participate in the Bumble Bee Watch program have a range of bumble bee identification experience ranging from complete novice (majority of users) to expert (small number of users) (MacPhail et al. 2020b), there could be user bias or influence in the percent agreement between the user submitted name and expert verified one for some species. For example, if one user submitted most of the data for a specific species, and they are an individual with high identification accuracy, this could skew the percent agreement results as compared to species with identifications contributed by users with an average skill level. The reverse could also be true for a user with a lower than average identification accuracy.

We hypothesized 1) that there are differences in user identification accuracy among species; 2) that the agreement (relationship) between expert and user identifications is not due to chance alone; 3) that users have a higher accuracy of identification for common species than at-risk species; 4) that users and experts would have different perceptions of ease of identification; and 5) that the user perception of ease of identification would match their actual observed accuracy of identifications.

Methods

Data collection

As Bumble Bee Watch users submit photos of bumble bees, they are prompted to identify the bumble bee using a pictorial key filtered by location with choices amongst a group of options for various identification features (e.g. colour-pattern). Submissions are marked as pending until they are reviewed by experts (those individuals determined by program administrators as having significant expertise in bumble bee identification) on Bumble Bee Watch, after which they are

marked as verified (the expert confirms the species identification or corrects it as necessary), tentative (reviewed by an expert but uncertainty around the identification still exists) or invalid (identified by an expert to not be *Bombus*).

In this study, we compared the user submitted names to the final expert verified names. All nest and bee records were exported from Bumble Bee Watch on July 19, 2019 (The Xerces Society for Invertebrate Conservation et al. 2019). Records marked as pending and tentative were not included in any analyses of accuracy. Records marked as verified and invalid were included in analyses of accuracy except where the original user submitted name was not known (the original identification field was added to the database after its launch, and not all original identifications could be retroactively determined), or where the verified species name was “sp” (unknown *Bombus* species); in these latter two cases the records were excluded from analyses.

Percent Agreement Analyses

To determine the first measure of accuracy of user identifications, we calculated the percent agreement (represented by $U_c/U_t \times 100$, where U_c is the total number of user submitted records that were verified by experts as being correct and U_t is the total number of user submitted records) for each of the expert reviewed (verified and invalid) species submitted to Bumble Bee Watch, and averaged the individual values for an overall result. This is the same as “recorder success” in Falk et al. (2019), “recorder accuracy” and “recorder identification ability” in Comont and Ashbrook (2017), and “precision” in Roy et al. (2016).

Veracity Analyses

To calculate the second measure of accuracy of user identifications, we calculated the veracity of the user identifications (represented by $U_c/E*100$, where U_c is the number of correct user submitted records and E is the total number of expert verified records) for each of the reviewed species submitted to Bumble Bee Watch. This is the same as “recorder accuracy” in Falk et al. (2019), which can be converted to the “miss rate” in Roy et al. (2016) if subtracted from one (i.e. miss rate=1-recorder accuracy) (Comont and Ashbrook (2017) do not investigate this metric).

Comparing Percent Agreement and Veracity

To investigate the overall agreement between the two methods of determining user accuracy (percent agreement and veracity), we used a Fisher’s Exact Test to compare the values calculated for each species. We also subtracted the veracity calculation from the percent agreement to note the difference between the two methods for each species.

User versus Expert Identifications

We also tested for significant relationships amongst the user vs expert species identifications overall and for each species individually using Chi-Square tests. For the main analyses (all species being considered at once), we calculated the total number of records per species for every combination of user submitted and expert verified identification (creating a grid with expert species names across the top row and user species names down the first column), and then compared this observed data to the expected data (equation: row total*column total/overall total) to see if the user and expert identifications were related.

For the individual species comparisons, we created new “user_species_x” and “expert_species_x” columns in our data (where “species_x” was replaced with each individual species name; all species names that had been submitted or verified were included) and populated them with a 1 or a 0 depending if that record’s user submitted name or expert identification matched the “species_x” name (=1) or not (=0). These data could then be summarized in a 2x2 table, to allow for calculations of observed versus expected for each species to test for relatedness.

When the Chi-square test assumption of all expected values being >0 and 80% of records being >5 were not met, Fisher’s Exact Tests were conducted to provide the significance (p) values, except for when all species were being compared at one time, in which case the Monte Carlo method was used to obtain an approximation of the Fisher’s Exact test.

As users might correctly identify a bumble bee simply by chance, we also calculated the Cohen’s Kappa (K) statistic (Landis and Koch 1977; Lombard et al. 2002; McHugh 2012). Cohen’s Kappa statistic can take into account chance agreement due to uncertainty by the raters (e.g. in our case, agreement between users and experts even when the users are guessing) (Cohen 1960; McHugh 2012). It involves the calculation of probability of observed agreement (i.e. true accuracy) and probability of chance agreement. Kappa values can range from <0 (no observer agreement) to 1 (perfect observer agreement) (Landis and Koch 1977), although McHugh (2012) suggests that low negative values (at or close to the maximum lowest value of -1) are not meaningful and suggest randomness or errors. While there is no specific agreement on what each Kappa value represents, Lombard et al. (2002) and McHugh (2012) suggest that a Kappa of

0.8 or more represents a strong or true agreement while low Kappas (e.g. under 0.6) represent a weak agreement.

We used SPSS ver 24 (IBM Corp 2016) to conduct all statistical analyses.

Identification and reporting of at-risk species

As community scientists have previously over-reported rare or at-risk species of other taxa (Dickinson et al. 2010; Gardiner et al. 2012; Comont and Ashbrook 2017), which would lead to a low accuracy rate, as well as making rare species look artificially common, we assessed this for all bumble bee species, as divided into categories based on their IUCN Red List category (IUCN Standards and Petitions Committee 2019).

We hypothesized that over-reporting of species would result in a low percent accuracy (i.e. users wanted to find rare species and reported observations as such but were incorrect), and thus we expected a relationship between accuracy and IUCN rank. We used a Generalized Linear Model, with a negative binomial distribution model and log link, followed by pair-wise mean contrast Bonferroni-corrected post-hoc tests, to investigate the relationship between the percent agreement and veracity values for each species (dependent variables, tested separately) and its IUCN rank (predictor variable) (species that are considered Data Deficient were excluded). Percent agreement and veracity values were rounded to the nearest integer for this test.

Common Misidentifications

As some bumble bee species are commonly mistaken for other species, we contrasted the names and numbers of the actual expert verified species for every user submitted species name. We also

contrasted the reverse: the number of user submitted species names for each expert verified species name. This was done by plotting user submitted names against the later expert verified names in Microsoft Excel (Microsoft Office 365) to visually compare the number of correct and incorrect identifications.

User Bias

To evaluate the relative contribution of users, and their potential impact or bias on results (e.g. one user contributing a large majority of the records for a specific species, which, if they had better or worse identification accuracy than most users, could affect the results), we calculated the total, maximum, minimum, and average number of users per species, and their overall relative contribution of records by each user to each user submitted name and expert confirmed species. This was conducted in Microsoft Excel.

Perceived Ease of Identification

To investigate if accuracy is related to perceived ease of identification, we included a question about the ease of identification in a larger online survey of users and experts about the value of the Bumble Bee Watch program (as discussed in MacPhail et al. (2020b)). We recruited participants to complete the anonymous voluntary user survey (Article C.S1) through information provided in the January 2018 Bumble Bee Watch e-newsletter and posted on social media. The user survey was open for 33 days. The expert survey (Article C.S2) participants were determined by the authors: the initial list of expert participants was based on verifiers on Bumble Bee Watch who had extensive experience in the *Bombus* field. Invitations were sent to 15 experts in early 2018. Upon analysis of the initial data, to increase the sample size of expert responses,

we approached another 17 experts (predominantly non-verifiers on Bumble Bee Watch but who have similar levels of experience in the *Bombus* field) in late 2019. Respondents in this second round of expert surveys had an identical questionnaire to the one sent out in 2018 except for the removal of an invitation and link to complete the general user survey that had been in the initial survey (Article C.S2).

As part of the survey, we asked respondents a question about species identification difficulty (questions 19 and 20 in Article C.S1 [users] and questions 14 and 15 in Article C.S2 [experts]). Species for the respondents' given geographic area were to be ranked from 1 to 5, where 1 was considered easy to identify and 5 was considered difficult to identify from a photograph (we did not define the quality of the photograph in the survey). Respondents could also choose to select n/a or skip the response for one or more species. If a respondent filled out the ease of identification ranking section for both regions only the data for their identified region was kept.

There were 24 species included in the Eastern region (east of the Mississippi in the United States, and east of Ontario (including Ontario) in Canada) and 34 in the Western region (west of the Mississippi in the United States and west of Manitoba in Canada). We selected these species based on previous Bumble Bee Watch submissions and species listed in Williams et al. (2014), including species with overlapping colour patterns, with co-occurring species, common species, and species of conservation interest. Although species were presented for ranking based on geographic area, analyses were conducted independent of region, with data being pooled for each of the 18 species found in both regions.

We collected the data from both surveys using Google Forms, and later exported it to Microsoft Excel. We calculated descriptive statistics of rank responses (including n, mean, se mean, median) for each species in Excel. Median ranks were used in analyses as they accounted for unequal numbers of responses due to skipped species and potential outlier ranks. Mann-Whitney U-tests were conducted in SPSS to compare the median ease of identification rank responses of users to those of experts for each species (i.e. to see if users and experts agree on difficulty level).

We converted the observed accuracy measures (percent agreement and veracity) to a rank following the assumption that species considered by experts to be easy to identify should have high identification accuracy rates, and those that are difficult to identify should have low accuracy rates. Thus, an accuracy (percent agreement and veracity) of 0-20% was given a rank of five, 21-40% as four, 41-60% as three, 61-80% as two, and 81-100% as one.

We then compared these two converted accuracy ranks to the median perceived ease of identification ranks for users and experts. If the percent agreement or veracity calculated from the Bumble Bee Watch dataset, as converted to a rank, matched the median rank value as determined from the survey responses, it was considered a match between perceived ease of identification and actual identification accuracy. We then tested for significant differences between each of the user and expert median ranks as compared to the percent agreement and accuracy rank (to see if perceptions of ease of identification were the same as observed accuracy), for all species combined, using Chi-Square tests or, if assumptions of expected values being >0 or 80% of values >5 were not met, Fisher's Exact Tests.

This survey of users and experts was approved by York University's Faculty of Environmental Studies (November 2017, no reference number (internal approval by Drs. Colla and Meyers)) and the data re-approved for use by York University's Office of Research Ethics (September 2019, ref# STU 2019-097).

Results

Data collection

We obtained 22,159 reviewed bumble bee records (i.e. verified and invalid submissions to Bumble Bee Watch with a known original user submitted name, excluding those verified as “sp” by experts) for our analyses. After expert review, this represented 39 species and three other species categories (two species complexes and an unknown/not a bumble bee category) (hereafter all referred to as species) being represented in the records (Table 5.2).

Experts verified that there were 11,690 records (52.76%) that were correctly identified to species upon initial submission by users. An additional 2,037 records (9.19%) were invalid (not a bumble bee), while the remaining 8,432 records (38.05%) were bumble bees that had been incorrectly identified by the user, for a total of 10,469 (47.24%) incorrect user identifications overall.

The most commonly found species after expert review were *B. impatiens* Cresson, 1863 (4,205 records, 18.98% of all reviewed submissions), followed by unknown/not a bumble bee (2,037 records, 9.19%), and *B. griseocollis* (DeGeer, 1773) (1,520 records, 6.86%) (Table 5.2). The

least commonly found species were *B. suckleyi* Greene, 1860 (1 record, 0%) *B. bohemicus* Seidl, 1838 (2 records, 0.01%), and *B. kirbiellus* Curtis, 1835 (3 records, 0.01%) (Table 5.2).

Records were submitted from all 13 Canadian provinces and territories and 49 US states (including District of Columbia) where bumble bees are found (Hawaii does not have any bumble bees). The numbers submitted per jurisdiction were variable, ranging from 6,147 records in Ontario (27.74% of all records) to two records from each of West Virginia and Yukon (0.01% of all records each) (Table C.S1). The top four jurisdictions accounted for 65.03% of all records (Table C.S1).

A total of 342 individuals responded to the Bumble Bee Watch user survey, representing 5.4% of all Bumble Bee Watch participants (individuals who had submitted records to the program as of the survey close date) (MacPhail et al. 2020b). Fifteen of the 32 experts (46.9%) invited responded to the expert survey, with 8 selecting the Eastern Region as the area they were most familiar with and 7 selecting the Western Region. Nine of the 15 responding experts (60%) had previously verified records on Bumble Bee Watch (MacPhail et al. 2020b). As respondents could skip questions, the total number of respondents (both users and experts) providing their ranked perception of ease of identification varied from two to 13 per species.

Percent Agreement Analyses

There was an average of 53.20% percent agreement (number of records correctly identified by users compared to all user submitted records)(i.e $U_c/U_t \times 100$) across all species, with a range of 0 (*B. bohemicus*, *B. franklini* (Frison, 1921), and *B. kirbiellus*, with no correct user submissions) to

100% (*B. cryptarum* (Fabricius, 1775), with all user submissions having the correct identification) per species (Table 5.3).

Veracity Analyses

The average veracity rate (number of records correctly identified by users compared to all verified records)($U_c/E*100$) was 55.86%, although this varied by species, ranging from 0 (*B. bohemicus* and *B. kirbiellus*, with no records submitted by users with the correct identification despite two and three records verified as being present in the data per species, respectively) to 100% (*B. fraternus* (Smith, 1854) and *B. suckleyi*, with all verified records having been submitted with the correct identification by the users) (Table 5.3).

Comparing Percent Agreement and Veracity

There was no significant difference in percent agreement as compared to veracity when looking at all species together (Fisher's Exact Test=19.829, $df=16$ $p=.075$). However, there were differences noted between the two metrics for all species except for *B. bohemicus* and *B. kirbiellus*. The results of subtracting veracity from percent agreement ranged from -62.2% (*B. cryptarum*) to 98.11% (*B. suckleyi*) (Table 5.3).

User versus Expert Individual Species Identifications

The difference in user submitted names versus expert verified names was significant over all species (i.e. the user and expert responses were not related) (Fisher's Exact Test=65,217.914, $df=1681$, $p<0.001$, $\kappa=0.5$). The user versus expert identification agreement, when investigated for each species separately, was also significantly different for all species except for *B.*

bohemicus (which had no correct original identifications by users although there were misidentified submissions that were later verified to be *B. bohemicus*) (Table C.S2).

For some species, the percent agreement or veracity measures between user and expert identifications is likely not a true agreement and due in large part to chance: for example, the Kappa values of 0.21-0.40 suggested *B. caliginosus* (Frison, 1927), *B. frigidus* Smith, 1854, *B. insularis* (Smith, 1861), and *B. sylvicola* Kirby, 1837 were all minimal or fair agreement (Table C.S2). For other species, the percent agreement is more likely a true agreement between users and experts and not just agreement due to chance: for example, 14 species all had moderate or substantial agreement (Kappa values from 0.61-0.80). Two species, *B. bohemicus* and *B. kirbiellus*, had 0% agreement, which is supported by Kappa values of zero (Table C.S2).

Identification and Reporting of At-risk Species

The level of rarity, according to the IUCN Red List ranking, has a significant predictive effect on percent agreement (Wald Chi-Square=19.821, df=3, sig<0.0002). The only significant differences were between IUCN rank 1 (Least Concern) and rank 3 (Endangered) (p=0.002), and rank 1 and rank 4 (Critically Endangered) (p=0.002), with percent agreement values decreasing as the IUCN rank increases (Tables C.S3, C.S4). The level of rarity also has a significant predictive effect on veracity (Wald Chi-Square=141.320, df=3, sig<0.0001), but the opposite effect as percent agreement. All pair-wise comparisons were significantly different (p<0.05) except for IUCN ranks 3 and 4 (p=1.00), with higher values of veracity as the IUCN rank increases (Tables C.S3, C.S4). Table C.S4 presents the means and estimates of the marginal means for each IUCN rank for both percent agreement and veracity.

Common Misidentifications

The number of expert verified species names that an original user submitted name turned out to be ranged from 32 to 1, depending on the species (Tables 5.2, C.S5). Records submitted by users as *B. fervidus* (Fabricius, 1798) resulted in 32 different verified species while *B. rufocinctus* Cresson, 1863 resulted in 28 different verified species. At the opposite end of the spectrum, *B. bohemicus* user submitted records led to 5 different verified species, *B. franklini* to 2 different verified species, and only 1 for *B. cryptarum*.

The number of user submitted species per verified species ranged from 32 to 0 (Table 5.2, C.S5). The highest was *B. rufocinctus* (32 species as identified and submitted by users) followed by *B. impatiens* (28 species submitted), and *B. fervidus* (27 species submitted). The lowest was *B. crotchii* Cresson, 1878 (2 species submitted) followed by *B. bohemicus*, *B. fraternus*, *B. kirbiellus* Curtis, 1835, and *B. suckleyi* (1 species submitted for each); no records were verified as *B. franklini* or *B. variabilis* Cresson, 1872 despite user submissions as such. Additionally, 41 species had been identified and submitted by users for records that were not actually of bumble bees (i.e. invalid records once reviewed by experts). Note that the above summaries (Table 5.2) deal with the actual number of incorrect species names; it is not the same as the accuracy of identification, which can be determined by evaluating the relative percent agreement and veracity values in Table 5.3.

User Bias

The 22,159 records used in these analyses were submitted by 4,912 different users. The number of records submitted per user ranged from 1 record to 448, with a mean of 4.5 ± 0.27 records per

person. The number of unique users per reviewed species varied, but an average of 162.9 ± 34.89 people submitted records for each reviewed species (Table C.S6). This ranged from 1 user (*B. bohemicus* and *B. suckleyi*) to 1447 users (*B. impatiens*). The average number of records per reviewed species submitted per user ranged from 1 (no standard error, single observation only) (*B. kirbiellus* and *B. suckleyi*) to 6.51 ± 0.89 records (*B. bifarius* Cresson, 1878). The maximum number of observations per species per user ranged from 1 (33.3% of all records of that species for *B. kirbiellus* and 100% all records of that species for *B. suckleyi*) to 271 (6.73% of all records for *B. impatiens*).

The maximum relative numbers of records submitted by one user per verified species (i.e. the maximum contribution per person per verified species) (Table C.S6) ranged from 0.98% (unknown, not a bumble bee) and 2.86% (*B. vosnesenskii* or *caliginosus* group) through to 100% (*B. bohemicus* and *B. suckleyi*), with the overall contribution of 2.02% per user per species. However, sample size effects these results; for example, there was only one user who submitted verified records each of *B. bohemicus* and *B. suckleyi*. When at least ten users had submitted verified records of a species, the range went from 0.98% (unknown, not a bumble bee) to a maximum contribution per user per species of 40.0% for *B. frigidus* (Table C.S6).

Perceived Ease of Identification

When we compared the percent agreement and veracity ranks (Table 5.3) per species to the median perception of ease of identification ranks (Table 5.4), we found that neither accuracy rank was statistically different as compared to the user median perception rank (Fisher's Exact Test=7.562, df=8, p=0.396 and Fishers Exact Test=5.016, df=8, p=0.836, respectively). The

percent agreement was significantly different from the expert median perception rank (Fisher's Exact Test=27.074, df=16, p=0.002) but the veracity was not (Fisher's Exact Test=16.694, df=16, p=0.239, respectively).

There was a significant difference between users' and experts' perceived ease of identification (Table 5.4) for 24/40 species (60%). Users usually considered it harder to identify species than experts, as 23/24 (95.3%) of the species with significant differences had a higher median score given (i.e. more difficult to identify) by users than experts (Table 5.4).

Three of the 40 species (*B. flavidus* Eversmann, 1852, *B. kirbiellus*, *B. variabilis*) were considered hardest by users to identify, having a median rank of 5 – Difficult, while no species were considered easy or somewhat easy (i.e. none had a median rank of 1 or 2) to identify by users, 8 species had a median rank of 3 – medium (Table 5.4). Three of the 40 species (*B. flavidus*, *B. kirbiellus*, *B. sandersoni* Franklin, 1913) were considered hardest by experts to identify having a median rank of 5 – Difficult, while 15/40 were given a median rank of 1- Easy (Table 5.4).

Discussion

The accuracy of initial identification is important for determining the utility and quality of community science-collected data (Gardiner et al. 2012). We found that records submitted by Bumble Bee Watch community scientists have an overall percent agreement of 52.76% (range 0-100%, average 53.20%), when comparing the number of correct user submitted records (as determined by expert review) to the total number of user submitted records (i.e. $U_c/U_t \times 100$).

This compares closely to the overall “recorder success” for BeeWatch at 59% (range 4-84%, average 60%) and Blooms for Bees at 40% (range 0-100%, average 21%) (Falk et al. 2019), “recorder accuracy” and “recorder identification ability” for BeeWatch at 59% (range 51-64%) (Comont and Ashbrook 2017), as well as “precision” at 44% (range 0-86%) for Big Bumblebee Discovery (Roy et al. 2016).

Our overall veracity (proportion of all verified records correctly identified by users) (i.e. $Uc/E \times 100$) was 52.76%, (range 0-100%, average 55.86%). This compares to an overall value of 49% (range of 42-78%, average 45%) in BeeWatch and 44% (range of 0-100%, average 39%) in Blooms for Bees (Falk et al. 2019) and 63% (range 0-83%, average 45%) in Big Bumblebee Discovery (Roy et al. 2016) (note that Comont and Ashbrook (2017) did not investigate this metric), suggesting that Bumble Bee Watch participants miss fewer identifications than in other programs.

While we used two different ways of calculating accuracy, percent agreement and veracity, we found that there was no significant difference between them over all species combined, although there were large differences observed for some species (e.g. observers captured 97% of all verified *B. affinis* Cresson, 1863 records in their submissions, although their percent agreement of identifications was low with only 44% of their total *B. affinis* submissions being correct).

While the interpretation of Cohen’s Kappa statistic is not consistent across researchers, our Kappa values do suggest that the percent agreement and veracity values calculated for a number of species in our study should be interpreted with caution as the agreement between users and

experts is likely a result of chance. For instance, of the 41 species we calculated the statistic for in our study, 9 had Kappa values of less than 0.40, which is considered only a slight or fair agreement by Landis and Koch (1977) and no or minimal agreement by McHugh (2012), and another 17 species had values less than 0.60, which while considered a moderate agreement by Landis and Koch (1977), is considered a weak agreement by McHugh (2012). These low values of agreement (high involvement of chance) may be due to the small sample size observed with some species, and/or the small number of correct observations submitted by users.

While ten of the 42 species in our analyses (*B. bifarius*, *B. borealis* Kirby, 1837, *B. cryptarum*, *B. huntii*, *B. impatiens*, *B. mixtus* Cresson, 1878, *B. perplexus* Cresson, 1863, *B. ternarius* Say, 1837, *B. vosnesenskii* Radoszkowski, 1862, and *B. vosnesenskii* or *caliginosus*) were at or above the suggested level of 80% percent agreement that would eliminate or reduce the need for expert review (Aceves-Bueno et al. 2017), the remaining 32 species were below this level. Falk et al. (2019) had two (of 22) species above the 80% threshold in the BeeWatch program and one (of 24) species in the Blooms for Bees programs, while Roy et al. (2016) had two (out of 5 colour groups) above the 80% threshold for the Big Bumblebee Discovery program. It is not uncommon for community science programs to be under the 80% threshold, as Aceves-Bueno et al. (2017) found that only 52% of programs were at or above that value. This does, however, reinforce the need for expert-review in our program and others that involve bumble bee identification by community scientists.

Critically endangered and endangered species were more likely to be misidentified in our study than species considered to be at least risk of extinction when percent agreement was evaluated,

but the opposite trend was seen with veracity, where, except for between endangered and critically endangered species, levels of veracity increased as risk of extinction increased, although there was a low sample size in the higher risk of extinction levels. The low percent agreement could be because some at-risk species are more cryptic or difficult to identify as compared to other at-risk species and common species (i.e. uncommonness may or may not result in difficulty in identification). There is also increasingly more guidance and education about how to identify some rare species, and many of these species (e.g. *B. affinis*, *B. occidentalis* Greene, 1858) are targeted in searches and programs for their conservation; while these targeted searches may increase the total veracity by capturing more of the actual occurrences in the initial identifications, it may also result in users misidentifying more observations due to a desire to find the rare species or because they recognize that species name in the list of options, therefore dropping the percent agreement (number of correct observations compared to all submitted observations of that species).

We anticipated that experts in bumble bee biology, particularly those with extensive identification experience, would be better able to rank the difficulty of identifying species by photos than users, which we did not clearly see in this study. We also anticipated that species that are perceived as easy to identify would have a higher identification accuracy. Although there was a significantly different relationship with expert rank of ease of identification and actual observed percent agreement of identification rates in this paper (i.e. the expert prediction did not match the observed percent agreement), the veracity was not different from the expert perception (i.e. the expert view was similar to the veracity observed over all records). This difference in findings could be related to users misidentifying a number of species in their submitted

identifications and thus skewing the percent agreement results as compared to the overall perception of experts. There was no difference with users and observed percent agreement or veracity, although the predicted range rarely met the observed range of percent agreement. It is also possible that experts do not fully understand how difficult users find the identification process and the perceptions of the two groups could be quite different and the findings only relevant to that specific group.

Experts generally ranked species as easier to identify than users. This may be because experts have a lot more experience and training, look for features that users do not, and know more ‘exceptions’ to the typical or standard appearance, and thus have less confusion or hesitation over identifications than users may have. The respondents to the user survey were not entirely representative of contributors to Bumble Bee Watch overall, with the respondents tending to submit more records than users overall (MacPhail et al. 2020a). It is possible that the rankings would be different than that given by a truly representative sample of contributors, particularly those who only submitted one record. However, many users may not actually know enough to be willing to offer a ranking; in our user survey, the number of respondents who ranked a species ranged from 39 to 209 respondents per species out of the 342 respondents in total. Similarly, a low number of experts contributed to ranks of some species in the expert survey, ranging from 2 to 13 respondents per species out of 15 total respondents. It is possible that if a larger sample of both users and experts were obtained, results closer to observed may be obtained. Additionally, no photographs or illustrations were provided for the species in the survey, so users may have had difficulty assigning a rank as they were unsure what that bee looked like; future investigations should provide standardized photos or illustrations (e.g. colour pattern guides as

used in Williams et al. (2014)). In the future, experts could be specifically asked their perceptions on how easy or hard it is for the average user to identify the species, rather than their own perceptions.

The range in numbers of user submitted names per expert assigned species, and vice versa, was extensive. Mimicry and cryptic coloration patterns may cause greater difficulty in accurate species identification than species with consistent patterns. Identification guides do show the variations present in some species, with *B. rufocinctus* being the most diverse (Williams et al. 2014). Additionally, some species may have had more incorrect species names because they are a wide-ranging species and thus more potential for confusion with other co-occurring species in different parts of its range. These are two areas that could be investigated further.

As noted above, some species can be hard to identify, with specific photo angles needed to showcase identifying characteristics, and/or with characteristics best seen under a microscope using a physical specimen. In some cases, experts may still be able to identify the specific species without a microscope using just the photos provided, often based on gestalt or intuition built on past experience; this may also explain why experts in our study perceived similar-looking species (e.g. *B. sandersoni* and *B. vagans* Smith, 1854) as being at different levels of identification difficulty (levels 5 and 3, respectively).

Bumble Bee Watch uses two species complexes or groups to help in situations when the observation can be narrowed down to one of a few similar-looking species, but confirmation of the exact species cannot be made. These include *B. vagans*, *B. sandersoni*, and *B. perplexus* (the

two-striped group) and *B. vosnesenskii* and *B. caliginosus* (the yellow-faced group). When the percent agreement is calculated with the allowance that any of the user-submitted species is correct if it is verified as being either that species or one of the species in the associated complex, the percent agreement increases, sometimes drastically, as compared to strictly considering the single species in isolation.

For example, of the 516 records that had been submitted as *B. vagans*, 333 were verified as either being *B. vagans*, *B. sandersoni*, *B. perplexus*, or part of the complex, leading to a potential 64.53% percent agreement if any of those responses were to be considered correct, as compared to original comparison of 239 being verified as *B. vagans* alone (46.32% percent agreement). For *B. sandersoni*, the percent agreement increases to 38.58% from the original 3.15% with the extra allowance, and for *B. perplexus*, 86.44% from the original 83.02%. Similarly, for *B. vosnesenskii*, the percent agreement increases to 96.20% from 79.95% if you include all records verified as *B. vosnesenskii*, *B. caliginosus*, or the complex, and for *B. caliginosus*, 95.26% from 18.53%. This suggests that, at least for some hard to identify species, users may not be as “wrong” or inaccurate as the main calculation shows (i.e. they were “close” to the correct identification), an additional area for consideration.

The Bumble Bee Watch platform has a system of checks in place that only allow for species known to be in that provincial/territorial/state jurisdiction to be entered, reducing the number of potential incorrect species options for species. While the program’s interactive identification key and filter also allow for greater accuracy, it also introduces a potential source of error related to

the identification of male specimens: males do not always follow the same colour patterns as females, but the program's keys and filters focus solely on the female patterns.

To increase the percent agreement and veracity of community science-collected data, professional scientists may install quality control and assurance methods (Freitag et al. 2016; Kosmala et al. 2016; Aceves-Bueno et al. 2017). Bumble Bee Watch could update its various existing filters and checkpoints, or what have also been referred to as “automated error checking capabilities” (Crall et al. 2011), or “smart filter” systems (Freitag et al. 2016), throughout the identification key for at-risk species, males of species that differ in appearance from the females, and for other species that are frequently misidentified. A similar validation method is used by Project FeederWatch, a community science program where a system of semi-automated, novel filters for each US state or Canadian province and territory dictates the submission of records by users (Bonter and Cooper 2012). The Project FeederWatch program uses historical data to help detect potential errors in bird identification, for example, records submitted in locations outside of known ranges (Bonter and Cooper 2012). This system had an initial accuracy of 97.7% by participants over three consecutive years (Bonter and Cooper 2012). Bumble Bee Watch currently has a data validation pathway during identification to restrict based on range, but could add in prompts with tips and checks to help users become aware of potential mimics and to discern the differences in the frequently misidentified species.

For our analyses, we removed records that could not be determined to species by experts; this was often due to the submission of poor-quality photos or photos missing key features/angles needed for identification. It is possible that these unknown bumble bee species had in fact been

correctly identified by the user but the records were not verifiable. To increase the amount of verifiable records, additional fact sheets and tutorials can be provided. When users have a better understanding of the specific features needed for identification of each bumble bee species, they can take photos that allow for easier and more accurate expert identifications (Suzuki-Ohno et al. 2017). Continued participation in the program could also have users increase their accuracy, particularly when they have previously submitted less than ten records (Aceves-Bueno et al. 2017; Falk et al. 2019). Supporting the user experience would increase retention and participation rates, which would improve the dataset.

While observer bias could influence percent agreement, particularly when the number of observers and/or the number of records are small, it is unlikely to be a problem in our study for most species. The vast majority of the 4,912 users only submitted one or two photos, and their overall contribution was also low per species. There are a few exceptions where observer bias would likely play a role, such as for *B. bohemicus* and *B. suckleyi* as only 1 user submitted verified records of each, as well as *B. kirbiellus* with 3 users and *B. crotchii* with 5 users. While *B. frigidus* had 12 users who submitted verified records, the most frequent user had submitted 40% of the records, which could influence the accuracy if they were a high or low skill level for identification.

An assumption behind Cohen's Kappa is each observer (in our case users and experts) independently classify their observations. From an analysis of our data (not presented in the text), 673 of the 22159 total reviewed records (3.04%) were self-verified (i.e. submitted by and reviewed by the same individual), which would violate the assumption. However, since it is such

a small value, and the verifications do not usually occur at the same time as the original submissions, we do not believe it would cause an impact on the analyses.

A current challenge with the Bumble Bee Watch program, and one other bumble bee community science programs face (Comont and Ashbrook 2017; Falk et al. 2019), is the delay that may exist in the time it takes a record to be reviewed by an expert and the user receiving confirmation of the identification; this was noted as one of the most common drawbacks to the program in a recent user survey (MacPhail et al. 2020a). While each record currently is reviewed by experts regardless as to its probable accuracy, the current structure of the verification side of the database allows for accurate identifications to be reviewed and generalized feedback (often just a brief thank you) to be given much faster than when the identification needs to be changed or personalized feedback given (although currently even the generalized feedback needs to be expert generated versus automatically generated as is the case with BeeWatch (Falk et al. 2019)). Increasing the initial user accuracy on Bumble Bee Watch therefore means record validation may proceed more quickly and efficiently, as experts would spend less time correcting an identification and providing feedback to participants about why the identification is wrong, and more time processing submissions, thus providing a faster turnaround time from the time a participant submits a record to the time they get a confirmation. If the percent agreement for a species is reliably high, over time it may be possible for experts to skip the review process for those records and/or verify a sub-sample only, thus further freeing up resources to focus on the more commonly misidentified species.

An assumption of Bumble Bee Watch is that the expert reviewers are always “correct”.

However, experts are not always correct or consistent (e.g. (Stribling et al. 2008; Austen et al. 2016, 2018; Kosmala et al. 2016; Suzuki-Ohno et al. 2017)). Misidentifications may have little impact but could have serious repercussions, particularly related to noting species declines, conserving endangered species, tracking invasive or harmful species, and other related environmental protections and conservation activities (Stribling et al. 2008; Austen et al. 2016). It is therefore important to make sure taxonomic identifications are validated (Packer et al. 2018). More investigations into the accuracy and consistency of expert identifications of bumble bees, particularly from field photos, should be conducted, and additional quality control procedures implemented in the Bumble Bee Watch database.

The Bumble Bee Watch program has thus far recorded 39 unique species from across North America. There are 46 species listed as being found in North America by Williams et al. (2014): the missing ones include *B. distinguendus* Morawitz, 1869, *B. franklini*, *B. hyperboreus* Schönherr, 1809, *B. jonellus*, *B. neoboreus* Sladen, 1919, *B. polaris* Curtis, 1835, and *B. variabilis*. It is not surprising that these species are missing. *Bombus franklini* is suspected to be extinct, previously occupying an extremely narrow range in southern Oregon to northern California (Williams et al. 2014). *Bombus variabilis* is one of the rarest bumble bees in North America and has been extremely infrequently seen (Williams et al. 2014). All the other missing species are only found in the tundra/taiga in the far north (Williams et al. 2014), where there are few humans let alone participants with the Bumble Bee Watch program. That said, there may be records of these species still awaiting review on Bumble Bee Watch, or that have previously been verified as an unknown bumble bee species, as these species are frequently difficult to

identify, particularly from photos. We have already encountered a few photos from the far north that we cannot comfortably identify: in some cases a tentative identification was discussed in the comments (e.g. bee record 3547 is a tentative *B. hyperboreus* and bee record 4922 is a tentative *B. polaris*) while others were generally identified simply as “sp” (e.g. bee records 15468, 15540). The encouragement and allowance of more photos or videos to be submitted per record (the current maximum is 3 photos), and the additional guidance of best features to photograph per species, may allow further identifications to occur in the future. Users submitting images of these potential species could also be contacted in order to obtain more photos and/or physical specimens for confident identifications to be made.

Bumble Bee Watch data has already been shown to add important information for species conservation status assessments. A next step is comparing user and expert collected data to see if they show the same trends for more species; if this is the case, then community scientists may be capturing an accurate representation of the wild bumble bee community, which are essential baseline data for conservation purposes. Examining accuracy can also lead to increased understanding of participants’ motivations, for example if submissions of a species (and related misidentifications) peak in correlation to federal listing activity, or relatedly, if at-risk species are reported more frequently than are found. There were 45 provinces/territories/states with less than 100 records submitted and reviewed in this data set (Table C.S1). Promotion of the program in jurisdictions with low participation, particularly in the areas with less than 5 records as of the date of our data export (Alaska, District of Columbia, Rhode Island, South Dakota, West Virginia, and the Yukon) can also help to increase the coverage and value of the program.

Conclusion

The goal of Bumble Bee Watch is to track and conserve the bumble bees of North America. It has been successful in collecting tens of thousands of species records over broad temporal and geographic scales, including records of at-risk species, and the data has already fed into status assessments and other conservation tools and actions. With an urgency in the lack of local and global pollinator species data available (Potts et al. 2010), projects such as Bumble Bee Watch are filling a time-sensitive gap. For community science programs to produce scientifically rigorous data for conservation policy and management, data must undergo quality assurance protocols. Our work found that for Bumble Bee Watch, the accuracy of user identification varies greatly depending on the species, and expert review is needed for most records, but at-risk species are not always over-reported as compared to common ones.

Work to increase the accuracy of species identification in community science may benefit the users, experts, and project overall. Further investigations into the trends and causes of overall initial accuracy is needed. New educational materials and various checkpoints in the pathways to identification should be developed to assist in identification: this could speed up or potentially even eliminate the need for expert review for at least some species, and help users increase their knowledge and identification skills.

Future research may also focus on examining the connection between government activity and/or media attention (e.g. listing of a species as endangered, regional program spotlights) and increases in community scientist participation. Relatedly, it is also important to determine how best to recruit and maintain the interest of a diverse group of users from across North America, to

ensure the Bumble Bee Watch program increases its capacity to capture a detailed picture of our bumble bees.

Tables

Table 5.1. The common and scientific names and taxonomic authorities for the 46 species of bumble bees (*Bombus* spp.) found in North America (from (Williams et al. 2014)), as well as their IUCN Red List extinction risk status for their North American range as per a July 30, 2019 export (IUCN 2019). IUCN status abbreviations are as follows: DD – Data Deficient; LC – Least Concern; VU – Vulnerable; EN – Endangered; CR – Critically Endangered.

Genus	Species	Authority	Common Name	IUCN Status
<i>Bombus</i>	<i>affinis</i>	Cresson, 1863	Rusty-Patched Bumble Bee	CR
<i>Bombus</i>	<i>appositus</i>	Cresson, 1878	White-Shouldered Bumble Bee	LC
<i>Bombus</i>	<i>auricomus</i>	(Robertson, 1903)	Black and Gold Bumble bee	LC
<i>Bombus</i>	<i>bifarius</i>	Cresson, 1878	Two Form Bumble Bee	LC
<i>Bombus</i>	<i>bimaculatus</i>	Cresson, 1863	Two-spotted Bumble Bee	LC
<i>Bombus</i>	<i>bohemicus</i>	Seidl, 1838	Ashton Cuckoo Bumble Bee	DD
<i>Bombus</i>	<i>borealis</i>	Kirby, 1837	Northern Amber Bumble Bee	LC
<i>Bombus</i>	<i>caliginosus</i>	(Frison, 1927)	Obscure Bumble Bee	VU
<i>Bombus</i>	<i>centralis</i>	Cresson, 1864	Central Bumble Bee	LC
<i>Bombus</i>	<i>citrinus</i>	(Smith, 1854)	Lemon Cuckoo Bumble Bee	LC
<i>Bombus</i>	<i>crotchii</i>	Cresson, 1878	Crotch Bumble Bee	EN
<i>Bombus</i>	<i>cryptarum</i>	(Fabricius, 1775)	Cryptic Bumble Bee	DD
<i>Bombus</i>	<i>distinguendus</i>	Morawitz, 1869	Northern Yellow Bumble Bee	DD
<i>Bombus</i>	<i>fervidus</i>	(Fabricius, 1798)	Yellow Bumble Bee	VU
<i>Bombus</i>	<i>flavidus</i>	Eversmann, 1852	Fernald Cuckoo Bumble Bee	DD
<i>Bombus</i>	<i>flavifrons</i>	Cresson, 1963	Yellow Head Bumble Bee	LC
<i>Bombus</i>	<i>franklini</i>	(Frison, 1921)	Franklin Bumble Bee	CR
<i>Bombus</i>	<i>fraternus</i>	(Smith, 1854)	Southern Plains Bumble Bee	EN
<i>Bombus</i>	<i>frigidus</i>	Smith, 1854	Frigid Bumble Bee	LC
<i>Bombus</i>	<i>griseocollis</i>	(DeGeer, 1773)	Brown-belted Bumble Bee	LC
<i>Bombus</i>	<i>huntii</i>	Greene, 1860	Hunt Bumble Bee	LC
<i>Bombus</i>	<i>hyperboreus</i>	Schönherr, 1809	High Arctic Bumble Bee	DD
<i>Bombus</i>	<i>impatiens</i>	Cresson, 1863	Common Eastern Bumble Bee	LC

Genus	Species	Authority	Common Name	IUCN Status
<i>Bombus</i>	<i>insularis</i>	(Smith, 1861)	Indiscriminate Cuckoo Bumble Bee	LC
<i>Bombus</i>	<i>jonellus</i>	(Kirby, 1802)	White Tail Bumble Bee	DD
<i>Bombus</i>	<i>kirbiellus</i>	Curtis, 1835	High Country Bumble Bee (<i>B. balteatus</i> Dahlbom, 1832 in Williams et al. 2014)	DD
<i>Bombus</i>	<i>melanopygus</i>	Nylander, 1848	Black Tail Bumble Bee	LC
<i>Bombus</i>	<i>mixtus</i>	Cresson, 1878	Fuzzy-horned Bumble Bee	LC
<i>Bombus</i>	<i>morrisoni</i>	Cresson, 1878	Morrison Bumble Bee	VU
<i>Bombus</i>	<i>neoboreus</i>	Sladen, 1919	Active bumble bee	DD
<i>Bombus</i>	<i>nevadensis</i>	Cresson, 1874	Nevada Bumble Bee	LC
<i>Bombus</i>	<i>occidentalis</i>	Greene, 1858	Western Bumble Bee	VU
<i>Bombus</i>	<i>pensylvanicus</i>	(DeGeer, 1773)	American Bumble Bee	VU
<i>Bombus</i>	<i>perplexus</i>	Cresson, 1863	Confusing Bumble Bee	LC
<i>Bombus</i>	<i>polaris</i>	Curtis, 1835	Polar Bumble Bee	DD
<i>Bombus</i>	<i>rufocinctus</i>	Cresson, 1863	Red-belted Bumble Bee	LC
<i>Bombus</i>	<i>sandersoni</i>	Franklin, 1913	Sanderson Bumble Bee	LC
<i>Bombus</i>	<i>sitkensis</i>	Nylander, 1848	Sitka bumble bee	LC
<i>Bombus</i>	<i>suckleyi</i>	Greene, 1860	Suckley Cuckoo Bumble Bee	CR
<i>Bombus</i>	<i>sylvicola</i>	Kirby, 1837	Forest Bumble Bee	LC
<i>Bombus</i>	<i>ternarius</i>	Say, 1837	Tri-colored Bumble Bee	LC
<i>Bombus</i>	<i>terricola</i>	Kirby, 1837	Yellow-banded Bumble Bee	VU
<i>Bombus</i>	<i>vagans</i>	Smith, 1854	Half-black Bumble Bee	LC
<i>Bombus</i>	<i>vandykei</i>	(Frison, 1927)	Van Dyke Bumble Bee	LC
<i>Bombus</i>	<i>variabilis</i>	Cresson, 1872	Variable Cuckoo Bumble Bee	CR
<i>Bombus</i>	<i>vosnesenskii</i>	Radoszkowski, 1862	Vosnesensky Bumble Bee	LC

Table 5.2. The number and relative abundance of the bumble bee species records reviewed by experts and identified to a specific *Bombus* species or category, as well as the number of species names that were originally submitted by users for each expert-reviewed species name (i.e. for every species that was verified or marked invalid by experts, what those records were actually submitted as), and the total number of species that each original user-submitted species identification was later identified by experts to be. Note that *Bombus bohemicus* was not correctly identified by any users so the count of one original species identification per verified species is not including an accurate submission. Records verified as “sp” (unknown *Bombus*) were excluded from our data set.

<i>Bombus</i> Species	Total # Reviewed Records	Relative Abundance of Reviewed Records (%)	# Original Species Names Submitted by Users per Reviewed Species	# Verified Species Names for each User-Submitted Species Name
<i>affinis</i>	345	1.56	3	12
<i>appositus</i>	198	0.89	13	16
<i>auricomus</i>	105	0.47	10	16
<i>bifarius</i>	1387	6.26	19	22
<i>bimaculatus</i>	1340	6.05	21	9
<i>bohemicus</i>	2	0.01	1	5
<i>borealis</i>	328	1.48	14	9
<i>caliginosus</i>	60	0.27	5	9
<i>centralis</i>	476	2.15	14	9
<i>citrinus</i>	94	0.42	16	10
<i>crotchii</i>	9	0.04	2	10
<i>cryptarum</i>	107	0.48	7	1
<i>fervidus</i>	563	2.54	27	32
<i>flavidus</i>	125	0.56	14	8
<i>flavifrons</i>	919	4.15	26	18
<i>franklini</i>	0	0.00	0	2
<i>fraternus</i>	20	0.09	1	9
<i>frigidus</i>	20	0.09	6	8
<i>griseocollis</i>	1520	6.86	22	17
<i>huntii</i>	659	2.97	15	11
<i>impatiens</i>	4205	18.98	28	18
<i>insularis</i>	240	1.08	16	19

<i>Bombus</i> Species	Total # Reviewed Records	Relative Abundance of Reviewed Records (%)	# Original Species Names Submitted by Users per Reviewed Species	# Verified Species Names for each User-Submitted Species Name
<i>kirbiellus</i>	3	0.01	1	23
<i>melanopygus</i>	599	2.70	18	23
<i>mixtus</i>	731	3.30	21	13
<i>morrisoni</i>	46	0.21	6	10
<i>nevadensis</i>	442	1.99	13	20
<i>occidentalis</i>	242	1.09	7	19
<i>pensylvanicus</i>	93	0.42	10	13
<i>perplexus</i>	297	1.34	16	10
<i>rufocinctus</i>	937	4.23	32	28
<i>sandersoni</i>	21	0.09	7	13
<i>sitkensis</i>	113	0.51	11	6
sp.	n/a	n/a	n/a	37
<i>suckleyi</i>	1	0.00	1	14
<i>sylvicola</i>	46	0.21	7	17
<i>ternarius</i>	1154	5.21	17	11
<i>terricola</i>	279	1.26	12	20
Unknown (non- <i>Bombus</i>)	2037	9.19	41	n/a
<i>vagans</i>	539	2.43	21	14
<i>vagans</i> , <i>sandersoni</i> or <i>perplexus</i>	292	1.32	18	n/a
<i>vandykei</i>	69	0.31	12	7
<i>variabilis</i>	0	0.00	0	6
<i>vosnesenskii</i>	1112	5.02	15	9
<i>vosnesenskii</i> or <i>caliginosus</i>	384	1.73	18	1
Grand Total	22159	100.00	42	43

Table 5.3. A comparison of the number of records per species submitted by users to the Bumble Bee Watch citizen science program (U_t), the number that were correctly identified by users according to experts (U_c), the percent agreement (U_c/U_t*100) and percent agreement rank between users and experts, the total number of verified records per species overall (E), the veracity ($U_c/E*100$) and veracity rank between users and experts, as well as the difference between percent agreement and veracity measures. The percent agreement and veracity ranks were calculated as follows: 1: 81-100%; 2: 61-80%; 3: 41-60%; 4: 21-40%; 5: 0-20%. Species or species equivalents (e.g. non-*Bombus* observations) that were not available for selection by users were not included in analyses of percent agreement or veracity. *Bombus variabilis* and *B. franklini* were removed from analyses involving veracity there were no verified records in the dataset. Observations submitted by users as unidentified *Bombus* sp. were removed from the original dataset but experts could later identify other submissions as *Bombus* sp.

<i>Bombus</i> species	# Correct User- Submissions (U_c)	# Total User- Submissions (U_t)	Percent Agreement (U_c/U_t*100)	Percent Agreement Rank	# Total Expert- Verified Records (E)	Percent Veracity ($U_c/E*100$)	Veracity Rank	Difference b/w Percent Agreement, Veracity
<i>affinis</i>	333	762	43.70	3	345	96.52	1	52.82
<i>appositus</i>	138	176	78.41	2	198	69.70	2	-8.71
<i>auricomus</i>	72	189	38.10	4	105	68.57	2	30.48
<i>bifarius</i>	985	1228	80.21	2	1387	71.02	2	-9.20
<i>bimaculatus</i>	800	1166	68.61	2	1340	59.70	3	-8.91
<i>bohemicus</i>	0	27	0.00	5	2	0.00	5	0.00
<i>borealis</i>	191	220	86.82	1	328	58.23	3	-28.59
<i>caliginosus</i>	43	232	18.53	5	60	71.67	2	53.13

<i>Bombus</i> species	# Correct User- Submissions (Uc)	# Total User- Submissions (Ut)	Percent Agreement (Uc/Ut*100)	Percent Agreement Rank	# Total Expert- Verified Records (E)	Percent Veracity (Uc/E* 100)	Veracity Rank	Difference b/w Percent Agreement, Veracity
<i>centralis</i>	291	381	76.38	2	476	61.13	2	-15.24
<i>citrinus</i>	43	100	43.00	3	94	45.74	3	2.74
<i>crotchii</i>	8	19	42.11	3	9	88.89	1	46.78
<i>cryptarum</i>	40	40	100.00	1	107	37.38	4	-62.62
<i>fervidus</i>	368	643	57.23	3	563	65.36	2	8.13
<i>flavidus</i>	57	87	65.52	2	125	45.60	3	-19.92
<i>flavifrons</i>	461	656	70.27	2	919	50.16	3	-20.11
<i>franklini</i>	0	5	0.00	5	0	n/a	n/a	n/a
<i>fraternus</i>	20	44	45.45	3	20	100.00	1	54.55
<i>frigidus</i>	14	55	25.45	4	20	70.00	2	44.55
<i>griseocollis</i>	921	1283	71.78	2	1520	60.59	2	-11.19
<i>huntii</i>	446	531	83.99	1	659	67.68	2	-16.31
<i>impatiens</i>	2539	2994	84.80	1	4205	60.38	3	-24.42
<i>insularis</i>	75	216	34.72	4	240	31.25	4	-3.47
<i>kirbiellus</i>	0	134	0.00	5	3	0.00	5	0.00
<i>melanopygus</i>	309	517	59.77	3	599	51.59	3	-8.18
<i>mixtus</i>	437	491	89.00	1	731	59.78	3	-29.22
<i>morrisoni</i>	32	60	53.33	3	46	69.57	2	16.23
<i>nevadensis</i>	333	457	72.87	2	442	75.34	2	2.47
<i>occidentalis</i>	218	372	58.60	3	242	90.08	1	31.48
<i>pensylvanicus</i>	45	124	36.29	4	93	48.39	3	12.10
<i>perplexus</i>	98	118	83.05	1	297	33.00	4	-50.05
<i>rufocinctus</i>	422	906	46.58	3	937	45.04	3	-1.54
<i>sandersoni</i>	4	127	3.15	5	21	19.05	5	15.90

Bombus species	# Correct User-Submissions (Uc)	# Total User-Submissions (Ut)	Percent Agreement (Uc/Ut*100)	Percent Agreement Rank	# Total Expert-Verified Records (E)	Percent Veracity (Uc/E* 100)	Veracity Rank	Difference b/w Percent Agreement, Veracity
<i>sitkensis</i>	38	67	56.72	3	113	33.63	4	-23.09
<i>sp.</i>	n/a	4876	n/a	n/a	n/a	n/a	n/a	n/a
<i>suckleyi</i>	1	53	1.89	5	1	100.00	1	98.11
<i>sylvicola</i>	24	170	14.12	5	46	52.17	3	38.06
<i>ternarius</i>	727	791	91.91	1	1154	63.00	2	-28.91
<i>terricola</i>	198	268	73.88	2	279	70.97	2	-2.91
Unknown (Non- <i>Bombus</i>)	n/a	n/a	n/a	n/a	2037	n/a	n/a	n/a
<i>vagans</i>	239	516	46.32	3	539	44.34	3	-1.98
<i>vagans, sandersoni or perplexus</i>	n/a	n/a	n/a	n/a	292	n/a	n/a	n/a
<i>vandykei</i>	25	48	52.08	3	69	36.23	4	-15.85
<i>variabilis</i>	0	141	0.00	5	0	n/a	n/a	n/a
<i>vosnesenskii</i>	694	868	79.95	2	1112	62.41	2	-17.54
<i>vosnesenskii or caliginosus</i>	1	1	100.00	1	384	0.26	5	-99.74
Total	11690	22159	52.76	3	22159	52.76	3	0.00
Average	278.33	515.33	53.20	2.86	503.61	55.86	2.73	0.00

Table 5.4. Comparison of the rankings of perception of ease of identification between users and experts in the Bumble Bee Watch survey. Species that occurred in both the Eastern and Western regions of the surveys had their responses combined. A median response of 1 indicated respondents perceived the species to be easy to identify, with the range extending to 5, which was for species perceived to be difficult to identify. M-W U stat = Mann-Whitney U-test Statistic, p-value = Exact Significance (2-tailed), Sig? = significant difference between users and experts?, n = number of respondents, perceived harder? = who (user or expert) perceived the species identification to be hardest?

Species (part 1)	<i>affinis</i>	<i>appositus</i>	<i>auricomus</i>	<i>bifarius</i>	<i>bimaculatus</i>	<i>bohemicus</i>	<i>borealis</i>	<i>caliginosus</i>	<i>centralis</i>	<i>citrinus</i>	<i>crotchii</i>	<i>cryptarum</i>	<i>fervidus</i>	<i>flavidus</i>
M-W U stat	176.5	42	905	58.5	160.5	633.5	279	99	76	393	30.5	35	403.5	281.5
p-value	0.003	0.001	0.437	0.005	0.001	0.058	0	0.139	0.02	0.001	0	0.054	0	0.899
Sig?	yes	yes	no	yes	yes	no	yes	no	yes	yes	yes	no	yes	no
perceived harder?	user	user	n/a	user	user	n/a	user	n/a	user	user	user	n/a	user	n/a

[illegible]

Species (part 2)	<i>flavifrons</i>	<i>franklini</i>	<i>fraternus</i>	<i>frigidus</i>	<i>griseocollis</i>	<i>impatiens</i>	<i>insularis</i>	<i>jonellus</i>	<i>kirbiellus</i>	<i>melanopygus</i>	<i>mixtus</i>	<i>morrisoni</i>
M-W U stat	116	23	64	438	289	572.5	665.5	34	48	63	68.5	93
p-value	0.079	0.006	0	0.032	0	0	0.127	0.063	0.456	0.007	0.073	0
Sig?	no	yes	yes	yes	yes	yes	no	no	no	yes	no	yes
perceived harder?	n/a	user	user	user	user	user	n/a	n/a	n/a	user	n/a	user
expert n	6	4	9	10	12	13	12	4	2	6	5	8
expert median	2	2	1	3	1	1	4	2	5	2	1	1
expert mean	2.3	2.0	1.4	3.4	1.2	1.3	3.4	2.3	5.0	2.0	2.2	1.8
expert se mean	0.6	0.6	0.3	0.4	0.2	0.2	0.5	0.8	0.0	0.4	0.7	0.4
user n	66	46	134	142	200	209	147	39	84	56	54	132
user median	4	4	4	4	4	3	4	4	5	4	4	4
user mean	3.4	3.6	4.0	4.1	3.2	2.7	4.2	3.6	4.3	3.4	3.6	4.0
user se mean	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1

Chapter 6. Community science participants gain environmental awareness and contribute high quality data but improvements are needed: insights from Bumble Bee Watch

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Abstract

Bumble Bee Watch is a community science program where participants submit photos of bumble bees from across Canada and the United States for expert verification. The data can be used to help better understand bumble bee biology and aid in their conservation. Yet for community science programs like this to be successful and sustainable, it is important to understand the participant demographics, what motivates them, and the outcomes of their participation, as well as areas that are working well or could be improved. It is also important to understand who verifies the submissions, who uses the data and their views on the program.

Of the surveyed users, most participate to contribute to scientific data collection (88%), because of a worry about bees and a desire to help save them (80%), to learn more about species in their property (63%) or region (56%), and because of a personal interest (59%). About 77% report increased awareness of species diversity, while 84% report improvement in their identification skills. We found that 81% had at least one college or university degree. There were more respondents from suburban and rural areas than urban areas, but area did not affect numbers of

submissions. While half were between 45 and 64 years of age, age did not influence motivation or number of submissions. Respondents were happy with the program, particularly the website resources, the contribution to knowledge and conservation efforts, the educational values, and the ability to get identifications. Areas for improvement included app and website functionality, faster and more detailed feedback, localized resources, and more communication. Most respondents participate rarely and have submitted fewer than ten records, although about five percent are super users who participate often and submit more than fifty records. Suggested improvements to the program may increase this participation rate. Indeed, increased recruitment and retention of users in general is important, and advertising should promote the outcomes of participation.

Fifteen experts responded to a separate survey and were favorable of the program although there were suggestions on how to improve the verification process and the quality of the submitted data. Suggested research questions that could be asked or answered from the data included filling knowledge gaps (species diversity, ranges, habitat, phenology, floral associations, etc.), supporting species status assessments, effecting policy and legislation, encouraging habitat restoration and management efforts, and guiding further research. However, only about half have used data from the project to date.

Further promotion of Bumble Bee Watch and community science programs in general should occur amongst academia, conservationists, policy makers, and the general public. This would help to increase the number and scope of submissions, knowledge of these species, interest in conserving them, and the overall program impact.

Introduction

Community science, which is also commonly known as citizen science, is a fast-growing field where participants commonly collect and/or analyse data as part of a scientific study, often overseen by professional scientists (Silvertown 2009; Griffin Burns and Harasimowicz 2012; Miller-Rushing et al. 2012; Birkin and Goulson 2015). These projects can deliver baseline or monitoring data, answer research questions, provide skills training and specific knowledge, increase stewardship and awareness, and influence conservation actions and policies (Bonney et al. 2009b; Wiggins and Crowston 2011; Conrad and Hilchey 2011; Griffin Burns and Harasimowicz 2012; Newman et al. 2012; Danielson et al. 2014; Follett and Strezov 2015; Jordan et al. 2016; Thomas 2016; Le Féon et al. 2016; Acorn 2017). While the majority of community science projects involve a biological topic, other examples exist ranging from other sciences (e.g. astronomy, atmospheric sciences) to traditional ecological knowledge, model building, monitoring traffic, medical fields, and informational sciences (Wiggins and Crowston 2011; Shirk et al. 2012; Follett and Strezov 2015). Yet the need to create community science frameworks that are successful and sustainable is consistent across all types of projects.

An important part of any successful community science project is an understanding of who the participants are, their reasons for participating, and how their experiences have been to date (Bonney et al. 2009a, b; Silvertown 2009; Van Den Berg et al. 2009). Community science volunteers, particularly those in nature-focused programs, participate for many reasons, such as to learn more about the world around them (Bonter et al. 2012; Griffin Burns and Harasimowicz 2012; Shirk et al. 2012; Trautmann et al. 2012; Russell 2014; van der Wal et al. 2015), to contribute to our overall body of knowledge (Dickinson and Bonney 2012; Griffin Burns and

Harasimowicz 2012; Shirk et al. 2012; Trautmann et al. 2012; Russell 2014), to aid in conservation efforts (Shirk et al. 2012; van der Wal et al. 2015), to increase personal skills and abilities (Bell et al. 2008; Bonter et al. 2012; Dickinson and Bonney 2012; Shirk et al. 2012; van der Wal et al. 2015), and/or to simply spend time in nature or with like-minded people (Bell et al. 2008). Individuals who have participated in nature-related projects often participate in other nature-related activities (Federal Provincial and Territorial Governments of Canada 2014), and many community scientists have knowledge or skills in the area they volunteer in (Bell et al. 2008; Bonter et al. 2012; Cooper et al. 2012; Hames et al. 2012; Miller-Rushing et al. 2012; Shirk et al. 2012). While anyone can be a community scientist, participants tend to be highly educated, white, female, and late middle aged through the early senior years (Bonter et al. 2012; Purcell et al. 2012; Toomey and Domroese 2013). They tend to participate infrequently, submitting few records per person (Worthington et al. 2012; Silvertown et al. 2013, 2015; Kelling et al. 2015b; Domroese and Johnson 2017).

There are often spatial biases in community science programs with more data coming from heavily human populated areas than less populated areas (Cooper et al. 2012; van der Wal et al. 2015) as there are more potential participants there and it may be easier for them to participate close to their homes (Davies et al. 2011; van der Wal et al. 2015), although there are exceptions (Cooper et al. 2012). As well, while individuals may have strong conservation views regardless of where they live (Lutz et al. 1999), some studies have found that urban dwellers may have stronger environmental and conservation views (Berenguer et al. 2005; Olive 2014, 2015). Different regions and audiences also may need different approaches to outreach and education (Bubela et al. 2009; Nisbet and Scheufele 2009; Chu et al. 2012).

Bumble Bee Watch is a community science program run across Canada and the United States in collaboration by the Xerces Society for Invertebrate Conservation, York University, Wildlife Preservation Canada, and other organizations. It collects information on bumble bee (*Bombus* spp.: Apidae) species phenology, distribution, and more, with the goal to use these data to help conserve at-risk bumblebees. It was launched in 2014 with a web-based platform (www.bumblebeewatch.org), with mobile applications for iOS and Android launched in 2017 and 2018 respectively. Based on the idea that bumble bees may, in many cases, be identifiable to species from photographs (Lye et al. 2011; Suzuki-Ohno et al. 2017; Falk et al. 2019), participants take photos of bumble bees and submit through the web or app, along with a date observed and location information. They have the option to use an interactive key or smart filter to assign species name (pre-limited by location), and regional experts verify the identifications. The website also includes resources for the general public and conservationists, including an increasing photo gallery of verified species images, and allows individuals to view data for species, months, areas, and/or to request data for specific project needs.

We wanted to compare metrics on the Bumble Bee Watch program participants, including their knowledge about bumble bees, experience with bumble bee identification, and general feedback, in order to compare it to other community science programs. While Bumble Bee Watch data are currently being used by researchers, such as for species conservation assessments (Szymanski et al. 2016; Committee on the Status of Endangered Wildlife in Canada 2018; MacPhail et al. 2019) and regional checklists (Gibbs et al. 2017), we also wanted to know how experts in the field of bumble bee biology and conservation perceive the program, including their experiences with verifying data for the program and actual or potential uses of the data. With over a quarter of our

North American bumble bees in decline (IUCN Red List of Threatened Species 2019), and continuing stressors identified (Cameron and Sadd 2020; Soroye et al. 2020), this program has the potential to help contribute data for conservation efforts. However, not all community science programs are successful, failing or being shut down due to a variety of reasons, from poor study design to a lack of funding (Conrad and Hilchey 2011; Dickinson and Bonney 2012; Silvertown et al. 2013; Hannibal 2016; Acorn 2017). One very important area that can be neglected is the need to ensure that volunteers have a good experience and have their expectations for participating met (Silvertown 2009; Conrad and Hilchey 2011; Chu et al. 2012; Fitzpatrick 2012; Greenwood 2012; Purcell et al. 2012; Silvertown et al. 2013).

Our main research questions were:

1. What motivates Bumble Bee Watch participants to participate in the program ?
2. Are the demographics of participants and participation rates similar to other community science programs?
3. Are there more participants and submissions from urban areas than rural or suburban ones?
4. Do individuals from urban areas have stronger views related to conservation than suburban or rural ones?
5. Do participants increase their knowledge about bumble bees after participating in the program?
6. Do participants increase their skill in bumble bee identification after participating in the program?
7. Have experts used Bumble Bee Watch data in their own research to date?

8. What aspects of the Bumble Bee Watch program are working well, and which ones can be improved?

Methods

Design of User Survey

The user survey consisted of demographic questions and questions about users' motivations to participate in and feedback about Bumble Bee Watch. There were 21 questions in total (see Article C.S1 for the entire survey), based on those discussed in the evaluation of other community science programs, such as The Great Pollinator Project (Domroese and Johnson 2017), eBird program (Wood et al. 2011), and mammal monitoring study (Newman et al. 2003), amongst others (e.g. reviews in (Silvertown et al. 2013; Lewandowski and Specht 2015)). Response options, such as motivations for participation, were generated based on these evaluations as well as informal discussions with and feedback from Bumble Bee Watch participants at training workshops and via e-mail and social media communications. As there is no consistent definition for urban, suburban, and rural areas (see discussion in (du Plessis et al. 2002; Ratcliffe et al. 2016)), respondents were asked to self-identify based on their perceptions of their communities. The survey was administered using Google Forms from January 23 to February 28, 2018.

Participants were recruited to complete the voluntary user survey through the Bumble Bee Watch e-newsletter and links to the newsletter and survey posted on social media. Respondents were not required to have previously submitted observations to Bumble Bee Watch but previous participation experience was implied. A total of 342 individuals responded to the survey and gave consent for their participation and use of data by reviewing a consent letter and checking a

consent box (see Article C.S1). The number of respondents was a small percentage of the total number of registered and active Bumble Bee Watch users (2.1% of registered Bumble Bee Watch users (342/16,055) and 5.4% (342/6,292) of all users having submitted at least one record).

Design of Expert Survey

The expert survey consisted of fewer demographic questions, and more questions related to community science research and its application, as compared to the user survey (see Article C.S2 for survey and consent form).

The expert survey participants were determined by the authors. The initial list of expert participants was based on Bumble Bee Watch verifiers but was revised to reflect those most applicable or best suited to respond, including others in the field. Invitations to complete the Google Forms expert survey were sent out by e-mail in February and March 2018 to these 15 individuals. To increase sample size, an additional 17 experts were approached in October 2019. The survey these experts received was identical to the one sent out in 2018 (see Article C.S2) with the exception of the removal of the invitation and link to complete the general user survey. In total, 32 experts were invited to participate, and 15 responses were collected.

This survey of users and experts was approved by York University's Faculty of Environmental Studies (November 2017, no reference number (internal approval)) and the data re-approved for use by York University's Office of Research Ethics (September 2019, ref# STU 2019-097).

Data from Bumble Bee Watch Program

An export of the main Bumble Bee Watch program database, including both pending, tentative, and verified nest and bee records, was obtained on February 28, 2018. Summaries were calculated in Excel (Microsoft Office 365) to compare responses obtained in the user survey to metrics from the database, such as the relative number of contributors and the number of submissions per person and per province/state/territory (“jurisdiction”). The number of registered users of Bumble Bee Watch was provided by Rich Hatfield of the Xerces Society for Invertebrate Conservation to VJM on February 28, 2018; this number differs from that of the number of contributors to the Bumble Bee Watch database as not everyone who had created an account had submitted records.

Comparison Demographics from Canada and the United States

To allow for comparisons of Bumble Bee Watch respondents to the broader public, demographic data was obtained for both Canada and the United States through their respective census agencies. This included population by age group, federal jurisdiction, and education (Statistics Canada 2016c, 2017a; United States Census Bureau 2017a, b).

Coding, Analysis of Data

Data collected through the surveys were exported from Google Forms into an Excel spreadsheet. Blank values or skipped responses were removed for the analyses of that question. Basic summaries were completed in Excel, while statistical analyses were carried out using SPSS ver 24 (IBM Corp 2016). Kruskal-Wallis tests were used to investigate if the number of submissions or motivations varied depending on the number of years the respondents have been

involved in the program, the age of respondents, or the area (urban, suburban, rural) they lived in. To control for false discovery rates we used the Benjamini-Hochberg procedure to adjust the p-values (Pike 2011) for all analyses involving the same variable (i.e. years involved, age, area). Dunn's post-hoc pair-wise comparisons were run when significant differences ($p < 0.05$) were found, with the resulting significance values adjusted by the Benjamini-Hochberg procedure. Note that the variables tested (e.g. number of submissions, years involved, age) were collected as factors or categories (e.g. <10 submissions, 10-20 submissions, etc.) and not on a numerical range.

Questions 10 (bumble bee training), 11 (wildlife identification skills) and 16 (education) on the user survey and Questions 9 (used data from program) on the expert survey had an open-form "other" response option. These responses were re-classed into the provided category options for each question as applicable (i.e. the open-form text responses were coded into one or more of the originally provided response options). For example, for question 10, responses such as "I have been taking pictures of bumble bees for years" and "I'm a beekeeper (*Apis mellifera*)" were classified as "no" for specialized training in bumble bees, while responses such as "We did a year long project on native bumble bees in our area and spent a year learning to identify them, including meeting with experts, such as T'ai Roulston, UVA, and Sam Droege" and "Field Experience with [Wildlife Preservation Canada]" were classified as yes.

Qualitative open-form responses were coded and then categorized (Strauss and Corbin 1998; Saldana 2009; Newing 2010). The number of individuals who made statements captured by each

first level descriptive code and second level axial category were summed, which permitted quantitative analyses.

Analyses, results and discussions on the surveys related to the perceived ease of species identification for both users (questions 19, 20) and experts (questions 14, 15) is discussed in MacPhail et al. (in review)(**edit for thesis version of paper: now published as (MacPhail et al. 2020b)*)).

Results

User Survey

A total of 342 individuals responded to our user survey. An overwhelming majority of respondents participate in Bumble Bee Watch to contribute to scientific data collection (88.3%) and because they were worried about bees and want to help save them (80.3%) (Table 6.1). This is followed by a majority wanting to learn more about species on their property or region (62.6% and 56.1% respectively), and because they have a personal interest in bumble bees (59.4%), among other motivations (Table 6.1). For those who wrote in other motivations (25 individuals), 36% indicated they participate because they want to share information with others, 16% participate to improve mental health, be part of natural world, or enjoy a hobby, and 12% participate because they wanted to attract and support pollinators, particularly with their own gardens. Note that individuals could have multiple motivations.

There were no significant differences in any motivations for participation as compared to age of respondents (various K-W tests, $df=7$, $p>0.05$; Table D.S1), years of participation (various K-W tests, $df=4$, $p>0.05$; Table D.S1), or area lived in (various K-W tests, $df=2$, $p>0.05$; Table D.S1).

More than three quarters (77.2%) of respondents report an increased awareness of bumble bee species diversity, and 84.8% report probable improvement in their identification skills as a result of participation in Bumble Bee Watch (63.5% yes, 21.3% maybe, 7.6% no, and 7.6% I don't know). Most had only moderate to low confidence in their identification skills (2.9% said very confident, 12.0% said confident, 41.8% said somewhat confident, 40.9% said not confident, and 2.3% were unsure). This may be explained by the amount of training they have had with bumble bee identification, with the majority (89.5%) reporting no specialized training; 7.9% had some training, 2.0% may or may not have had training, and 0.6% did not answer the question. However, over 85% of respondents indicated they had some (62.3%) or many (22.8%) other wildlife identification skills, while 0.9% said just identification skills with bumble bees, and 14.0% said they had no skills at all (0.6% did not respond).

Of the 87 respondents who had specified specific wildlife identification skills in the optional text box, the majority had experience with birds (60.9%), followed by plants (39.1%), lepidopterans (26.4%), other insects/invertebrates (18.4%) (excluding other bees and odonates that were each reported 11.5%), general species identification (14.9%), mammals (13.8%), amphibians (4.6%), reptiles (3.4%), fish (2.3%), and three other groups (1.1% each) (numbers can add to >100% as multiple responses could have been recorded per person).

More than half of the survey respondents have been involved in naturalist, gardening, or wildlife groups, being currently active (51.2%) or active in the past (8.8%), while 39.5% have not been members, and 0.6% did not respond.

Many of the respondents (n=210) gave feedback about ways to improve Bumble Bee Watch, with the most common category being IT (information technology) related (41.9% of respondents), followed by improved feedback (27.6%), and additional tools and resources (19.1%), although 15.7% indicated that they were happy and had no further suggestions (Table D.S2).

Two hundred and fifty-five respondents provided feedback on what they liked best about the program. The top four best liked features included the resources on the website (38.8%), the contribution to their own and more general knowledge and conservation efforts (including policy) (33.7%), the educational values (24.7%), getting identifications and feedback on submitted records (18.0%) (Table 6.2).

Many respondents were from suburban areas (39.5%), followed by rural (34.2%) and finally urban (26.3%) areas. Most respondents had higher education with 81.0% having at least one post-secondary degree (college through PhD), while a further 12.9% had some college or university, 1.8% vocation/trade training, 3.5% high school diploma, and 0.6% some high school.

Each of the age classes from age 12 to 75+ were represented in our survey. Of the respondents, 50.9% were in the 55-64 and 45-54 age groups, which is more than twice the relative percent of the US and Canadian population in those two categories (Table 6.1). Only 1.75% of respondents were between 12 and 24 years of age, which is less than a quarter of the relative corresponding national populations (Table 6.3).

Respondents were closely split between geographic regions: 197 (57.6%) from the Eastern Region and 145 (42.4%) from the Western Region. The relative percent of respondents per province/state/territory (“jurisdiction”) is similar to the relative percent of records per region that have been submitted to the database with only three jurisdictions having >2% difference in relative percent between the respondents and the database (Colorado, Ontario, Washington) (Table D.S1). However, 14 (28.6%) jurisdictions had >2% difference in relative percent between respondents and the national population (Table D.S3)(Statistics Canada 2017b; United States Census Bureau 2017a). A total of 49 jurisdictions were represented by respondents, while records exist in Bumble Bee Watch for these and 13 others (Table D.S3).

A third of respondents (33.0%) had been participating with Bumble Bee Watch for two years, followed by those with less than one year of participation (23.7%), one year (20.5%), three years (16.5%), or all four years since the program launched in 2014 (6.4%). However, only a few respondents submit records often (7.0%); most reported only rarely (43.0%) or sometimes (42.7%) submitting photos, with a few submitting only if it is a rare or uncommon species (7.3%). Indeed, more than half of respondents (69.0%) have submitted less than 10 records, although this is lower than the percent of Bumble Bee Watch contributors who also submitted less than 10 records (94.2%) (Table 6.4).

There is a significant difference in the number of records (as divided into groupings) made to Bumble Bee Watch as compared to the years of involvement (K-W H statistic = 55.313, df=4, $p<0.001$), with a greater number of records being submitted per accumulated years of participation, except between those who had zero and one or zero and two years of experience

(see Table D.S4). There was no significant difference in the number of photos submitted by age group (K-W H statistic = 5.983, df=7, p=0.774) or by type of area (urban/suburban/rural) (K-W H statistic = 1.009, df=2, p=0.755).

Expert Survey

Fifteen individuals responded to the expert survey: eight from the Eastern region (east of the Mississippi in the United States, and east of Ontario (including Ontario) in Canada) and seven from the Western region (west of the Mississippi in the United States and west of Manitoba in Canada). At the time of their responses (April 2018 or November 2019), 60% of the respondents had verified records on Bumble Bee Watch directly or indirectly, with 80% of the remaining five experts willing to verify in the future. Almost 3/4 of the expert respondents (73.3%) had not submitted records to Bumble Bee Watch, but about half (46.7%) have participated in other community science programs.

About half (46.7%) of the experts have used Bumble Bee Watch data in their research. Example usage included “[collecting] information from Bumble Bee Watch for Special Concern Species in WI [Wisconsin] for the WI DNR [Department of Natural Resources]. This information gets used for conservation of the species”, “looking up records for *B. affinis*”, “[using] recent sightings...for site selection”, and for published manuscripts on species ranges and conservation status. All expert respondents provided examples of research questions that Bumble Bee Watch data could help to answer, including those related to species ranges, phenology, floral associations, detection and monitoring, and more (Table 6.5).

Ten of the expert respondents provided open feedback on ways to improve submitting, verifying and/or using records, which was then condensed down into four categories. The most frequent comments related to app or website features (e.g. being able to take a photo from main screen of app rather than from a species page, uploading multiple images at once, making the interface faster, downloading the data easier). This was followed by ways to improve the original data submission (e.g. instruct users to submit photos showing key identification features, autopopulate the location field based on metadata in photo, capture additional habitat information) and verification process.

Discussion

Bumble Bee Watch participants are highly motivated by the desire to contribute to scientific data collection and to help save bumble bees, as well as to further their own education, such as learning about local species, and for social reasons, such as an activity to participate in with family and friends and/or as part of a special event, in addition to general enjoyment. These motivations were consistent across ages of participants, years of participation, and areas they live in. Most of the participants reported becoming more aware about bumble bee diversity and improving their identification skills after participating, and the top feature of the program they liked were the resources on the website. To keep the program current and sustainable, it is important to understand and continue to motivate participants.

The motivations noted above are all common motivations in community science projects (Bonney et al. 2009a, b; Van Den Berg et al. 2009; Bonney and Dickinson 2012; Chu et al. 2012; Newman et al. 2012; Shirk et al. 2012; Silvertown et al. 2013). Our results also show that the desire for bumble bee conservation is as high as the general contribution of scientific data;

participants could be given more concrete ways that they can help and/or they could be recruited by other projects to help move conservation efforts forward in their areas. Bees are popular animals right now, and The Great Pollinator Project (Domroese and Johnson 2017), found that volunteers ranked the desire for education and learning about pollinators to be the number one motivation followed by the participation in a community science project.

These results are consistent with other research which show programs with a nature-based theme often recruit individuals who care about the environment and wish to take action to help, unlike broader public education programs where participants are motivated by other reasons, such as career advancement (Guiney and Oberhauser 2009; Van Den Berg et al. 2009; Newman et al. 2012; Lewandowski and Oberhauser 2017). Regardless, it is important for each project to recognize the motivations driving their volunteers and to ensure these desires are met in order to keep interest and thus retention high (Bonney et al. 2009b, a; Silvertown 2009; Conrad and Hilchey 2011; Chu et al. 2012; Fitzpatrick 2012; Greenwood 2012; Purcell et al. 2012; Silvertown et al. 2013; Domroese and Johnson 2017). In the case of Bumble Bee Watch, this can be accomplished by showing the participants the scientific value of their data (e.g. frequent summaries of the data and examples of how it has been used, such as through selected publications) and how it is helping to meet the project goals (e.g. where it has been used in species at risk policy designations, conservation decisions), in addition to providing more educational resources to the participants (e.g. tips on creating nesting habitat, best flower species to plant, guidance on how to reach out to decision makers). This has already been occurring through the use of an e-newsletter and blog hosted by The Xerces Society for Invertebrate

Conservation (2020) but more frequent and regional communications would be beneficial to keep interest high.

It is also important to improve the user experience with the program to encourage continued participation, from the initial recruitment and registration through reporting and retention stages. Community science projects traditionally have low participation versus registration rates, and low contributions on a per person basis (Worthington et al. 2012; Silvertown et al. 2013, 2015; Kelling et al. 2015b; Domroese and Johnson 2017); Bumble Bee Watch is no exception. About 39% of registered Bumble Bee Watch users submitted at least one record, which is higher than other programs, such the 25% of registrants in the Great Pollinator Project (Domroese and Johnson 2017) and 30% of those who contacted organizers in the Protea Atlas Project (Silvertown et al. 2013).

Virtually all (94%) of the Bumble Bee Watch database contributors contributed only a few (<10) records, with only a few (0.3%) of participants submitting >100 records (17.1% of the data). This was also seen among our survey respondents. Similarly, the Protea Atlas Project found that only 20% of their participants submitted more than 50 site records, and 2.5% more than 1000 (Silvertown et al. 2013); with the eBird program, 10% of the participants submitted 90% of the records (Wood et al. 2011). These are low numbers of active users but quantity of participants and quality of the resulting dataset are not always equal. These super volunteers or power users often contribute high amounts of high quality data to a program that can help to offset the low participation; these individuals should be especially targeted for retention (Wood et al. 2011; Hames et al. 2012; Silvertown et al. 2013; Kelling et al. 2015b; Hannibal 2016).

Programs generally want to increase the number of new participants each year to both grow the program and offset participants who do not return. For example, FeederWatch has a 70% annual retention rate, but needs 3,000 to 4,000 new participants annually to keep participant numbers and geographic coverage consistent (Bonter et al. 2012). It could be expected that distribution of years of participation would be greatest numbers in the most recent cohort and lower numbers each year. This was seen in the Great Pollinator Project where 41%, 36%, 17%, and 7% of survey respondents participated in one to four years, respectively, of the project (Domroese and Johnson 2017), but the greatest number of our Bumble Bee Watch survey respondents were not from under one year or first year participants but for second years (33%), although the fewest numbers of respondents (6.4%) had been the early adopters, participating for four years. This may be a feature of program roll-out and advertisement being stronger at the time these second-year participants started; further investigations into the actual numbers of new and returning users as compared to promotion efforts would be needed to better identify any correlation. However, it is clear that volunteer retention is key; indeed, Sheppard et al. (2017) believe retention is a measurement that can account for both data quality and volunteer engagement.

Our user survey respondents had a number of similar responses in terms of what they liked about the program and what could be improved. Commonly stated areas for improvement related to their motivation to learn and to see that they are helping science. Users wanted to get faster feedback on their submissions, more tools and resources to identify and attract pollinators, and increased communication to learn what others have been finding and how the data has been used. In regards to the communications with others, in-person workshops and direct contact with experts are not always possible, but there may be a role for virtual training and online

community discussion forums in sharing information and experiences and getting feedback and advice (Bonney and Dickinson 2012; Bonter et al. 2012; Triezenberg et al. 2012; Toomey and Domroese 2013; Austen et al. 2018).

The Great Pollinator Project also struggled with meeting the desired speed of feedback and sharing of data to users, particularly for higher level summaries and reports that can take a long time before analyses can be completed, and encouraged program leads to find solutions for this common problem (Domroese and Johnson 2017). While providing feedback can be time intensive, the Bee Watch program developed an automated natural language generated feedback program that immediately gave generalized feedback and information to users after expert review based on the species being (mis)identified (Blake et al. 2012; van der Wal et al. 2016).

The Bee Watch program found that this automated feedback greatly increased participant learning, skill, and retention (Blake et al. 2012; van der Wal et al. 2016). The Evolution MegaLab project gave immediate automated feedback to users upon record submission, including text and figures comparing their submission to historic records in the same area, which also helped to motivate their participants (Worthington et al. 2012). Several community science programs, such as iNaturalist, Pl@ntNet, and Merlin Bird ID, use an artificial intelligence and deep learning computer programs to suggest identifications based on comparison to other photos in their database and nearby records, which provides instant feedback to users (Wäldchen and Mäder 2018; Ceccaroni et al. 2019). The use of new technologies, including new software programs, will help to remedy some currently existing challenges in both Bumble Bee Watch and community science programs in general to improve data collection and the user experience going forward (Newman et al. 2012; Wäldchen and Mäder 2018; Ceccaroni et al. 2019).

The areas of improvement noted by Bumble Bee Watch users were also commonly the main areas users enjoy with the program, such as the resources available on the website and their ability to help save the bees through the sharing of their data. This suggests that although more can be done, such as customized regional bee identification workshops or pollinator-friendly gardening guides, program organizers are on the right track with the provided features. We do not discuss the accuracy or perception of user and expert identification in this paper as has been done for other bumble bee community science programs (Lye et al. 2011; Suzuki-Ohno et al. 2017; Falk et al. 2019), but this information (including commonly mis-identified species) would also help to improve the program and data quality (but see MacPhail et al. in review) (**edit for thesis version of paper: now published as (MacPhail et al. 2020b)*).

Our survey was conducted in the winter months when bumble bees are not active across most of North America, and submissions to the program are thus low. It is possible that users might have had slightly different opinions, or different rankings of opinions, than if we had done the survey during the peak of the active season. For instance, respondents may have forgotten difficulties such as potential issues with the submission process but been more aware of the delays in getting verification of their photos. However, as some respondents had multiple years of participation to reflect on and some submit their photos throughout the fall and winter, and as a wide variety of responses were recorded across the participants, any temporal-related biases in our results are likely low.

The experts who responded to our survey were generally pleased with the Bumble Bee Watch program, although they also had suggestions on how to improve the program interface and

quality of the data. The main areas that they believed the data could be used for included filling knowledge gaps, supporting provincial and federal assessments, effecting policy and legislation, encouraging habitat restoration and management efforts, and guiding further research. However, despite the many areas of potential use, only about half of the experts have actually used Bumble Bee Watch data in their research. The advertisement of the dataset availability and example questions may be worthwhile for Bumble Bee Watch to share with researchers and conservationists through formal academic means and social media. As the program and dataset grow, more avenues to use the data will also evolve. Indeed, Bumble Bee Watch data are routinely accepted into the Bumble Bees of North America database managed by Dr. Leif Richardson and the USGS BISON (Biodiversity Information Serving Our Nation) database (<https://bison.usgs.gov>), and has also been added to other national and regional databases, so the data are increasingly becoming available to researchers.

Over half of our user survey respondents were middle-aged, between 45 and 64 years of age, which is common of many programs as they include the group who often have more time to volunteer as they have older children and more stable employment or have retired (Guiney and Oberhauser 2009; Purcell et al. 2012; Toomey and Domroese 2013; Domroese and Johnson 2017; Sheppard et al. 2017). Interestingly, we had more individuals that were 75 years of age and older respond to our survey than those under 24 years of age. While we had few respondents in the latter group, this may be because most youth under 18 would only participate with an adult and/or under an adult's account. Yet there are benefits for youth participation, not only to get them started on a life-long love of nature and contribution to community science and conservation projects but also because they can often be single-focused and energetic, and be

more skilled than adults in some areas (Wells and Lekies 2006; Guiney and Oberhauser 2009; Griffin Burns and Harasimowicz 2012; Silvertown et al. 2013). Our results show that there was no difference in the number of records submitted per age group. Our program encourages people to get outside and be active while enjoying their local gardens or trails, which is a necessary part of having a healthy physical, mental, and social life, especially for older adults who tend to become inactive over time (Buchner et al. 1992; Wagner, E., La Croix, AZ., Buchner, DM., Larson 1992; Phillips et al. 2004; Bushway et al. 2011).

While every province, state and territory that have bumble bees were represented in the Bumble Bee Watch database, some of these regions have low participation rates as compared to the relative proportion of the population and to the entire program as a whole. Increased promotion of the program in these areas, including through targeted presentations, "bee walks", and dedicated survey programs could help to increase data coverage. For example, one of us (VJM), gave a public presentation, bee walk, and CBC media interview on Prince Edward Island in August 2019, and in the following three months the number of submissions had almost doubled (1.8 times) what had been submitted from the province in the previous five and a half years combined; in fact, 25.5 times more records were submitted in the three-month August through October 2019 period as compared to the average of the same three months in the preceding five years. After a single CBC media interview in New Brunswick in August 2019, about 5.8 times the number of records were submitted in August through October time period compared to the average of those months over the previous 5 years. General advertising should account for the motivations of residents from different types of areas of physical and demographic communities, such as advertising the ability to find and share rare species to those in rural and suburban areas

or to participate in special events to those in urban areas. Although there was no difference in the number of records submitted based on the area in which people live, urban residents had the least number of respondents in our survey; it is possible that this is due to the erroneous belief that cities do not contain bumble bees or that they are already well surveyed: advertising could help alleviate these concerns. As we did not provide definitions as to what constituted urban, suburban, or rural, it is also possible that some respondents identified with the suburban category instead of the urban category, explaining the lower number in the latter group.

While there are challenges with community science programs, there is an increased understanding of the need for good practices, from data collection and validation to participant communications and retention (Bell et al. 2008; Silvertown 2009; Conrad and Hilchey 2011; Cooper et al. 2012; Phillips et al. 2012; Worthington et al. 2012). The development of appropriate protocols and supports (administrative, technological, and financial), can overcome the challenges and ensure the positive, long-lasting outcomes of these programs (Conrad and Hilchey 2011; Cooper et al. 2012; Dickinson and Bonney 2012; Pocock et al. 2015).

Conclusion

Bumble Bee Watch has the potential to engage the public, answer research questions, and increase the conservation of bumble bees across the United States and Canada through avenues resulting from having thousands of participants of various ages from rural through urban location increasing their understanding of bumble bee diversity and their desire to conserve them while generating the data for research and conservation purposes via photo submissions of the bumble bees they see across the landscape. Improvements are needed in order to maximize volunteer retention and data quality, which could include the adoption of new technology such as

automated feedback and the provision of more targeted resources such as identification guides and species lists. Further promotion of community science programs amongst academia, conservationists, policy makers, politicians, and the general public should occur in order to increase the number of participants and submissions (both geographically and temporally), the use of the data amongst a broader group of stakeholders and finally, our knowledge of species and our interest in conserving them.

Tables and Figures

Table 6.1: Motivations for participating, as selected by user survey respondents from a provided list of options. Respondents (n=342) could select more than one motivation so numbers do not add up to 342 respondents or 100%.

Motivations	Number of respondents	Percent of respondents
To contribute to scientific data collection	302	88.30
I'm worried about bees and want to help save them	284	83.04
I want to learn what species are on my property	214	62.57
I have a personal interest in bumble bees	203	59.36
I want to learn how to identify the biodiversity in my region	192	56.14
To share the uncommon or rare species I find	126	36.84
Recreational learning/Family activity	120	35.09
Participation in special events (e.g. Great Canadian Bumble Bee Count or a Bioblitz)	47	13.74
The preservation of ecological diversity	1	0.29

Table 6.2. Categories of feedback about what respondents (n=255) to the user survey liked best about the Bumble Bee Watch program. Note that respondents could make multiple suggestions so the total of all categories do not add up to 100%. Free-form responses were initially coded into one of 31 categories by three individuals, and then further collapsed into these 7 categories. Respondents who provided feedback that was not related to the question were excluded.

Program Features Liked Best	Number of Respondents	Percent of Respondents
Resources on the website (including identification keys, data/records, photos, maps)	99	38.82
Contributing to both user and general knowledge, and contribution to conservation efforts about bumble bees, incl helping to influence policy	86	33.73
Educational - helps with learning about bumble bees	63	24.71
Identification and feedback on submitted records	46	18.04
Fun, family-friendly outdoor based hobby, community of users	45	17.65
Easy to use, works great	33	12.94
Availability of app	7	2.75

Table 6.3. A comparison of the Bumble Bee Watch user survey respondents' age groups to the combined United States and Canadian populations in 2016 (Statistics Canada 2017a; United States Census Bureau 2017a). Note that the age groupings varied between the survey and the national demographics for the two youngest classes. Total number of respondents to the survey was 342. The total population aged 10-75+ was 280,705,770 in the United States and 17,858,089 in Canada, for a combined total of 298,563,859.

Age Group	Percent of User Survey Respondents	Percent of US and Canada Combined Population
12 to 17 (survey) or 10 to 19 (US & Canada)	0.29	15.55
18 to 24 years survey or 20 to 24 years (US & Canada)	1.75	8.20
25 to 34 years	8.19	15.75
35 to 44 years	15.20	14.48
45 to 54 years	21.05	15.21
55 to 64 years	30.99	14.23
65 to 74 years	19.88	9.58
75 plus	2.63	7.00

Table 6.4. The relative percent of Bumble Bee Watch user survey respondents (342 individuals) and program contributors (6,292 unique individuals across both nest and bee records, as of February 28, 2018) per number of records submitted to the Bumble Bee Watch database.

Number of Records Submitted to Bumble Bee Watch	Percent of User Survey Respondents	Percent of Database Contributors
Less than 10	69.0	94.2
10-20	17.0	3.8
More than 20	8.8	1.3
More than 50	5.0	0.76
(blank)	0.3	n/a
Grand Total	100.0	100.0

Table 6.5. Ideas of questions that Bumble Bee Watch data can be used to answer, according to respondents to the expert survey (n=15). Free-form responses were summarized and coded to get to these categories.

Categories	Number of Respondents	Percent of Respondents
Species ranges, including current distributions, range contractions and expansions, species distribution models	13	86.67
Phenology for each bee species, including different castes	7	46.67
Collecting information on rare species, comparing ratios and trends in ratios of common to uncommon species, investigating changes in diversity, and calculating species status/extinction risk	5	33.33
Floral associations, including changes in	4	26.67
Understanding species diversity and habitat preferences	2	13.33
Monitoring, detection and prevalence studies	2	13.33
“So many” [ways data can be used]	2	13.33
To see if participation in Bumble Bee Watch affects participant behaviour	1	6.67
To feed into studies looking at different factors to see if they affect bumble bees (e.g. climate change, habitat loss)	1	6.67
Machine learning based identifications	1	6.67
Bee identification success rates	1	6.67
Identification of sites for research and restoration work	1	6.67

Chapter 7. Conclusion

Victoria J. MacPhail

Biodiversity loss is a huge concern worldwide, particularly with the effects of climate change starting to be felt, and evidence of our being in the sixth mass species extinction event becoming obvious (Memmott et al. 2007; Ceballos et al. 2017; World Wildlife Federation 2018; Jarvis 2018; Goulson 2019; IPBES 2019; Sánchez-Bayo and Wyckhuys 2019; Didham et al. 2020; Williams et al. 2020). This is happening at a time when government funding and monitoring efforts related to conservation are often being cut back (Gardner et al. 2003; Conrad and Hilchey 2011; Bonter et al. 2012; Dickinson and Bonney 2012; Silvertown et al. 2013; Newediuk et al. 2021). Community science programs are a cost-effective way of increasing data collection and can supplement or yield cost effective alternatives to the traditional scientific approach (Silvertown 2009; Conrad and Hilchey 2011; Hoyer et al. 2012; Birkin and Goulson 2015; Le Féon et al. 2016; NASEM 2018). Bumble bees are just one of the many groups with species facing declines in North America, and for which more information is needed to help conserve them (Colla and Packer 2008; Cameron et al. 2011b; Bartomeus et al. 2013; Colla 2016; Williams et al. 2020). The Bumble Bee Watch (BBW) community science program was created with the goal of conserving bumble bees, via data obtained through photographs taken by volunteers across the US and Canada and identified by regional experts.

Community science involves projects where, most commonly, professional scientists oversee non-professional volunteers in collecting and/or analyzing data to answer a specific question or to advance scientific knowledge, although non-professionals may also design the research program (Eitzel et al. 2017; McKinley et al. 2017; NASEM, 2018; Auerbach et al. 2019; Heigl et

al. 2019b; Lepczyk et al. 2020). There are many benefits of community science to the participants, researchers, society, and the environment. However, this is a field that is relatively new and fast growing, and thus is still lacking a lot of cohesiveness regarding areas from definitions through protocols. For this dissertation, I reviewed key literature in the field to date, discussed benefits, successes, and challenges and suggested best practices that can make projects more efficacious on many levels (Ch 2). These included areas such as experimental design, data analysis and quality control; volunteer recruitment, training, and retention; motivations for and effects of participation; data management and security; data sharing and project overlap; obtaining funding and other resources; economic, social, and political controversies; project assessment and evaluation; and new technologies. While more research and cohesiveness are needed, interdisciplinary teams are best able to plan and administer programs, sharing successes, failures, and insights amongst those working in community science field is needed, and the broader public and scientific community need to be made more aware of this field's potential.

Having detailed information on a species, such as their habitat and life history needs, is essential for not only their conservation but to answer other questions now and into the future (Potts et al. 2010; Tylianakis et al. 2010; Burkle et al. 2013; Goulson et al. 2015; Colla 2016; McKinley et al. 2017; MacPhail et al. 2018). Indeed, every single observation recorded now represents a unique point that will never occur again and cannot be recreated, and thus could be invaluable. In comparing BBW data to that of the most comprehensive source of *Bombus* data for Canada and the United States, the Bumble Bees of North America database (Richardson 2020) it is clear that BBW complements and adds to our overall knowledge, from total number of records to examples of range in-fill and expansion and a greater diversity of plant forage hosts (Chapter 3).

As an additional “bonus”, BBW accomplishes this using non-lethal techniques, reducing concerns about surveying in areas where at-risk species may be located and accidentally collected, the need for specialized equipment or training of individuals, and the need to kill individuals for identifications to take place.

Instances of increased information related to range and specific locations of species are common with community-science programs (Munson et al. 2010; Losey et al. 2012; Dennis et al. 2017; Zapponi et al. 2017; Soroye et al. 2018; Flockhart et al. 2019). Programs may even indirectly gather information now that may later be of benefit, from weather conditions to genetic material to co-occurring species (McClenachan 2009; Miller-Rushing et al. 2012; Albani Rocchetti et al. 2021). For example, the BBW analysis of plant species was based on user-submitted plant identifications, and not all records had this information entered: additional information could be further gathered through identification of the forage species in the submitted photos by a plant biologist.

It can be difficult to document species that only occur in remote regions where there are not as many human observers, particularly as compared to urban areas (van der Wal et al. 2015; Blaney et al. 2016), but targeted promotion of community science programs to people living or working in these areas, with an emphasis on the value of and need for their observations, can help (Chu et al. 2012; van der Wal et al. 2015). Indeed, community science programs are known for often finding species and collecting information from regions not commonly visited by professional researchers (Losey et al. 2012; Zapponi et al. 2017; Soroye et al. 2018).

Many conservation actions cannot occur until a species has been assessed as being at-risk of extinction (Rodrigues et al. 2006; Baillie et al. 2008; Mace et al. 2008; Cardoso et al. 2011; Colla 2016; MacPhail et al. 2018; Lemieux et al. 2021; Newediuk et al. 2021). Yet assessments are often hindered by a lack of data (Potts et al. 2010; Colla 2016; Lemieux et al. 2021; Newediuk et al. 2021). Chapter 4 showed that BBW data can be used in conjunction with traditional scientific data sources (e.g. the BBNA database) to increase the overall sample size and to add new locations of the species for conservation assessments. As the variables investigated in conservation status assessments can be influenced by survey effort (e.g. (Royal Botanic Gardens Kew 2017)), the greater the data set, the more accurate the assessment will be. Community science programs therefore have the potential to greatly assist in our understanding of the current population levels and distribution of species across small and large scales, and influence the conservation actions that can occur.

In order for data to be used in conservation assessments and policy and management, it must be of high quality with few to no errors. To achieve this, BBW uses an expert-assisted verification process, whereby participants may choose to assign a species name to their submission, but regional experts will confirm or change the identification as appropriate. A comparison of the original identification to the expert identification for BBW submissions (Chapter 5) found that the participant was correct only about half the time, although it varied greatly by species. Only 10 of the 42 species in our analyses were at or above the suggested level of 80% percent agreement that would eliminate or reduce the need for expert review (Aceves-Bueno et al. 2017), confirming the value of the approach of community science programs like BBW of reviewing each record.

There are challenges with identifying species from photos, particularly in the case of cryptic species (Williams et al. 2014, 2016; Sheffield et al. 2019, 2020; Sikes and Rykken 2020), or if the photos are of low quality or missing key identification features (Lye et al. 2011; Acorn 2017; Krell and Marshall 2017; Austen et al. 2018; MacPhail et al. 2020b). Yet, it is possible for most *Bombus* species, and this technique is increasingly being used by researchers (Lye et al. 2011; Roy et al. 2016; Comont and Ashbrook 2017; Suzuki-Ohno et al. 2017; Falk et al. 2019; Richardson et al. 2019)(in addition to the work discussed in this thesis). It is important to determine the species most commonly mis-identified and potential reasons for this, impact of observer bias, perceived ease of identification, and the role of conservation status in levels of agreement (Ch 5). The development of more resources to help participants learn to take the best photos and angles, interface prompts during the submission process, and increased filters and checkpoints on the database, can help increase the accuracy of identifications, which in turn can benefit the participants, experts and the program overall (Crall et al. 2011; Bonter and Cooper 2012; Freitag et al. 2016; Kosmala et al. 2016; Aceves-Bueno et al. 2017; Suzuki-Ohno et al. 2017).

It is important for community science programs to understand the demographics of participants, their reasons for participating in and views on the programs, and any outcomes of their participation, as well as the views of program administrators and end users of the data (Bonney et al. 2009a, b; Silvertown 2009; Van Den Berg et al. 2009). They can then ensure that the needs and desires of volunteers are met, and problem areas addressed (Bonney et al. 2009b, a; Silvertown 2009; Conrad and Hilchey 2011; Chu et al. 2012; Fitzpatrick 2012; Greenwood 2012;

Purcell et al. 2012; Silvertown et al. 2013; Domroese and Johnson 2017). Survey results of both participants and experts involved with BBW showed that there was high appreciation of program, with many positive experiences reported (Ch 6). These are common motivations and outcomes of participants in nature-based programs, but it is still important to keep working to improve experiences (Guiney and Oberhauser 2009; Van Den Berg et al. 2009; Newman et al. 2012; Lewandowski and Oberhauser 2017). Although the expert respondents generated a list of multiple areas where BBW data could help, such as filling knowledge gaps (species diversity, ranges, habitat, phenology, floral associations, etc.), supporting species status assessments, effecting policy and legislation, encouraging habitat restoration and management efforts, and guiding further research, only about half had used data from BBW at the time of the survey: this is an indication that more promotion of the dataset is needed.

One of the most biggest challenges with the BBW program (Ch 6), and that of similar ones (Comont and Ashbrook 2017; Falk et al. 2019), is the time lag that exists between a participant submitting an observation and receiving feedback on it, as well as the amount and type of feedback given (Blake et al. 2012; van der Wal et al. 2016; Domroese and Johnson 2017; Falk et al. 2019). Reviewers on BBW are primarily experts contributing their time voluntarily, in conjunction with their other responsibilities, so they cannot always keep up with the influx of new submissions, particularly during the field season. Artificial Intelligence (AI) programs that provide “instant” identifications may help give participants immediate feedback, and potentially reduce the need for manual review of every single observation, instead allowing sub-samples/spot-checks of identifications of common species with high predicted match accuracy, freeing up more time for experts to concentrate on more uncommon or harder to identify species

(Wäldchen and Mäder 2018; Ceccaroni et al. 2019). As this conclusion was being written, a beta version of an AI program was being tested for BBW, where users could click through and get a predicted identification after submitting their observation. This AI program was trained on the large gallery of verified images available on BBW. Another AI program, known as the “BeeMachine” and created by Spiesman et al. (2021), has shown early success in providing identifications of bumble bee images; this model is another that could be incorporated into BBW. Automatically generated feedback, such as done with the UK BeeWatch program, and/or the ability for experts to choose from a list of common feedback, can also help to increase the amount of information participants receive along with the identification (e.g. natural history facts about the species identified, differences between similar-looking species with misidentifications), and improve their learning and skill levels as well (Blake et al. 2012; van der Wal et al. 2016; Domroese and Johnson 2017; Falk et al. 2019).

While survey respondents were generally quite positive about their experiences, it is clear that the overall participation and retention rate for BBW is low (Ch 6) (as is common with most community science programs (Worthington et al. 2012; Silvertown et al. 2013, 2015; Kelling et al. 2015b; Domroese and Johnson 2017)). For example, as of May 18, 2021, when this conclusion was being written, BBW had 33,483 registered users; however, of these, only 12,804 had submitted records. Similarly, the two apps have been downloaded 47,177 times in the US and Canada (with additional downloads from outside that region), but not always opened or used. However, while most participants submit <10 observations, some have submitted hundreds and even over a thousand records; it is this latter group, the “super users” or “super volunteers” that are especially important to recognize and retain (Wood et al. 2011; Hames et al. 2012;

Silvertown et al. 2013; Kelling et al. 2015b; Hannibal 2016). The participant experience can be improved in several ways. In addition to speeding up the verification and feedback as mentioned above, giving participants frequent communications is critical (Ch 2, 6). Examples include providing summaries of the program and its progress towards its goals; examples of how their data has been used (e.g. recent publications); highlighting interesting news (e.g. records of rare species, volunteer profiles); and providing new educational resources (e.g. regional bee identification guide, plant list for attracting bumble bees).

The collection and verification of data are not enough for conservation to happen: the data must be used by researchers, land managers, conservationists, policy makers, and others. BBW data have now been used in other conservation status assessments (Szymanski et al. 2016; Committee on the Status of Endangered Wildlife in Canada 2018), regional checklists (Gibbs et al. 2017), and in the identification of sites for specialized research or as part of larger data sets for modelling work (Gibson et al. 2019; Liczner and Colla 2020), but more promotion of the data should still occur amongst those in the relevant fields. While BBW data can be viewed in real time via an interactive map or gallery on the website or app, and relevant sections of the database shared with users who request it via a data request form on the website, researchers have other options to access the data. BBW also began providing annual data dumps to BISON and GBIF (two large internationally recognized databases) in late 2015/early 2016, and with BBNA in 2016/2017, as well as upon request to national and regional databases, so data are slowly becoming more available. Additionally, by getting more participants involved, and by increasing the awareness of the general public about the plight of the bumble bee and other species, the probability of actions being undertaken by governments, conservation groups, and the public will

also increase (Bickford et al. 2012; Colla and MacIvor 2017; Underwood et al. 2017; Cardoso and Gonçalves 2018; Hall and Steiner 2019; Hall and Martins 2020; Requier et al. 2020; Vierssen Trip et al. 2020; Althaus et al. 2021; Albani Rocchetti et al. 2021).

From the time Bumble Bee Watch was launched on January 22, 2014 until May 18, 2021, a total of 79,617 bee and nest observations had been submitted. This number is ever increasing, particularly as more formal survey programs involving community scientists use it (Tompkins and Rowe 2020; The Xerces Society for Invertebrate Conservation 2021). As seen throughout the preceding chapters, these data have great value for the conservation of *Bombus* across North America, complementing work done by experts, as well as having positive impacts on participants. BBW is therefore an example of a community science program that, while improvements can be made, is invaluable even as it continues to grow.

In conclusion, this research shows the value of community science programs, and the power of combining both researcher and community science data to answer broad-scale, ecological research questions. They can fill knowledge gaps, increase conservation status assessments, recommend recovery actions, and influence policy, in addition to meeting the public's desire to contribute to science, learn about the world around them, and to help save species. While there are challenges to running a successful program, an increasing number of protocols and supports are being developed and shared amongst those working in the field. Further promotion of community science programs amongst academia, conservationists, policy makers, politicians, and the public should occur in order to increase their impact.

References

- Aceves-Bueno E, Adeleye AS, Feraud M, et al (2017) The accuracy of citizen science data: a quantitative review. *Bull Ecol Soc Am* 98:278–290. doi: 10.1002/bes2.1336
- Acorn JH (2017) Entomological citizen science in Canada. *Can Entomol* 785:1–12. doi: 10.4039/tce.2017.48
- Agricorp (2016a) 2016 Corn Harvest at a glance (yield map). In: Corn Harvest. yields. <http://www.agricorp.com/en-ca/News/2017/Pages/PI-MapsShowAverageCornSoybeanYields.aspx>
- Agricorp (2016b) 2016 Soybean Harvest at a glance (yield map). In: Soybean Harvest. yields. <http://www.agricorp.com/en-ca/News/2017/Pages/PI-MapsShowAverageCornSoybeanYields.aspx>
- Agriculture and Agri-Food Canada (2017) Bee Health Roundtable. <http://www.agr.gc.ca/eng/industry-markets-and-trade/value-chain-roundtables/bee-health/?id=1409832956249>. Accessed 2 Mar 2017
- Albani Rocchetti G, Armstrong CG, Abeli T, et al (2021) Reversing extinction trends: new uses of (old) herbarium specimens to accelerate conservation action on threatened species. *New Phytol* 171:133. doi: 10.1111/nph.17133
- Althaus SL, Berenbaum MR, Jordan J, Shalmon DA (2021) No buzz for bees: Media coverage of pollinator decline. *PNAS* 118:e2002552117. doi: 10.1073/pnas.2002552117
- Ancker JS, Flanagan A (2007) A comparison of conflict of interest policies at peer-reviewed journals in different scientific disciplines. *Sci Eng Ethics* 13:147–157. doi: 10.1007/s11948-007-9011-z
- Andow DA, Borgida E, Hurley TM, Williams AL (2016) Recruitment and Retention of

- Volunteers in a Citizen Science Network to Detect Invasive Species on Private Lands. *Environ Manage* 58:606–618. doi: 10.1007/s00267-016-0746-7
- Arbetman MP, Gleiser G, Morales CL, et al (2017) Global decline of bumblebees is phylogenetically structured and inversely related to species range size and pathogen incidence. *Proc R Soc B Biol Sci* 284:. doi: 10.1098/rspb.2017.0204
- Ascher JS, Marshall L, Meiners J, et al (2020) Heterogeneity in large-scale databases and the role of climate change as a driver of bumble bee decline. *Science* 367:685–688
- Auerbach J, Barthelmess EL, Cavalier D, et al (2019) The problem with delineating narrow criteria for citizen science. *Proc Natl Acad Sci U S A* 116:15336–15337. doi: 10.1073/pnas.1909278116
- Austen GE, Bindemann M, Griffiths RA, Roberts DL (2016) Species identification by experts and non-experts: comparing images from field guides. *Sci Rep* 6:33634. doi: 10.1038/srep33634
- Austen GE, Bindemann M, Griffiths RA, Roberts DL (2018) Species identification by conservation practitioners using online images: accuracy and agreement between experts. *PeerJ* 6:e4157. doi: 10.7717/peerj.4157
- Bachman S, Moat J, Hill AW, et al (2011) Supporting red list threat assessments with GeoCAT: Geospatial conservation assessment tool. *Zookeys* 150:117–126. doi: 10.3897/zookeys.150.2109
- Baillie JEM, Collen B, Amin R, et al (2008) Toward monitoring global biodiversity. *Conserv Lett* 1:18–26. doi: 10.1111/j.1755-263x.2008.00009.x
- Ballard HL, Dixon CGH, Harris EM (2017) Youth-focused citizen science: Examining the role of environmental science learning and agency for conservation. *Biol Conserv* 208:65–75.

doi: 10.1016/j.biocon.2016.05.024

- Bartomeus I, Ascher JS, Gibbs J, et al (2013) Historical changes in northeastern US bee pollinators related to shared ecological traits. *Proc Natl Acad Sci U S A* 110:4656–60. doi: 10.1073/pnas.1218503110
- Bartomeus I, Ascher JS, Wagner D, et al (2011) Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proc Natl Acad Sci* 108:20645–20649. doi: 10.1073/pnas.1115559108
- Beckham JL, Atkinson S (2017) An updated understanding of Texas bumble bee (Hymenoptera: Apidae) species presence and potential distributions in Texas, USA. *PeerJ* 5:e3612. doi: 10.7717/peerj.3612
- Bell S, Marzano M, Cent J, et al (2008) What counts? Volunteers and their organisations in the recording and monitoring of biodiversity. *Biodivers Conserv* 17:3443–3454. doi: 10.1007/s10531-008-9357-9
- Berenguer J, Corraliza JA, Martin R (2005) Rural-Urban differences in environmental concern, attitudes, and actions. *Eur J Psychol Assess* 21:128–138. doi: 10.1027/1015-5759.21.2.128
- Bickford D, Posa MRC, Qie L, et al (2012) Science communication for biodiversity conservation. *Biol Conserv* 151:74–76. doi: 10.1016/j.biocon.2011.12.016
- Birkin L, Goulson D (2015) Using citizen science to monitor pollination services. *Ecol Entomol* 40:3–11. doi: 10.1111/een.12227
- Black SH, Hodges N, Vaughan M, Shepherd M (2007) *Pollinators in Natural Areas: A Primer on Habitat Management*
- Blake S, Sharma N, Darvill B, et al (2012) Natural language generation for nature conservation: Automating feedback to help volunteers identify bumblebee species. *Proc Conf Comput*

Linguist 2012 Tech Pap 2012:311–324

Blaney RJP, Philippe ACV, Pocock MJO, Jones GD (2016) Citizen science and environmental monitoring: Towards a methodology for evaluating opportunities, costs and benefits

Bonney R (1996) Citizen Science - A Lab Tradition. *Living Bird* 15:7–15

Bonney R, Ballard H, Jordan R, et al (2009a) Public Participation in Scientific Research: Defining the Field and Assessing Its Potential for Informal Science Education. A CAISE Inquiry Group Report. A CAISE Inq Gr Rep 58

Bonney R, Cooper CB, Dickinson J, et al (2009b) Citizen science: A developing tool for expanding science knowledge and scientific literacy. *Bioscience* 59:977–984. doi: 10.1525/bio.2009.59.11.9

Bonney R, Dickinson JL (2012) Overview of Citizen Science. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 19–26

Bonney R, Phillips TB, Ballard HL, Enck JW (2016) Can citizen science enhance public understanding of science? *Public Underst Sci* 25:2–16. doi: 10.1177/0963662515607406

Bonney R, Shirk JL, Phillips TB, et al (2014) Citizen science: Next steps for citizen science. *Science* 343:1436–1437. doi: 10.1126/science.1251554

Bonter DN, Cooper CB (2012) Data validation in citizen science: A case study from Project FeederWatch. *Front Ecol Environ* 10:305–307. doi: 10.1890/110273

Bonter DN, Oberhauser KS, Marra PP, et al (2012) Projects and possibilities: Lessons from citizen science projects. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 27–57

- Bozeman B, Gaughan M (2007) Impacts of grants and contracts on academic researchers' interactions with industry. *Res Policy* 36:694–707. doi: 10.1016/j.respol.2007.01.007
- Bubela T, Nisbet MC, Borchelt R, et al (2009) Science communication reconsidered. *Nat Biotechnol* 27:514–518. doi: 10.1038/nbt0609-514
- Buchmann SL, Nabhan GP (1996) *The forgotten pollinators*. Island Press, Washington, D.C.
- Buchner DM, Beresford SAA, Larson EB, et al (1992) Effects of physical activity on health status in older adults II: Intervention studies. *Annu Rev Public Health* 13:469–488. doi: 10.1146/annurev.publhealth.13.1.469
- Burgess HK, DeBey LB, Froehlich HE, et al (2017) The science of citizen science: Exploring barriers to use as a primary research tool. *Biol Conserv* 208:113–120. doi: 10.1016/j.biocon.2016.05.014
- Burkle LA, Marlin JC, Knight TM (2013) Plant-Pollinator Interactions over 120 Years: Loss of Species, Co-Occurrence, and Function. *Science* 339:1611–1615. doi: 10.1126/science.1232728
- Bushway L, Dickinson J, Stedman R, et al (2011) Benefits, motivations, and barriers related to environmental volunteerism for older adults: Developing a research agenda. *Int J Aging Hum Dev* 72:189–206. doi: 10.2190/AG.72.3.b
- California Academy of Sciences (2019) *Citizen science toolkit - teaching science through citizen science*, 2015th edn.
- Cameron S, Jepsen S, Spevak E, et al (2011a) *North American Bumble Bee Species Conservation Planning Workshop Final Report*
- Cameron SA, Lim HC, Lozier JD, et al (2016) Test of the invasive pathogen hypothesis of bumble bee decline in North America. *Proc Natl Acad Sci* 113:4386–4391. doi:

10.1073/pnas.1525266113

Cameron SA, Lozier JD, Strange JP, et al (2011b) Patterns of widespread decline in North American bumble bees. *Proc Natl Acad Sci U S A* 108:662–667. doi:

10.1073/pnas.1014743108

Cameron SA, Sadd BM (2020) Global Trends in Bumble Bee Health. *Annu Rev Entomol* 65:1–24. doi: 10.1146/annurev-ento-011118-111847

Cameron SA, Williams PH, Day L (2001) E-mail communications regarding bee stings. In: *Bombus-L List*. <https://listserv.umd.edu/cgi-bin/wa?A2=ind0104&L=BOMBUS-L&P=R214&I=-3>. Accessed 9 Jul 2018

Cardoso MC, Gonçalves RB (2018) Reduction by half: the impact on bees of 34 years of urbanization. *Urban Ecosyst* 21:943–949. doi: 10.1007/s11252-018-0773-7

Cardoso P, Erwin TL, Borges PA V, New TR (2011) The seven impediments in invertebrate conservation and how to overcome them. *Biol Conserv* 144:2647–2655. doi: 10.1016/j.biocon.2011.07.024

Ceballos G, Ehrlich PR, Dirzo R (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proc Natl Acad Sci U S A* 114:E6089–E6096. doi: 10.1073/pnas.1704949114

Ceccaroni L, Bibby J, Roger E, et al (2019) Opportunities and Risks for Citizen Science in the Age of Artificial Intelligence. *Citiz Sci Theory Pract* 4:1–14. doi: <https://doi.org/10.5334/cstp.241> ESSAY

Chandler M, Rullman S, Cousins J, et al (2017) Contributions to publications and management plans from 7 years of citizen science: Use of a novel evaluation tool on Earthwatch-supported projects. *Biol Conserv* 208:163–173. doi: 10.1016/j.biocon.2016.09.024

- Chandler M, See L, Copas K, et al (2016) Contribution of citizen science towards international biodiversity monitoring. *Biol Conserv.* doi: 10.1016/j.biocon.2016.09.004
- Chu M, Leonard P, Stevenson F (2012) Growing the Base for Citizen Science - Recruiting and Engaging Participants. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 69–81
- Citizen Science Association (2020) Current Working Groups.
<https://www.citizenscience.org/get-involved/working-groups/>. Accessed 6 May 2020
- CitizenScience.gov (2020) Federal Crowdsourcing and Citizen Science Toolkit. In: U.S. Gen. Serv. Adm. <https://www.citizenscience.gov/toolkit/#>. Accessed 6 May 2020
- Cohen J (1960) A coefficient of agreement for nominal scales. *Educ Psychol Meas* XX:37–46
- Colla SR (2016) Status, threats and conservation recommendations for wild bumble bees (*Bombus* spp.) in Ontario, Canada: A review for policymakers and practitioners. *Nat Areas J* 36:412–426. doi: 10.3375/043.036.0408
- Colla SR (2017) Recovery Strategy for the Gypsy Cuckoo Bumble Bee (*Bombus bohemicus*) in Ontario. Ontario Recovery Strategy Series. Peterborough, Ontario
- Colla SR, Ascher JS, Arduser M, et al (2012a) Documenting persistence of most eastern North American bee species (Hymenoptera: Apoidea: Anthophila) to 1990– 2009. *J Kansas Entomol Soc* 85:14–22. doi: 10.2307/41681218
- Colla SR, Dumesh S (2010) The bumble bees of Southern Ontario: notes on natural history and distribution. *J Entomol Soc Ontario* 141:39–68. doi: 10.1007/s00442-011-2179-6
- Colla SR, Gadallah F, Richardson L, et al (2012b) Assessing declines of North American bumble bees (*Bombus* spp.) using museum specimens. *Biodivers Conserv* 21:3585–3595. doi:

10.1007/s10531-012-0383-2

Colla SR, MacIvor JS (2017) Questioning public perception, conservation policy, and recovery actions for honeybees in North America. *Conserv Biol* 31:1202–1204. doi:

10.1111/cobi.12839

Colla SR, Packer L (2008) Evidence for decline in eastern North American bumblebees

(Hymenoptera: Apidae), with special focus on *Bombus affinis* Cresson. *Biodivers Conserv* 17:1379–1391. doi: 10.1007/s10531-008-9340-5

Colla SR, Taylor-Pindar A (2011) Recovery Strategy for the Rusty-patched Bumble Bee

(*Bombus affinis*) in Ontario. Ontario Ministry of Natural Resources, Peterborough, Ontario

Colla SSR, Otterstatter MMC, Gegear RJR, Thomson JD (2006) Plight of the bumble bee:

Pathogen spillover from commercial to wild populations. *Biol Conserv* 129:461–467. doi:

10.1016/j.biocon.2005.11.013

Collen B, Bohm M, Kemp R, Baillie JE. (2012) Spineless: Status and Trends of the World's

Invertebrates. Zoological Society of London, London, United Kingdom

Collins HM, Evans R (2002) The Third Wave of Science Studies: Studies of Expertise and

Experience. *Soc Stud Sci* 32:235–296. doi: 10.1177/0306312702032002003

Committee on the Status of Endangered Wildlife in Canada (2014) COSEWIC assessment and

status report on the Gypsy Cuckoo bumble bee *Bombus bohemicus* in Canada. Ottawa,

Ontario

Committee on the Status of Endangered Wildlife in Canada (2018) COSEWIC assessment and

status report on the American Bumble Bee *Bombus pensylvanicus* in Canada - In Press.

Ottawa, Ontario

Committee on the Status of Species at Risk in Ontario (2010) COSSARO Candidate Species at

Risk Evaluation Form for Rusty-patched Bumble Bee (*Bombus affinis*).

https://files.ontario.ca/environment-and-energy/species-at-risk/stdprod_086371.pdf

Committee on the Status of Species at Risk in Ontario, COSSARO (2014) Ontario species at risk evaluation report for Gypsy Cuckoo bumble bee (*Bombus bohemicus*). Minist Nat Resour 1–10

Comont RF, Ashbrook K (2017) Evaluating promotional approaches for citizen science biological recording: bumblebees as a group versus *Harmonia axyridis* as a flagship for ladybirds. *BioControl* 62:309–318. doi: 10.1007/s10526-016-9771-y

Conrad CC, Hilchey KG (2011) A review of citizen science and community-based environmental monitoring: Issues and opportunities. *Environ Monit Assess* 176:273–291. doi: 10.1007/s10661-010-1582-5

Cooper C, Dickinson J, Phillips T, Bonney R (2007) Citizen science as a tool for conservation in residential ecosystems. *Ecol Soc* 12:11. doi: 11

Cooper CB, Hawn CL, Larson LR, et al (2021) Inclusion in citizen science: The conundrum of rebranding. *Science* 372:1386–1388. doi: 10.1126/science.abi6487

Cooper CB, Hochachka WM, Dhondt AA (2012) The opportunities and challenges of citizen science as a tool for ecological research. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 99–113

Corbet SA, Williams IH, Osborne JL (1991) Bees and the pollination of crops and wild flowers in the european community. *Bee World* 72:47–59. doi: 10.1080/0005772X.1991.11099079

Cornell Lab of Ornithology (2018) Mission: Citizen Science.

<http://www.birds.cornell.edu/page.aspx?pid=1664>. Accessed 19 Apr 2018

COSEWIC (2014a) COSEWIC Assessment and Status Report Gypsy Cuckoo Bumble Bee

Bombus bohemicus in Canada. Ottawa, Ontario

COSEWIC (2010) COSEWIC assessment and status report on the rusty-patched bumble bee

Bombus affinis in Canada. Committee on the Status of Endangered Wildlife in Canada

COSEWIC (2014b) COSEWIC assessment and status report on the Western Bumble Bee

Bombus occidentalis, *occidentalis* subspecies (*Bombus occidentalis occidentalis*) and the *mckayi* subspecies (*Bombus occidentalis mckayi*) in Canada. Committee on the Status of Endangered Wildlife in Canada

COSEWIC (2015) COSEWIC Assessment and Status Report Yellow-banded Bumble Bee

Bombus terricola in Canada

Crall AW, Newman GJ, Stohlgren TJ, et al (2011) Assessing citizen science data quality: An

invasive species case study. *Conserv Lett* 4:433–442. doi: 10.1111/j.1755-263X.2011.00196.x

Danielson F, Jensen PM, Burgess ND, et al (2014) A multicountry assessment of tropical

resource monitoring by local communities. *Bioscience* 64:236–251. doi: 10.1093/biosci/biu001

Daume S, Galaz V (2016) “Anyone know what species this is?” - Twitter conversations as

embryonic citizen science communities. *PLoS One* 11:e0151387. doi: 10.1371/journal.pone.0151387

Davies L, Kwiatkowski L, Gaston KJ, et al (2011) UK National Ecosystem Assessment:

Technical Report. United Nations Environ Program World Conserv Monit Cent 361–410

Defenders of Wildlife (2015) A Petition to list the Yellow Banded Bumble Bee (*Bombus*

terricola) as an Endangered, or Alternatively as a Threatened, Species Pursuant to the

- Endangered Species Act and for the Designation of Critical Habitat for this Species. 1–34
- del Savio L, Prainsack B, Buyx A (2016) Crowdsourcing the human gut. Is crowdsourcing also “citizen science”? *J Sci Commun* 15:1–16. doi: 10.22323/2.15030203
- Den Broeder L, Devilee J, Van Oers H, et al (2018) Citizen Science for public health. *Health Promot Int* 33:505–514. doi: 10.1093/heapro/daw086
- Dennis EB, Morgan BJT, Brereton TM, et al (2017) Using citizen science butterfly counts to predict species population trends. *Conserv Biol* 31:1350–1361. doi: 10.1111/cobi.12956
- Dickinson JL, Bonney R (2012) Introduction: why citizen science? and introductions to Parts I, II, III. In: Dickinson JL, Bonney R (eds) *Citizen science: public participation in environmental research*. Cornell University Press, Ithaca, New York
- Dickinson JL, Shirk J, Bonter D, et al (2012) The current state of citizen science as a tool for ecological research and public engagement. *Front Ecol Environ* 10:291–297. doi: 10.1890/110236
- Dickinson JL, Zuckerberg B, Bonter DN (2010) Citizen science as an ecological research tool: challenges and benefits. *Annu Rev Ecol* 41:149–172. doi: 10.1146/annurev-ecolsys-102209-144636
- Dicks L V., Abrahams A, Atkinson J, et al (2013) Identifying key knowledge needs for evidence-based conservation of wild insect pollinators: A collaborative cross-sectoral exercise. *Insect Conserv Divers* 6:435–446. doi: 10.1111/j.1752-4598.2012.00221.x
- Didham RK, Basset Y, Collins CM, et al (2020) Interpreting insect declines: seven challenges and a way forward. *Insect Conserv Divers* 13:103–114. doi: 10.1111/icad.12408
- Domroese MC, Johnson EA (2017) Why watch bees? Motivations of citizen science volunteers in the Great Pollinator Project. *Biol Conserv* 208:40–47. doi: 10.1016/j.biocon.2016.08.020

- Donovan BJ, Wier SS (1984) Development of hives for field population increase, and studies on the life cycles of the four species of introduced bumble bees in New Zealand. *New Zeal J Agric Res* 21:733–756. doi: 10.1080/00288233.1978.10427476
- du Plessis V, Beshiri R, Bollman RD, Clemenson H (2002) Definitions of “Rural”. Statistics Canada Agriculture Division Catalogue no. 21-601-MIE — No. 061. Agric Rural Work Pap Ser 66:
- EarthWatch (2018) Expeditions. <http://earthwatch.org/Expeditions/Expedition-Search>. Accessed 18 Apr 2018
- Eaton DP, Keuroghlian A, Santos M do CA, et al (2017) Citizen scientists help unravel the nature of cattle impacts on native mammals and birds visiting fruiting trees in Brazil’s southern Pantanal. *Biol Conserv* 208:29–39. doi: 10.1016/j.biocon.2016.09.010
- Edwards KJ, Gaber MM (2014) *Astronomy and Big Data*. Springer International Publishing, Cham
- Eitzel M V, Cappadonna JL, Santos-Lang C, et al (2017) Citizen science terminology matters: Exploring key terms. *Citiz Sci Theory Pract* 2:1–20. doi: 10.5334/cstp.96
- Ellwood ER, Crimmins TM, Miller-Rushing AJ (2017) Citizen science and conservation: Recommendations for a rapidly moving field. *Biol Conserv* 208:1–4. doi: 10.1016/j.biocon.2016.10.014
- Environment and Climate Change Canada (2016) Recovery Strategy for the Rusty-patched Bumble Bee (*Bombus affinis*) in Canada [Proposed]. Ottawa, Ontario
- ESRI (2016) ArcGIS Desktop 10.5. (Computer Program). Environmental Systems Research Institute, Redlands, California
- ESTR Secretariat (2016) Mixedwood Plains Ecozone+ evidence for key findings summary.

- Canadian biodiversity: ecosystem status and trends 2010, Evidence for Key Findings
Summary Report No. 7. Canadian Councils of Resource Ministers, Ottawa, Ontario, Ontario
- Falk S, Id GF, Comont R, et al (2019) Evaluating the ability of citizen scientists to identify
bumblebee (*Bombus*) species. PLoS One 14:e0218614. doi:
<https://doi.org/10.1371/journal.pone.0218614>
- Federal Provincial and Territorial Governments of Canada (2014) 2012 Canadian nature survey:
Awareness, participation, and expenditures in nature-based recreation, conservation, and
subsistence activities. Canadian Councils of Resource Ministers, Ottawa, Ontario
- Fink D, Hochachka WM (2012) Using Data Mining to Discover Biological Patterns in Citizen
Science Observations. In: Dickinson J, Bonney R (eds) Citizen Science: Public Participation
in Environmental Research. Cornell University Press, Ithaca, New York, pp 125–138
- Firehock K, West J (1995) A Brief History of Volunteer Biological Water Monitoring Using
Macroinvertebrates. J North Am Benthol Soc 14:197–202
- Fitzpatrick JW (2012) Afterword. In: Dickinson JL, Bonney R (eds) Citizen Science: Public
Participation in Environmental Research. Cornell University Press, Ithaca, New York, pp
235–240
- Flockhart DTT, Larrivée M, Prudic KL, Ryan Norris D (2019) Estimating the annual distribution
of monarch butterflies in Canada over 16 years using citizen science data. Facets 4:238–
253. doi: 10.1139/facets-2018-0011
- Follett R, Strezov V (2015) An analysis of citizen science based research: Usage and publication
patterns. PLoS One 10:1–14. doi: 10.1371/journal.pone.0143687
- Forrester TD, Baker M, Costello R, et al (2017) Creating advocates for mammal conservation
through citizen science. Biol Conserv 208:98–105. doi: 10.1016/j.biocon.2016.06.025

- Freitag A, Meyer R, Whiteman L (2016) Correction: Strategies Employed by Citizen Science Programs to Increase the Credibility of Their Data. *Citiz Sci Theory Pract* 1:12. doi: 10.5334/cstp.91
- Frigerio D, Pipek P, Kimmig S, et al (2018) Citizen science and wildlife biology: Synergies and challenges. *Ethology* 124:365–377. doi: 10.1111/eth.12746
- Gardiner MM, Allee LL, Brown PMJ, et al (2012) Lessons from lady beetles: Accuracy of monitoring data from US and UK citizenscience programs. *Front Ecol Environ* 10:471–476. doi: 10.1890/110185
- Gardner J, Sherlock C, Hunter G (2003) Appreciating the values, needs and potential of the stewardship and conservation sector in Canada: strategic directions for funding and other support. 137pp
- Garibaldi LA, Steffan-Dewenter I, Kremen C, et al (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits. *Ecol Lett* 14:1062–1072. doi: 10.1111/j.1461-0248.2011.01669.x
- Gaston KJ, Fuller RA (2009) The sizes of species' geographic ranges. *J Appl Ecol* 46:1–9. doi: 10.1111/j.1365-2664.2008.01596.x
- Gazdic M, Groom Q (2019) iNaturalist is an Unexploited Source of Plant-Insect Interaction Data. *Biodivers Inf Sci Stand* 3:e37303. doi: 10.3897/biss.3.37303
- Ghisbain G, Lozier JD, Rahman SR, et al (2020) Substantial genetic divergence and lack of recent gene flow support cryptic speciation in a colour polymorphic bumble bee (*Bombus bifarius*) species complex. *Syst Entomol* 45:635–652. doi: 10.1111/syen.12419
- Gibbs J, Ascher JS, Rightmyer MG, Isaacs R (2017) The bees of Michigan (Hymenoptera: Apoidea: Anthophila), with notes on distribution, taxonomy, pollination, and natural

- history. *Zootaxa* 4352:1–160. doi: 10.11646/zootaxa.4352.1.1
- Gibson SD, Liczner AR, Colla SR (2019) Conservation conundrum: at-risk bumble bees (*Bombus* spp.) show preference for Invasive Tufted Vetch (*Vicia cracca*) while foraging in protected areas. *J Insect Sci* 19:1–10. doi: 10.1093/jisesa/iez017
- Giles V, Ascher JS (2006) A survey of the bees of the Black Rock Forest Preserve, New York (Hymenoptera: Apoidea). *J Hymenopt Res* 15:208–231
- Gill RJ, Ramos-Rodriguez O, Raine NE (2012) Combined pesticide exposure severely affects individual- and colony-level traits in bees. *Nature* 491:105–8. doi: 10.1038/nature11585
- Gillespie S (2010) Factors affecting parasite prevalence among wild bumblebees. *Ecol Entomol* 35:737–747. doi: 10.1111/j.1365-2311.2010.01234.x
- Giraud C, Calenge C, Coron C, Julliard R (2016) Capitalizing on opportunistic data for monitoring relative abundances of species. *Biometrics* 72:649–658. doi: 10.1111/biom.12431
- Godfray HCJ, Blacquière T, Field LM, et al (2014) A restatement of the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proc R Soc B Biol Sci* 281:20140558. doi: 10.1098/rspb.2014.0558
- Godfray HCJ, Blacquière T, Field LM, et al (2015) A restatement of recent advances in the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proc R Soc B Biol Sci* 282:20151821. doi: 10.1098/rspb.2015.1821
- Gonsamo A, Chen JM, Wu C (2013) Citizen Science: linking the recent rapid advances of plant flowering in Canada with climate variability. *Sci Rep* 3:2239. doi: 10.1038/srep02239
- Gonzalez PA, Minkler M, Garcia AP, et al (2011) Community-based participatory research and policy advocacy to reduce diesel exposure in West Oakland, California. *Am J Public Health*

101:166–176. doi: 10.2105/AJPH.2010.196204

Google (2018) Google Maps. www.google.ca/maps

Goulson D (2015) Neonicotinoids impact bumblebee colony fitness in the field; a reanalysis of the UK's Food & Environment Research Agency 2012 experiment. *PeerJ* 3:e854. doi: 10.7717/peerj.854

Goulson D (2019) The insect apocalypse, and why it matters. *Curr Biol* 29:R967–R971. doi: 10.1016/j.cub.2019.06.069

Goulson D, Nicholls E, Botías C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:1255957. doi: 10.1126/science.1255957

Government of Ontario (2014) Pollinator Health: A Proposal for Enhancing Pollinator Health and Reducing the Use of Neonicotinoid Pesticides in Ontario

Government of Ontario (2017) Five-Year Review of Progress Towards the Protection and Recovery of Ontario's Species at Risk

Graves TA, Janousek WM, Gaulke SM, et al (2020) Western bumble bee: declines in the continental United States and range-wide information gaps. *Ecosphere* 11:e03141. doi: 10.1002/ecs2.3141

Graystock P, Blane EJ, McFrederick QS, et al (2016) Do managed bees drive parasite spread and emergence in wild bees? *Int J Parasitol Parasites Wildl* 5:64–75. doi: 10.1016/j.ijppaw.2015.10.001

Greenwood JJD (2012) Citizens, Science, and Environmental Policy - A British Perspective. In: Dickinson JL, Booney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 150–164

- Griffin Burns L, Harasimowicz E (2012) *Citizen Scientists: Be Part of Scientific Discovery from Your Own Backyard*. Henry Holt and Company, LLC, New York, New York
- Gixti JC, Wong LT, Cameron SA, Favret C (2009) Decline of bumble bees (*Bombus*) in the North American Midwest. *Biol Conserv* 142:75–84. doi: 10.1016/j.biocon.2008.09.027
- Guiney MS, Oberhauser KS (2009) Conservation volunteers' connection to nature. *Ecopsychology* 1:187–197. doi: 10.1089/eco.2009.0030
- Guralnick R, Van Cleve J (2005) Strengths and weaknesses of museum and national survey data sets for predicting regional species richness: Comparative and combined approaches. *Divers Distrib* 11:349–359. doi: 10.1111/j.1366-9516.2005.00164.x
- Hall DM, Martins DJ (2020) Human dimensions of insect pollinator conservation. *Curr Opin Insect Sci* 38:107–114. doi: 10.1016/j.cois.2020.04.001
- Hall DM, Steiner R (2019) Insect pollinator conservation policy innovations: Lessons for lawmakers. *Environ Sci Policy* 93:118–128. doi: 10.1016/j.envsci.2018.12.026
- Hames RS, Lowe JD, Rosenberg K V. (2012) Developing a Conservation Research Program with Citizen Science. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 139–149
- Hannibal ME (2016) *Citizen Scientist: Searching for Heroes and Hope in an Age of Extinction*. The Experiment, LLC, New York, New York
- Hatfield R, Colla SR, Jepsen S, et al (2015a) IUCN Assessments for North American *Bombus* spp. (February ed). 1–56
- Hatfield R, Colla SR, Jepsen S, et al (2015b) IUCN Assessments for North American *Bombus* spp. (February 2015 update). 1–56
- Hatfield R, Jepsen S, Thorp R, et al (2015c) The IUCN Red List of Threatened Species -

- <i>*Bombus fervidus*</I>. IUCN Red List Threat Species e.T21215132A21215225
- Hatfield R, Jepsen S, Thorp R, et al (2015d) The IUCN Red List of Threatened Species - *Bombus pensylvanicus*. IUCN Red List Threat Species e.T2121517:
- Hatfield R, Jepsen S, Thorp R, et al (2015e) The IUCN Red List of Threatened Species - <i>*Bombus terricola*</I>. IUCN Red List Threat Species e.T4493750:18
- Hatfield RG, LeBuhn G (2007) Patch and landscape factors shape community assemblage of bumble bees, *Bombus* spp. (Hymenoptera: Apidae), in montane meadows. Biol Conserv 119:150–158. doi: 10.1016/j.biocon.2007.06.019
- Health Canada (2017) Pollinator Protection. <http://www.hc-sc.gc.ca/cps-spc/pest/agri-commerce/pollinators-pollinisateurs/index-eng.php>. Accessed 1 Mar 2017
- Hecker S, Bonney R, Haklay M, et al (2018) Innovation in citizen science - perspectives on science-policy advances. Citiz Sci Theory Pract 3:4. doi: 10.5334/cstp.114
- Hecker S, Wicke N, Haklay M, Bonn A (2019) How Does Policy Conceptualise Citizen Science? A Qualitative Content Analysis of International Policy Documents. Citiz Sci Theory Pract 4:32. doi: 10.5334/cstp.230
- Heigl F, Kieslinger B, Paul KT, et al (2019a) Reply to Auerbach et al.: How our Opinion piece invites collaboration. Proc Natl Acad Sci U S A 116:15338. doi: 10.1073/pnas.1909628116
- Heigl F, Kieslinger B, Paul KT, et al (2019b) Toward an international definition of citizen science. Proc Natl Acad Sci U S A 116:8089–8092. doi: 10.1073/pnas.1903393116
- Hiller T, Haelewaters D (2019) A case of silent invasion: Citizen science confirms the presence of *Harmonia axyridis* (Coleoptera, Coccinellidae) in Central America. PLoS One 14:1–16. doi: 10.1371/journal.pone.0220082
- Hochachka WM, Fink D, Hutchinson RA, et al (2012) Data-intensive science applied to broad-

- scale citizen science. *Trends Ecol Evol* 27:130–137. doi: 10.1016/j.tree.2011.11.006
- Hoffmann D, Pettis JS, Neumann P (2008) Potential host shift of the small hive beetle (*Aethina tumida*) to bumblebee colonies (*Bombus impatiens*). *Insectes Soc* 55:153–162. doi: 10.1007/s00040-008-0982-9
- Howard E, Davis AK (2009) The fall migration flyways of monarch butterflies in eastern North America revealed by citizen scientists. *J Insect Conserv* 13:279–286. doi: 10.1007/s10841-008-9169-y
- Hoyer M V., Wellendorf N, Frydenborg R, et al (2012) A comparison between professionally (Florida Department of Environmental Protection) and volunteer (Florida LAKEWATCH) collected trophic state chemistry data in Florida. *Lake Reserv Manag* 28:277–281. doi: 10.1080/07438141.2012.736016
- IBM Corp (2016) IBM SPSS Statistics for Windows, Version 24.0
- Iles DT, Williams NM, Crone EE (2018) Source-sink dynamics of bumble bees in rapidly changing landscapes. *J Appl Ecol*. doi: 10.1111/1365-2664.13175
- Inouye DW (2008) Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology* 89:353–362
- IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany
- Irwin A (1995) Citizen science: A study of people, expertise and sustainable development
- Irwin A (2018) Citizen Science Comes of Age. *Nature* 562:480–482
- IUCN (2020) The IUCN Red List of threatened species. Version 2020-3.

<https://www.iucnredlist.org>. Accessed 24 Jan 2021

IUCN (2012a) IUCN Red List Categories and Criteria - Version 3.1. Gland, Switzerland and Cambridge, United Kingdom

IUCN (2012b) Guidelines for Application of IUCN Red List Criteria at Regional and National Levels: Version 4.0

IUCN Red List of Threatened Species (2019) Status of *Bombus* species in North America.

<https://www.iucnredlist.org/>. Accessed 30 Jul 2019

IUCN Standards and Petitions Committee (2019) Guidelines for using the IUCN Red List categories and criteria. Version 14. Prepared by the Standards and Petitions Committee. Downloadable from <http://www.iucnredlist.org/documents/RedListGuidelines.pdf>.

IUCN Standards and Petitions Subcommittee (2016) Guidelines for Using the IUCN Red List Categories and Criteria. Version 12.

Jacobson MM, Tucker EM, Mathiasson ME, Rehan SM (2018) Decline of bumble bees in northeastern North America, with special focus on *Bombus terricola*. *Biol Conserv* 217:437–445. doi: 10.1016/j.biocon.2017.11.026

Jarvis B (2018) The Insect Apocalypse Is Here. *N. Y. Times Mag.*

JASP Team (2020) JASP Version 0.14.1 (Computer software)

Johnson SD, Steiner KE (2000) Generalization versus specialization in plant pollination systems. *Trends Ecol Evol* 15:140–143. doi: 10.1016/S0169-5347(99)01811-X

Johnston A, Fink D, Hochachka WM, Kelling S (2018) Estimates of observer expertise improve species distributions from citizen science data. *Methods Ecol Evol* 9:88–97. doi: 10.1111/2041-210X.12838

Johnston A, Hochachka WM, Strimas-mackey ME, et al (2019) Best practices for making

reliable inferences from citizen science data: case study using eBird to estimate species distributions. *bioRxiv Prepr* 1–13. doi: <http://dx.doi.org/10.1101/574392>

Johnston A, Moran N, Musgrove A, et al (2020) Estimating species distributions from spatially biased citizen science data. *Ecol Modell* 422:108927. doi: [10.1016/j.ecolmodel.2019.108927](https://doi.org/10.1016/j.ecolmodel.2019.108927)

Joint Nature Conservation Committee (2017) Background Document for A2. Taking action for nature: volunteer time spent in conservation, part of Biodiversity Indicators 2017

Jordan R, Gray S, Sorensen A, et al (2016) Studying citizen science through adaptive management and learning feedbacks as mechanisms for improving conservation. *Conserv Biol* 30:487–495. doi: [10.1111/cobi.12659](https://doi.org/10.1111/cobi.12659)

Jordan RC, Ehrenfeld JG, Gray SA, et al (2012) Cognitive considerations in the development of citizen science projects. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 167–178

Kawrykow A, Roumanis G, Kam A, et al (2012) Phylo: A citizen science approach for improving multiple sequence alignment. *PLoS One* 7:. doi: [10.1371/journal.pone.0031362](https://doi.org/10.1371/journal.pone.0031362)

Kelling S (2012) Using Bioinformatics in Citizen Science. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 58–68

Kelling S, Fink D, La Sorte FA, et al (2015a) Taking a “Big Data” approach to data quality in a citizen science project. *Ambio* 44:S601–S611. doi: [10.1007/s13280-015-0710-4](https://doi.org/10.1007/s13280-015-0710-4)

Kelling S, Johnston A, Hochachka W, et al (2015b) Can Observation Skills of Citizen Scientists Be Estimated Using Species Accumulation Curves? *PLoS One* 10:1–20. doi: [10.1371/journal.pone.0121000](https://doi.org/10.1371/journal.pone.0121000)

10.5061/dryad.2k27f.Funding

- Kent CF, Dey A, Patel H, et al (2018) Conservation genomics of the declining North American bumblebee *Bombus terricola* reveals inbreeding and selection on immune genes. *Front Genet* 9:316. doi: 10.3389/FGENE.2018.00316
- Kerr JT, Pindar A, Galpern P, et al (2015) Climate change impacts on bumblebees converge across continents. *Science* 349:177–180. doi: 10.1126/science.aaa7031
- Kevan PG (1975) Forest application of the insecticide fenitrothion and its effect on wild bee pollinators (Hymenoptera: Apoidea) of lowbush blueberries (*Vaccinium* SPP.) in Southern New Brunswick, Canada. *Biol Conserv* 7:301–309. doi: 10.1016/0006-3207(75)90045-2
- Kevan PG, Greco CF, Belaoussoff S (1997) Log-Normality of Biodiversity and Abundance in Diagnosis and Measuring of Ecosystemic Health: Pesticide Stress on Pollinators on Blueberry Heaths. *J Appl Ecol* 34:1122. doi: 10.2307/2405226
- Kevan PG, Otis GW, Coffin RH, et al (1984) Hazards of carbaryl formulations to caged honeybees (*Apis mellifera*) foraging on flowering canola (*Brassica napus*) in Ontario. *Proc Entomol Soc Ontario* 115:49–54
- Khatib F, Cooper S, Tyka MD, et al (2011) Algorithm discovery by protein folding game players. *Proc Natl Acad Sci* 108:18949–18953. doi: 10.1073/pnas.1115898108
- Kjohl M, Anders N, Stenseth NC (2011) Potential effects of climate change on crop pollination. Rome, Italy
- Klein A-MA-MAM, Vaissière BE, Cane JH, et al (2007) Importance of pollinators in changing landscapes for world crops. *Proc R Soc B Biol Sci* 274:303–313. doi: 10.1098/rspb.2006.3721
- Kobori H, Dickinson JL, Washitani I, et al (2016) Citizen science: a new approach to advance

- ecology, education, and conservation. *Ecol Res* 31:1–19. doi: 10.1007/s11284-015-1314-y
- Koch JB, Rodriguez J, Pitts JP, Strange JP (2018) Phylogeny and population genetic analyses reveals cryptic speciation in the *Bombus fervidus* species complex (Hymenoptera: Apidae). *PLoS One* 13:1–20. doi: 10.1371/journal.pone.0207080
- Koffler S, Barbiéri C, Ghilardi-Lopes NP, et al (2021) A buzz for sustainability and conservation: The growing potential of citizen science studies on bees. *Sustainability* 13:959 (1–15). doi: 10.3390/su13020959
- Kosmala M, Wiggins A, Swanson A, Simmons B (2016) Assessing data quality in citizen science. *Front Ecol Environ* 14:551–560. doi: 10.1002/fee.1436
- Kraus FB, Wolf S, Moritz RFA (2009) Male flight distance and population substructure in the bumblebee *Bombus terrestris*. *J Anim Ecol* 78:247–252. doi: 10.1111/j.1365-2656.2008.01479.x
- Krell F-T, Marshall SA (2017) New Species Described From Photographs: Yes? No? Sometimes? A Fierce Debate and a New Declaration of the ICZN. *Insect Syst Divers* 1:3–19. doi: 10.1093/isd/ixx004
- Kremen C, Ullman KS, Thorp RW (2011) Evaluating the quality of citizen-scientist data on pollinator communities. *Conserv Biol* 25:607–617. doi: 10.1111/j.1523-1739.2011.01657.x
- Landis JR, Koch GG (1977) The Measurement of Observer Agreement for Categorical Data. *Biometrics* 33:159–174
- Laverty M, Harder D (1988) The bumble bees of eastern Canada. *Can Entomol* 120:965–987
- Le Féon V, Henry M, Guilbaud L, et al (2016) An expert-assisted citizen science program involving agricultural high schools provides national patterns on bee species assemblages. *J Insect Conserv* 20:905–918. doi: 10.1007/s10841-016-9927-1

- Lebuhn G, Droege S, Connor EF, et al (2013) Detecting Insect Pollinator Declines on Regional and Global Scales. *Conserv Biol* 27:113–120. doi: 10.1111/j.1523-1739.2012.01962.x
- Lemieux CJ, Halpenny EA, Swerdfager T, et al (2021) Free Fallin’? The decline in evidence-based decision-making by Canada’s protected areas managers. *Facets* 6:640–664. doi: 10.1139/FACETS-2020-0085
- León-Cortés JL, Cowley MJR, Thomas CD (1999) Detecting decline in a formerly widespread species: How common is the common blue butterfly *Polyommatus icarus*? *Ecography (Cop)* 22:643–650. doi: 10.1111/j.1600-0587.1999.tb00513.x
- Lepais O, Darvill B, O’Connor S, et al (2010) Estimation of bumblebee queen dispersal distances using sibship reconstruction method. *Mol Ecol* 19:819–831. doi: 10.1111/j.1365-294X.2009.04500.x
- Lepczyk CA, Boyle OD, Vargo TLV (2020) Handbook of citizen science in ecology and conservation. University of California Press, Oakland, California
- Lewandowski E, Specht H (2015) Influence of volunteer and project characteristics on data quality of biological surveys. *Conserv Biol* 29:713–723. doi: 10.1111/cobi.12481
- Lewandowski EJ, Oberhauser KS (2017) Butterfly citizen scientists in the United States increase their engagement in conservation. *Biol Conserv* 208:106–112. doi: 10.1016/j.biocon.2015.07.029
- Liberatore A, Bowkett E, MacLeod CJ, et al (2018) Social Media as a Platform for a Citizen Science Community of Practice. *Citiz Sci Theory Pract* 3:3. doi: 10.5334/cstp.108
- Liczner AR, Colla SR (2020) One-size does not fit all: at-risk bumble bee habitat management requires species-specific local and landscape considerations. *Insect Conserv Divers* 13:558–570. doi: 10.1111/icad.12419

- Liebenberg L, Steventon J, Brahman !Nate, et al (2017) Smartphone Icon User Interface design for non-literate trackers and its implications for an inclusive citizen science. *Biol Conserv* 208:155–162. doi: 10.1016/j.biocon.2016.04.033
- Lombard M, Snyder-duch J, Bracken CC (2002) Content Analysis in Mass Communication. *Hum Commun Res* 28:587–604
- Losey EJ, Vaughan M (2006) The Economic Value of Ecological Services Provided by Insects. *Bioscience* 56:311
- Losey J, Allee L, Smyth R (2012) The Lost Ladybug project: Citizen spotting surpasses scientist’s surveys. *Am Entomol* 58:22–24
- Lovell S, Hamer M, Slotow R, Herbert D (2009) An assessment of the use of volunteers for terrestrial invertebrate biodiversity surveys. *Biodivers Conserv* 18:3295–3307. doi: 10.1007/s10531-009-9642-2
- Lozier JD (2014) Revisiting comparisons of genetic diversity in stable and declining species: Assessing genome-wide polymorphism in North American bumble bees using RAD sequencing. *Mol Ecol* 23:788–801. doi: 10.1111/mec.12636
- Lozier JD, Cameron SA (2009) Comparative genetic analyses of historical and contemporary collections highlight contrasting demographic histories for the bumble bees *Bombus pensylvanicus* and *B. impatiens* in Illinois. *Mol Ecol* 18:1875–1886. doi: 10.1111/j.1365-294X.2009.04160.x
- Lozier JD, Strange JP, Stewart IJ, Cameron SA (2011) Patterns of range-wide genetic variation in six North American bumble bee (Apidae: *Bombus*) species. *Mol Ecol* 20:4870–4888. doi: 10.1111/j.1365-294X.2011.05314.x
- Lundin O, Rundlöf M, Smith HG, et al (2015) Neonicotinoid insecticides and their impacts on

- bees: A systematic review of research approaches and identification of knowledge gaps. PLoS One 10:1–20. doi: 10.1371/journal.pone.0136928
- Lutz AR, Simpson-Housley P, De Man AF (1999) Wilderness rural and urban attitudes and perceptions. *Environ Behav* 31:259–266. doi: 10.1177/00139169921972092
- Lye GC, Osborne JL, Park KJ, Goulson D (2011) Using citizen science to monitor *Bombus* populations in the UK: Nesting ecology and relative abundance in the urban environment. *J Insect Conserv* 16:697–707. doi: 10.1007/s10841-011-9450-3
- Mace GM, Collar NJ, Gaston KJ, et al (2008) Quantification of extinction risk: IUCN’s system for classifying threatened species. *Conserv Biol* 22:1424–1442. doi: 10.1111/j.1523-1739.2008.01044.x
- MacFarlane RP (1974) Ecology of Bombinae (Hymenoptera: Apidae) of Southern Ontario, with emphasis on their natural enemies and relationships with flowers
- Macfarlane RP, Patten KD, Royce LA, et al (1994) Management potential of sixteen North American bumble bee species. *Melandieria* 50:1–12
- MacKechnie C, Maskell L, Norton L, Roy D (2011) The role of “Big Society” in monitoring the state of the natural environment. *J Environ Monit* 13:2687–2691. doi: 10.1039/c1em10615e
- MacPhail VJ (2007) Pollination biology of wild roses (*Rosa* spp.) in Eastern Canada. University of Guelph
- MacPhail VJ, Colla SR (2020) Power of the people: A review of citizen science programs for conservation. *Biol Conserv* 249:108739. doi: 10.1016/j.biocon.2020.108739
- MacPhail VJ, Ferguson S, Tompkins H, Colla SR (2018) The missing link: A case for increased consideration for plant-pollinator interactions for species at-risk recovery in Ontario. *J. Nat. Conserv.* 42:1–6

- MacPhail VJ, Gibson SD, Colla SR (2020a) Community science participants gain environmental awareness and contribute high quality data but improvements are needed: insights from Bumble Bee Watch. *PeerJ* 8:e9141. doi: 10.7717/peerj.9141
- MacPhail VJ, Gibson SD, Hatfield R, Colla SR (2020b) Using Bumble Bee Watch to investigate the accuracy and perception of bumble bee (*Bombus* spp.) identification by community scientists. *PeerJ* 8:e9412. doi: 10.7717/peerj.9412
- MacPhail VJ, Richardson LL, Colla SR (2019) Incorporating citizen science, museum specimens, and field work into the assessment of extinction risk of the American Bumble bee (*Bombus pensylvanicus* De Geer 1773) in Canada. *J Insect Conserv.* doi: 10.1007/s10841-019-00152-y
- Martinet B, Dellicour S, Ghisbain G, et al (2020) Global effects of extreme temperatures on wild bumblebees. *Conserv Biol.* doi: 10.1111/cobi.13685
- Martinet B, Lecocq T, Brasero N, et al (2019) Integrative taxonomy of an arctic bumblebee species complex highlights a new cryptic species (Apidae: *Bombus*). *Zool J Linn Soc* 187:599–621. doi: 10.1093/zoolinnean/zlz041
- Mathiasson ME, Rehan SM (2019) Status changes in the wild bees of north-eastern North America over 125 years revealed through museum specimens. *Insect Conserv Divers* icad.12347. doi: 10.1111/icad.12347
- McCaffrey R (2005) Using citizen science in urban bird studies. *Urban Habitats* 3:70–86. doi: ISSN 1541-7115
- McClenachan L (2009) Documenting Loss of Large Trophy Fish from the Florida Keys with Historical Photographs. *Conserv Biol* 23:636–643. doi: 10.1111/j.1523-1739.2008.01152.x
- McDonough MacKenzie C, Murray G, Primack R, Weihrauch D (2017) Lessons from citizen

- science: Assessing volunteer-collected plant phenology data with Mountain Watch. *Biol Conserv* 208:121–126. doi: 10.1016/j.biocon.2016.07.027
- McFarland KP, Richardson LL, Zahendra S (2016) Vermont bumble bee survey: Faunal changes in Vermont, 1900-2014 - final report to the Vermont Fish and Wildlife Department. Vermont Cent Ecostudies
- McHugh ML (2012) Interrater reliability: the kappa statistic. *Biochem Medica* 22:276–282. doi: 10.11613/BM.2012.031
- McKinley DC, Miller-Rushing AJ, Ballard HL, et al (2017) Citizen science can improve conservation science, natural resource management, and environmental protection. *Biol Conserv* 208:15–28. doi: 10.1016/j.biocon.2016.05.015
- McMahon DP, Fürst MA, Caspar J, et al (2015) A sting in the spit: Widespread cross-infection of multiple RNA viruses across wild and managed bees. *J Anim Ecol* 84:615–624. doi: 10.1111/1365-2656.12345
- Meeus I, Brown MJF, De Graaf DC, Smagghe G (2011) Effects of Invasive Parasites on Bumble Bee Declines. *Conserv Biol* 25:662–671. doi: 10.1111/j.1523-1739.2011.01707.x
- Meiners JM, Orr MC, Riemer K, et al (2020) The influence of data type and functional traits on native bee phenology metrics: Opportunistic versus inventory records. *bioRxiv Ecol preprint*:1–33. doi: 10.1101/2020.04.16.044750
- Memmott J, Craze PG, Waser NM, Price M V. (2007) Global warming and the disruption of plant-pollinator interactions. *Ecol Lett* 10:710–717. doi: 10.1111/j.1461-0248.2007.01061.x
- Microsoft Office 365 Microsoft Excel. Version 2101 (Computer Program)
- Microsoft Office 365 Microsoft Excel. Version 1909 (Computer Program)
- Miller-Rushing A, Primack R, Bonney R (2012) The history of public participation in ecological

- research. *Front Ecol Environ* 10:285–290. doi: 10.1890/110278
- Miller-Struttmann NE, Geib JC, Franklin JD, et al (2015) Functional mismatch in a bumble bee pollination mutualism under climate change. *Science* 249:1541–1544. doi: 10.1126/science.aab0868
- Mola JM, Williams NM (2019) A review of methods for the study of bumble bee movement. *Apidologie* 50:497–514. doi: 10.1007/s13592-019-00662-3
- Mueller MA, Drake D, Allen ML (2019) Using citizen science to inform urban canid management
- Munson MA, Caruana R, Fink D, et al (2010) A method for measuring the relative information content of data from different monitoring protocols. *Methods Ecol Evol* 1:263–273. doi: 10.1111/j.2041-210X.2010.00035.x
- Nardone E (2013) The bees of Algonquin Park: a study of their distribution, their community guild structure, and the use of various sampling techniques in logged and unlogged hardwood stands. University of Guelph
- NASEM (2018) Learning through citizen science: Enhancing opportunities by design. National Academies of Sciences Engineering and Medicine. The National Academies Press, Washington, D.C.
- NatureServe (2021) NatureServe Explorer [web application]. In: NatureServe, Arlington, Virginia. <https://explorer.natureserve.org/>. Accessed 24 Jan 2021
- NatureServe (2015) NatureServe Explorer: An online encyclopedia of life [web application]. Version 7.1. In: NatureServe, Arlington, Virginia. <http://explorer.natureserve.org>. Accessed 3 Mar 2017
- NEIWPCC - New Englands Interstate Water Pollution Control Commission (2016) Guide for

- Development and Approval of Quality Assurance Project Plans (QA Project Plans). V2.0.
- Nestle M (2001) Food company sponsorship of nutrition research and professional activities: a conflict of interest? *Public Health Nutr* 4:1015–1022. doi: 10.1079/PHN2001253
- Newediuk L, Ethier JP, Boyle SP, et al (2021) Sociopolitical factors drive conservation planning timelines: A Canadian case study with global implications. *Biol Conserv* 257:109091. doi: 10.1016/j.biocon.2021.109091
- Newing H (2010) Processing and analysis of qualitative data. In: *Conducting Research in Conservation*. Routledge, New York, New York, p pp 241-246
- Newman C, Buesching CD, Macdonald DW (2003) Validating mammal monitoring methods and assessing the performance of volunteers in wildlife conservation - “Sed quis custodiet ipsos custodies?” *Biol Conserv* 113:189–197. doi: 10.1016/S0006-3207(02)00374-9
- Newman G, Chandler M, Clyde M, et al (2017) Leveraging the power of place in citizen science for effective conservation decision making. *Biol Conserv* 208:55–64. doi: 10.1016/j.biocon.2016.07.019
- Newman G, Wiggins A, Crall A, et al (2012) The future of Citizen science: Emerging technologies and shifting paradigms. *Front Ecol Environ* 10:298–304. doi: 10.1890/110294
- Nisbet MC, Scheufele DA (2009) What’s next for science communication? Promising directions and lingering distractions. *Am J Bot* 96:1767–1778. doi: 10.3732/ajb.0900041
- Oberhauser K, Lebuhn G (2012) Insects and plants: Engaging undergraduates in authentic research through citizen science. *Front Ecol Environ* 10:318–320. doi: 10.1890/110274
- Odenwald S (2019) Smartphone Sensors for Citizen Science Applications: Radioactivity and Magnetism. *Citiz Sci Theory Pract* 4:18. doi: 10.5334/cstp.158
- Olive A (2014) Urban awareness and attitudes toward conservation: A first look at Canada’s

- cities. *Appl Geogr* 54:160–168. doi: 10.1016/j.apgeog.2014.08.002
- Olive A (2015) Urban and Rural Attitudes Toward Endangered Species Conservation in the Canadian Prairies: Drawing Lessons From the American ESA. *Hum Dimens Wildl* 20:189–205. doi: 10.1080/10871209.2015.1004207
- Ollerton J, Winfree R, Tarrant S (2011) How many flowering plants are pollinated by animals? *Oikos* 120:321–326. doi: 10.1111/j.1600-0706.2010.18644.x
- Ontario Biodiversity Council (2010) State of Ontario’s Biodiversity 2010 - Highlights Report. Ontario Biodiversity Council, Peterborough, Ontario
- Ontario Biodiversity Council (2011) Ontario’s Biodiversity Strategy, 2011: Renewing Our Commitment to Protecting What Sustains Us. Ontario Biodiversity Council, Peterborough, Ontario
- Ontario Ministry of Agriculture Food and Rural Affairs, Government of Ontario (2016) Ontario’s Pollinator Health Action Plan. http://www.omafra.gov.on.ca/english/pollinator/action_plan.pdf
- Opar A (2017) Wyoming’s Anti-Science Laws Get a Second Look. In: NRDC.org. <https://www.nrdc.org/stories/wyomings-anti-science-laws-get-second-look>. Accessed 6 May 2020
- Osborne JL, Martin AP, Carreck NL, et al (2008) Bumblebee flight distances in relation to the forage landscape. *J Anim Ecol* 77:406–415. doi: 10.1111/j.1365-2656.2007.01333.x
- Otterstatter MC, Thomson JD (2008) Does pathogen spillover from commercially reared bumble bees threaten wild pollinators? *PLoS One* 3:. doi: 10.1371/journal.pone.0002771
- Owen RP, Parker AJ (2019) Citizen science in environmental protection agencies. *Citiz Sci* 284–300. doi: 10.2307/j.ctv550cf2.27

- Packer L, Monckton SK, Onuferko TM, Ferrari RR (2018) Validating taxonomic identifications in entomological research. *Insect Conserv Divers* 11:1–12. doi: 10.1111/icad.12284
- Papanikolaou AD, Kühn I, Frenzel M, Schweiger O (2017) Semi-natural habitats mitigate the effects of temperature rise on wild bees. *J Appl Ecol* 54:527–536. doi: 10.1111/1365-2664.12763
- Parker AJ, Thomson JD (2018) Citizen scientists document geographic patterns in pollinator communities. *J Pollinat Ecol* 23:90–97
- Parliament of Canada (2015) The Importance of Bee Health to Sustainable Food Production in Canada. <https://sencanada.ca/Content/SEN/Committee/412/agfo/rep/rep09may15-e.htm>. Accessed 2 Mar 2017
- Pastor J (2018) Natural History and Ecology: Three Books You Should Read (and a Few More) Reviewed. *Bull Ecol Soc Am* 99:242–250
- Peters CB, Zhan Y, Schwartz MW, et al (2017) Trusting land to volunteers: How and why land trusts involve volunteers in ecological monitoring. *Biol Conserv* 208:48–54. doi: 10.1016/j.biocon.2016.08.029
- Phillips EM, Schneider JC, Mercer GR (2004) Motivating elders to initiate and maintain exercise. *Arch Phys Med Rehabil* 85:52–57. doi: 10.1016/j.apmr.2004.03.012
- Phillips SJ, Dudík M, Elith J, et al (2009) Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. *Ecol Appl* 19:181–197. doi: 10.1890/07-2153.1
- Phillips T, Bonney R, Shirk JL (2012) What is our impact? Toward a unified framework for evaluating outcomes of citizen science participation. In: Dickinson J, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca,

New York, pp 82–96

- Pidot J (2015) Forbidden Data - Wyoming just criminalized citizen science. In: Slate.com. <https://slate.com/technology/2015/05/wyoming-law-against-data-collection-protecting-ranchers-by-ignoring-the-environment.html>. Accessed 6 May 2020
- Pike N (2011) Using false discovery rates for multiple comparisons in ecology and evolution. *Methods Ecol Evol* 2:278–282. doi: 10.1111/j.2041-210X.2010.00061.x
- Pimm SL, Jenkins CN, Abell R, et al (2014) The biodiversity of species and their rates of extinction, distribution, and protection. *Science* 344:. doi: 10.1126/science.1246752
- Pocock MJO, Chapman DS, Sheppard LJ, Roy HE (2014) A Strategic Framework to Support the Implementation of Citizen Science for Environmental Monitoring. Final Report to SEPA
- Pocock MJO, Newson SE, Henderson IG, et al (2015) Developing and enhancing biodiversity monitoring programmes: A collaborative assessment of priorities. *J Appl Ecol* 52:686–695. doi: 10.1111/1365-2664.12423
- Pocock MJO, Roy HE, Fox R, et al (2017) Citizen science and invasive alien species: Predicting the detection of the oak processionary moth *Thaumetopoea processionea* by moth recorders. *Biol Conserv* 208:146–154. doi: 10.1016/j.biocon.2016.04.010
- Poisson AC, McCullough IM, Cheruvilil KS, et al (2020) Quantifying the contribution of citizen science to broad-scale ecological databases. *Front Ecol Environ* 18:19–26. doi: 10.1002/fee.2128
- Ponti M, Hillman T, Kullenberg C, Kasperowski D (2018) Getting it Right or Being Top Rank: Games in Citizen Science. *Citiz Sci Theory Pract* 3:1. doi: 10.5334/cstp.101
- Portman ZM, Bruninga-Socular B, Cariveau DP (2020) The state of bee monitoring in the United States: A call to refocus away from bowl traps and towards more effective methods. *Ann*

- Entomol Soc Am 1–6. doi: 10.1093/aesa/saaa010
- Potts SG, Biesmeijer JC, Kremen C, et al (2010) Global pollinator declines: Trends, impacts and drivers. *Trends Ecol Evol* 25:345–353. doi: 10.1016/j.tree.2010.01.007
- Potts SG, Imperatriz-Fonseca VL, Ngo HT, et al (2016) The assessment report on pollinators, pollination and food production: Sumamary for policymakers. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany
- Prudic K, McFarland K, Oliver J, et al (2017) eButterfly: Leveraging Massive Online Citizen Science for Butterfly Consevation. *Insects* 8:53. doi: 10.3390/insects8020053
- Purcell K, Garibay C, Dickinson JL (2012) A Gateway to Science for All: Celebrate Urban Birds. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 191–200
- Pyke GH, Thomson JD, Inouye DW, Miller TJ (2016) Effects of climate change on phenologies and distributions of bumble bees and the plants they visit. *Ecosphere* 7:1–19. doi: 10.1002/ecs2.1267
- Queen’s Printer for Ontario (2016) O. Reg. 230/08: Species At Risk in Ontario List
- Rasmussen LM (2019) Confronting Research Misconduct in Citizen Science. *Citiz Sci Theory Pract* 4:1–11. doi: 10.5334/cstp.207
- Ratcliffe M, Burd C, Holder K, Fields A (2016) Defining Rural at the U.S. Census Bureau. American community survey and geography brief. US Census Bur ACSGEO-1:1–8
- Requier F, Fournier A, Rome Q, Darrouzet E (2020) Science communication is needed to inform risk perception and action of stakeholders. *J Environ Manage* 257:109983. doi: 10.1016/j.jenvman.2019.109983

- Reynolds MD, Sullivan BL, Hallstein E, et al (2017) Dynamic conservation for migratory species. *Sci Adv* 3:e1700707. doi: 10.1126/sciadv.1700707
- Richardson LL (2020) Bumble Bees of North America database.
<https://www.leifrichardson.org/bbna.html>. Accessed 28 May 2020
- Richardson LL, McFarland KP, Zahendra S, Hardy S (2019) Bumble bee (*Bombus*) distribution and diversity in Vermont, USA: a century of change. *J Insect Conserv* 23:45–62. doi: 10.1007/s10841-018-0113-5
- Rodrigues ASL, Pilgrim JD, Lamoreux JF, et al (2006) The value of the IUCN Red List for conservation. *Trends Ecol Evol* 21:71–76. doi: 10.1016/j.tree.2005.10.010
- Rosenstock L, Lee LJ (2002) Attacks on science: The risks to evidence-based policy. *Am J Public Health* 92:14–18. doi: 10.2105/AJPH.92.1.14
- Roy HE, Baxter E, Saunders A, Pocock MJO (2016) Focal Plant Observations as a Standardised Method for Pollinator Monitoring: Opportunities and Limitations for Mass Participation Citizen Science. *PLoS One* 11:e0150794. doi: 10.1371/journal.pone.0150794
- Roy HE, Pocock MJO, Preston CD, et al (2012) Understanding Citizen Science and Environmental Monitoring. *NERC Cent Ecol Hydrol Nat Hist Museum* 1 1–179
- Roy S, Edwards M (2019) Citizen Science During the Flint, Michigan Federal Water Emergency: Ethical Dilemmas and Lessons Learned. *Citiz Sci Theory Pract* 4:1–28. doi: 10.5334/cstp.154
- Royal Botanic Gardens Kew (2017) GeoCAT FAQ 4.9 Does the EOO value exclude “discontinuities or disjunctions” e.g. areas of obviously unsuitable habitat?
<https://www.kew.org/geocat-faqs#4>. Accessed 1 Jun 2017
- Russell SA (2014) Diary of a citizen scientist - chasing tiger beetles and other new ways of

engaging the world. Oregon State University Press, Corvallis, Oregon

Ryan SF, Adamson NL, Aktipis A, et al (2018) The role of citizen science in addressing grand challenges in food and agriculture research. *Proc R Soc B Biol Sci* 285:. doi: 10.1098/rspb.2018.1977

Saldana J (2009) *The Coding Manual for Qualitative Researchers*, ProQuest E. SAGE Publications, London, United Kingdom

Sánchez-Bayo F, Wyckhuys KAG (2019) Worldwide decline of the entomofauna: A review of its drivers. *Biol Conserv* 232:8–27. doi: 10.1016/j.biocon.2019.01.020

Sauermann H, Franzoni C (2015) Crowd science user contribution patterns and their implications. *Proc Natl Acad Sci U S A* 112:679–684. doi: 10.1073/pnas.1408907112

Schröter M, Kraemer R, Mantel M, et al (2017) Citizen science for assessing ecosystem services: Status, challenges and opportunities. *Ecosyst Serv* 28:80–94. doi: 10.1016/j.ecoser.2017.09.017

Schuttler SG, Sorensen AE, Jordan RC, et al (2018) Bridging the nature gap: can citizen science reverse the extinction of experience? *Front Ecol Environ* 16:405–411. doi: 10.1002/fee.1826

Schweitzer D, Capuano N, Young B, Colla S (2012) Conservation and Management of North American Bumble Bees. 1–18

Sharma N, Greaves S, Siddharthan A, et al (2019) From citizen science to citizen action: analysing the potential for a digital platform to cultivate attachments to nature. *J Sci Commun* 18:1–35. doi: <https://doi.org/10.22323/2.18010207>

Sheffield CS, Heron J, Gibbs J, et al (2019) Contribution of DNA barcoding to the study of the bees (Hymenoptera: Apoidea) of Canada: progress to date. *Can Entomol* 754:736–754. doi:

10.4039/tce.2017.49

Sheffield CS, Oram R, Heron JM (2020) *Bombus* (*Pyrobombus*) *johanseni* sladen, 1919, a valid North American bumble bee species, with a new synonymy and comparisons to other “red-banded” bumble bee species in north america (Hymenoptera, Apidae, Bombini). *Zookeys* 2020:59–81. doi: 10.3897/zookeys.984.55816

Sheppard SA, Turner J, Thebault-Spieker J, et al (2017) Never too old, cold or dry to watch the sky. *Proc ACM Human-Computer Interact* 1:1–21. doi: 10.1145/3134729

Shirk JL, Ballard HL, Wilderman CC, et al (2012) Public participation in scientific research: a framework for intentional design. *Ecol Soc* 17:29. doi: 10.5751/ES-04705-170229

Sikes DS, Rykken JJ (2020) Update to the identification guide to female Alaskan bumble bees and a summary of recent changes to the Alaskan bumble bee fauna. *AKES Newsl* 13:31–38. doi: 10.7299/X7GH9J8D

Silvertown J (2009) A new dawn for citizen science. *Trends Ecol Evol* 24:467–471. doi: 10.1016/j.tree.2009.03.017

Silvertown J, Bueshing CD, Jacobson SK, Rebelo T (2013) Citizen science and nature conservation. In: Macdonald DW, Willis KJ (eds) *Key Topics in Conservation Biology* 2, First Ed. John Wiley & Sons, Ltd., West Sussex, UK, pp 127–142

Silvertown J, Harvey M, Greenwood R, et al (2015) Crowdsourcing the identification of organisms: A case-study of iSpot. *Zookeys* 146:125–146. doi: 10.3897/zookeys.480.8803

Simon ADF (2020) Water into nectar: The effects of seasonal drought on bumble bee and flowering plant communities. MSc Thesis. School of Environmental Studies, University of Victoria. University of Victoria

Sirois-Delisle C, Kerr JT (2018) Climate change-driven range losses among bumblebee species

- are poised to accelerate. *Sci Rep* 8:14464. doi: 10.1038/s41598-018-32665-y
- Smith MA, McDonald J V., Kent M, et al (2017) The use of social media to document a range extension of an iconic social parasite ant. *J Entomol Soc Ontario* 148:1–5
- Snäll T, Kindvall O, Nilsson J, Pärt T (2011) Evaluating citizen-based presence data for bird monitoring. *Biol Conserv* 144:804–810. doi: 10.1016/j.biocon.2010.11.010
- Socientize Consortium (2013) Citizen Science for Europe: Towards a society of empowered citizens and enhanced research (Green paper on Citizen Science)
- Soroye P, Ahmed N, Kerr JT (2018) Opportunistic citizen science data transform understanding of species distributions, phenology, and diversity gradients for global change research. *Glob Chang Biol* 1–11. doi: 10.1111/gcb.14358
- Soroye P, Newbold T, Kerr J (2020) Climate change contributes to widespread declines among bumble bees across continents. *Science* 367:685–688
- Spiesman BJ, Gratton C, Hatfield RG, et al (2021) Assessing the potential for deep learning and computer vision to identify bumble bee species from images. *Sci Rep* 11:1–10. doi: 10.1038/s41598-021-87210-1
- Stafford R, Hart AG, Collins L, et al (2010) Eu-Social Science: The Role of Internet Social Networks in the Collection of Bee Biodiversity Data. *PLoS One* 5:1–7. doi: 10.1371/journal.pone.0014381
- Starr J, Schweik CM, Bush N, et al (2014) Lights, camera...citizen science: Assessing the effectiveness of smartphone-based video training in invasive plant identification. *PLoS One* 9:. doi: 10.1371/journal.pone.0111433
- Statistics Canada (2017a) Table: 17-10-0005-01 (formerly CANSIM 051-0001), Population estimates on July 1st [2016], by age and sex.

- <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501>. Accessed 22 Nov 2019
- Statistics Canada (2016a) Provinces/territories, cartographic boundary file - 2016 census (2016-11-16). <https://open.canada.ca/data/en/dataset/a883eb14-0c0e-45c4-b8c4-b54c4a819edb>
- Statistics Canada (2016b) Table 051-0001 - Estimates of population, by age group and sex for July 1, Canada, provinces and territories, annual (persons unless otherwise noted), CANSIM (database). <http://www5.statcan.gc.ca/cansim/a26>. Accessed 3 Mar 2017
- Statistics Canada (2016c) Census profile, 2016 census. <https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=PR&Code1=01&Geo2=&Code2=&SearchText=Canada&SearchType=Begins&SearchPR=01&B1=All&TABID=1&type=0>. Accessed 22 Nov 2019
- Statistics Canada (2017b) Population and dwelling counts, for Canada, provinces and territories, 2016 and 2011 censuses (table). Population and Dwelling Count Highlight Tables. 2016 Census. In: Stat. Canada Cat. no. 98-402-X2016001. <http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/hltfst/pd-pl/Tables/File.cfm?T=101&SR=1&RPP=25&PR=0&CMA=0&CSD=0&S=50&O=A&Lang=Eng&OFT=CSV>. Accessed 22 Nov 2019
- Sterling EJ, Betley E, Sigouin A, et al (2017) Assessing the evidence for stakeholder engagement in biodiversity conservation. *Biol Conserv* 209:159–171. doi: 10.1016/j.biocon.2017.02.008
- Stout JC, Goulson D (2000) Bumble bees in Tasmania: Their distribution and potential impact on Australian flora and fauna. *Bee World* 81:80–86. doi: 10.1080/0005772X.2000.11099475
- Strange JP, Tripodi AD (2019) Characterizing bumble bee (*Bombus*) communities in the United

- States and assessing a conservation monitoring method. *Ecol Evol* 9:1061–1069. doi: 10.1002/ece3.4783
- Strasser C, Cook R, Michener W, Budden A (2012) *Primer on Data Management: What you always wanted to know*
- Strauss A, Corbin J (1998) *Basics of Qualitative Research*, 2nd editio. SAGE Publications, Thousand Oaks, California
- Stribling JB, Pavlik KL, Holdsworth SM, Leppo EW (2008) Data quality, performance, and uncertainty in taxonomic identification for biological assessments. *J North Am Benthol Soc* 27:906–919. doi: 10.1899/07-175.1
- Sullivan BL, Phillips T, Dayer AA, et al (2017) Using open access observational data for conservation action: A case study for birds. *Biol Conserv* 208:5–14. doi: 10.1016/j.biocon.2016.04.031
- Sullivan BL, Wood CL, Iliff MJ, et al (2009) eBird: A citizen-based bird observation network in the biological sciences. *Biol Conserv* 142:2282–2292. doi: 10.1016/j.biocon.2009.05.006
- Suzuki-Ohno Y, Yokoyama J, Nakashizuka T, Kawata M (2017) Utilization of photographs taken by citizens for estimating bumblebee distributions. *Sci Rep* 7:11215. doi: 10.1038/s41598-017-10581-x
- Suzuki-Ohno Y, Yokoyama J, Nakashizuka T, Kawata M (2020) Estimating possible bumblebee range shifts in response to climate and land cover changes. *Sci Rep* 10:1–12. doi: 10.1038/s41598-020-76164-5
- Szabo ND, Colla SR, Wagner DL, et al (2012) Do pathogen spillover, pesticide use, or habitat loss explain recent North American bumblebee declines? *Conserv Lett* 5:232–239. doi: 10.1111/j.1755-263X.2012.00234.x

- Szymanski J, Smith T, Horton A, et al (2016) Rusty Patched bumble bee (*Bombus affinis*) species status assessment. Final Report, Version 1. United States Fish Wildl Serv 1–94
- Tang J, Wice J, Thomas VG, Kevan PG (2007) Assessment of Canadian federal and provincial legislation to conserve native and managed pollinators. *Int J Biodivers Sci Manag* 3:46–55
- Terry JCD, Roy HE, August TA (2020) Thinking like a naturalist: Enhancing computer vision of citizen science images by harnessing contextual data. *Methods Ecol Evol* 11:303–315. doi: 10.1111/2041-210X.13335
- The Xerces Society for Invertebrate Conservation (2020) Bumble Bee Watch, a collaborative website to track and conserve North America’s bumble bees. www.bumblebeewatch.org. Accessed 19 Aug 2020
- The Xerces Society for Invertebrate Conservation (2021) Community science projects. <https://xerces.org/community-science>. Accessed 4 Feb 2021
- The Xerces Society for Invertebrate Conservation, Wildlife Preservation Canada, York University, et al (2017) Bumble Bee Watch, a collaborative website to track and conserve North America’s bumble bees. <http://www.bumblebeewatch.org>
- The Xerces Society for Invertebrate Conservation, Wildlife Preservation Canada, York University, et al (2018) Data accessed from Bumble Bee Watch, a collaborative website to track and conserve North America’s bumble bees. Available from <http://www.bumblebeewatch.org/app/#/bees/lists>. Accessed January 31, 2018.
- The Xerces Society for Invertebrate Conservation, Wildlife Preservation Canada, York University, et al (2019) Data accessed from Bumble Bee Watch, a collaborative website to track and conserve North America’s bumble bees.
- Theobald EJ, Ettinger AK, Burgess HK, et al (2015) Global change and local solutions: Tapping

the unrealized potential of citizen science for biodiversity research. *Biol Conserv* 181:236–244. doi: 10.1016/j.biocon.2014.10.021

Thomas JA (2016) Butterfly communities under threat. *Science* 353:216–218. doi: 10.1126/science.aaf8838

Thorp RW, Horning Jr. DS, Dunning LL (1983) Bumble bees and cuckoo bumble bees of California (Hymenoptera: Apidae)

Thuermer AMJ (2020) EPA Knocks Wyo Plan To Bar Public' s Water Pollution Data. In: WyoFile. <https://county17.com/2020/04/24/epa-knocks-wyo-plan-to-bar-publics-water-pollution-data/>. Accessed 6 May 2020

Tidball KG, Krasny ME (2012) A Role for Citizen Science in Disaster and Conflict Recovery and Resilience. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 226–233

Tompkins H, Rowe G (2020) The power of the Pinery: Six years of bumble bee community science at Ontario's Pinery Provincial Park. In: *Xerces Soc. Invertebr. Conserv.* <https://xerces.org/blog/power-of-pinery-six-years-of-bumble-bee-community-science-at-ontarios-pinery-provincial-park>. Accessed 7 Dec 2020

Toomey AH, Domroese MC (2013) Can citizen science lead to positive conservation attitudes and behaviors? *Hum Ecol Rev* 20:50–62

Trautmann NM, Shirk JL, Fee J, Krasny ME (2012) Who poses the question? Using citizen science to help K-12 teachers to meet the mandate for inquiry. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 179–190

Triezenberg HA, Knuth BA, Yuan CY, Dickinson JL (2012) Internet-Based Social Networking

- and Collective Action Models of Citizen Science: Theory Meets Possibility. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 214–225
- Tweddle JC, Robinson LD, Pocock MJO, Roy HE (2012) *Guide to citizen science: developing, implementing and evaluating citizen science to study biodiversity and the environment in the UK*. Natural History Museum and NERC Centre for Ecology & Hydrology for UK-EOF
- Tylianakis JM, Laliberté E, Nielsen A, Bascompte J (2010) Conservation of species interaction networks. *Biol Conserv* 143:2270–2279. doi: 10.1016/j.biocon.2009.12.004
- Underwood E, Darwin G, Gerritsen E (2017) *Pollinator initiatives in EU member states: Success factors and gaps*. Report for European Commission under contract for provision of technical support related to Target 2 of the EU Biodiversity Strategy to 2020. Inst Eur Environ Policy, Brussels
- United States Census Bureau (2017a) *American Community Survey (ACS) Demographic and Housing Estimates, 2013-2017*. In: Am. Fact Finder. https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_17_5YR_DP05&src=pt%0A. Accessed 21 Nov 2019
- United States Census Bureau (2017b) Table 1. Educational Attainment in the United States: 2016. <https://www.census.gov/data/tables/2016/demo/education-attainment/cps-detailed-tables.html>. Accessed 22 Nov 2019
- United States Environmental Protection Agency (2002) *Guidance on Environmental Data Verification and Data Validation (EPA QA/G-8)*. Washington, D.C.
- United States Fish and Wildlife Service (USFWS) (2019a) *Draft recovery plan for Rusty Patched bumble bee (Bombus affinis)*. Midwest Regional Office, Bloomington, MN

United States Fish and Wildlife Service (USFWS) (2017) Endangered Species Status for Rusty Patched Bumble Bee. Fed Regist 82:3186–3209

United States Fish and Wildlife Service (USFWS) (2019b) Species Profile for the Yellow banded Bumble bee (*Bombus terricola*).

<https://ecos.fws.gov/ecp0/profile/speciesProfile?scode=I0YN>. Accessed 30 Jul 2019

United States Fish and Wildlife Service (USFWS) (2016) Evaluation of a Petition To List the Western Bumble Bee, Yellow-Banded Bumble Bee as an Endangered or Threatened Species Under the Act. Fed Regist 81:14071–14072

United States Fish and Wildlife Service (USFWS) (2019c) Species Profile for the Western Bumble bee (*Bombus occidentalis*). <https://ecos.fws.gov/ecp/species/10401>. Accessed 30 Sep 2019

United States Fish and Wildlife Service (USFWS) (2019d) Species Profile Franklin's bumblebee (*Bombus franklini*). <https://ecos.fws.gov/ecp0/profile/speciesProfile?sId=7022>. Accessed 30 Sep 2019

United States Fish and Wildlife Service (USFWS) (2021) Rusty Patched Bumble Bee (*Bombus affinis*). Status Endangered. <https://www.fws.gov/midwest/endangered/insects/rpbb/index.html>. Accessed 9 Nov 2017

United States Government (2017) American Innovation and Competitiveness Act. congress.gov, United States

US National Weather Service (2016) U.S. States and Territories - 11 August 2016. <https://www.weather.gov/gis/USStates>

Van Den Berg HA, Dann SL, Dirkx JM (2009) Motivations of adults for non-formal conservation education and volunteerism: Implications for programming. Appl Environ

- Educ Commun 8:6–17. doi: 10.1080/15330150902847328
- van der Velde T, Milton DA, Lawson TJJ, et al (2017) Comparison of marine debris data collected by researchers and citizen scientists: Is citizen science data worth the effort? *Biol Conserv* 208:127–138. doi: 10.1016/j.biocon.2016.05.025
- van der Wal RR, Anderson H, Robinson A, et al (2015) Mapping species distributions: A comparison of skilled naturalist and lay citizen science recording. *Ambio* 44:S584–S600. doi: 10.1007/s13280-015-0709-x
- van der Wal RR, Sharma N, Mellish C, et al (2016) The role of automated feedback in training and retaining biological recorders for citizen science. *Conserv Biol* 30:550–561. doi: 10.1111/cobi.12705
- Vierssen Trip N, MacPhail VJ, Colla SR, Olivastri B (2020) Examining the public’s awareness of bee (Hymenoptera: Apoidea: Anthophila) conservation in Canada. *Conserv Sci Pract* 2:1–12. doi: 10.1111/csp2.293
- Voss D, Dean A, Draguljic D (2017) *Design and Analysis of Experiments Springer Texts in Statistics*
- Wagner, E., La Croix, AZ., Buchner, DM., Larson E (1992) Effects of physical activity on health status in older adults. *Annu Rev Public Heal* 13:451–468
- Wagner DL, Grames EM, Forister ML, et al (2021) Insect decline in the Anthropocene: Death by a thousand cuts. *Proc Natl Acad Sci U S A* 118:1–10. doi: 10.1073/pnas.2023989118
- Wäldchen J, Mäder P (2018) Machine learning for image based species identification. *Methods Ecol Evol* 9:2216–2225. doi: 10.1111/2041-210X.13075
- Wells N, Lekies K (2006) *Nature and the Life Course: Pathways from Childhood Nature Experiences to Adult Environmentalism*. *Child Youth Environ* 16:1–24

- Wells NM, Lekies KS (2012) Children and Nature: Following the Trail to Environmental Attitudes and Behavior. In: Dickinson JL, Bonney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 201–213
- Whitehorn PPR, O'Connor S, Wackers FLF, Goulson D (2012) Neonicotinoid Pesticide Reduces Bumble Bee Colony Growth and Queen Production. *Science* 336:351–352. doi: 10.1126/science.1215025
- Wiggins A, Bonney R, Graham E, et al (2013) *Data Management Guide for Public Participation in Scientific Research*. Albuquerque, NM
- Wiggins A, Crowston K (2011) From conservation to crowdsourcing: a typology of citizen science. In: *Proceedings of the 44th Hawaii International Conference on System Sciences - 2011*. IEEE, pp 1–10
- Williams DR, Balmford A, Wilcove DS (2020) The past and future role of conservation science in saving biodiversity. *Conserv Lett* 13:1–7. doi: 10.1111/conl.12720
- Williams P, Thorp R, Richardson L, Colla S (2014) *Bumble Bees of North America*. Princeton University Press, Princeton, New Jersey
- Williams PH (1988) Habitat use by bumblebees (*Bombus* spp.). *Ecol Entomol* 13:223–238
- Williams PH (2021) Not just cryptic, but a barcode bush: PTP re-analysis of global data for the bumblebee subgenus *Bombus* s. str. supports additional species (*Apidae*, genus *Bombus*). *J Nat Hist* 55:271–282. doi: 10.1080/00222933.2021.1900444
- Williams PH, Araújo MB, Rasmont P (2007) Can vulnerability among British bumblebee (*Bombus*) species be explained by niche position and breadth? *Biol Conserv* 138:493–505. doi: 10.1016/j.biocon.2007.06.001

- Williams PH, Byvaltssev AM, Cederberg B, et al (2015) Genes suggest ancestral colour polymorphisms are shared across morphologically cryptic species in arctic bumblebees. *PLoS Med* 10:e0144544. doi: 10.1371/journal.pone.0144544
- Williams PH, Cannings SG, Sheffield CS (2016) Cryptic subarctic diversity: a new bumblebee species from the Yukon and Alaska (Hymenoptera: Apidae). *J Nat Hist* 50:2881–2893. doi: 10.1080/00222933.2016.1214294
- Wilson JS, Pan AD, General DEM, Koch JB (2020) More eyes on the prize: an observation of a very rare, threatened species of Philippine Bumble bee, *Bombus irisanensis*, on iNaturalist and the importance of citizen science in conservation biology. *J Insect Conserv* 1–3. doi: 10.1007/s10841-020-00233-3
- Wood C, Sullivan B, Iliff M, et al (2011) eBird: Engaging Birders in Science and Conservation. *PLoS Biol* 9:e1001220. doi: 10.1371/journal.pbio.1001220
- Wood TJ, Goulson D (2017) The Environmental Risks of neonicotinoid pesticides : a review of the evidence post-2013. *bioRxiv* 098897. doi: <http://dx.doi.org/10.1101/098897>
- World Wildlife Federation (2018) Living Planet Report 2018: Aiming Higher. Gland, Switzerland
- Worthington JP, Silvertown J, Cook L, et al (2012) Evolution MegaLab: A case study in citizen science methods. *Methods Ecol Evol* 3:303–309. doi: 10.1111/j.2041-210X.2011.00164.x
- Wyatt BK (1970) Ecology of Bumble Bees in Southern Ontario with Reference to Nest Development and Pollen Sources. University of Guelph
- Wyoming Department of Environmental Quality (2020) Wyoming’s Methods for Determining Surface Water Quality Condition - Proposed Draft 2020. Cheyenne, Wyoming
- Yackulic CB, Chandler R, Zipkin EF, et al (2013) Presence-only modelling using MAXENT:

- When can we trust the inferences? *Methods Ecol Evol* 4:236–243. doi: 10.1111/2041-210x.12004
- Yalden PE (1982) The effect of latitude on colony size in *Bombus monticola* Smith and *B. lapponicus* (Fabricius) (Hym., Apidae). *Fauna Nor Ser B, Nor J Entomol* 29:72–73
- Yanega D (2013) The status of Cockerell’s bumblebee, *Bombus* (*Pyrobombus*) *cockerelli* Franklin, 1913 (Hymenoptera: Apidae). *Southwest Entomol* 38:517–522
- Zapponi L, Cini A, Bardiani M, et al (2017) Citizen science data as an efficient tool for mapping protected saproxylic beetles. *Biol Conserv* 208:139–145. doi: 10.1016/j.biocon.2016.04.035
- Zayed A, Packer L (2005) Complementary sex determination substantially increases extinction proneness of haplodiploid populations. *Proc Natl Acad Sci U S A* 102:10742–6. doi: 10.1073/pnas.0502271102
- Zipkin EF, Saunders SP (2018) Synthesizing multiple data types for biological conservation using integrated population models. *Biol Conserv* 217:240–250. doi: 10.1016/j.biocon.2017.10.017
- Zuckerberg B, McGarigal K (2012) Widening the Circle of Investigation: The Interface between Citizen Science and Landscape Ecology. In: Dickinson J, Booney R (eds) *Citizen Science: Public Participation in Environmental Research*. Cornell University Press, Ithaca, New York, pp 114–124

List of Appendices and Further External Files

Appendix A. Supplementary Information for Chapter 3

Note: Tables A.S7, A.S8, and A.S11 will be provided in a separate Excel file

Appendix B. Supplementary Information for Chapter 4

Appendix C. Supplementary Information for Chapter 5

Note: Table C.S5 will be provided in a separate Excel file.

Appendix D. Supplementary Information for Chapter 6

Appendix E. Statement on Candidate's Contributions to Written Works

Appendix F. Copyright Agreements and Co-author Written Permissions for Inclusion of Manuscripts in the Dissertation

Appendix A. Supplementary Information for Chapter 3

Table A.S1. Current *Bombus* species that are considered as valid species for North America north of Mexico but that were not included in Williams et al. (2014). These species are newly described, recently re-validated, or still a point of disagreement for taxonomists.

<i>Bombus</i> species	Status in Williams et al. (2014)	Reference
<i>californicus</i> Smith, 1954 (but this species status is still uncertain)	was considered a conspecific of <i>B. fervidus</i> (Fabricius, 1798) but note that although Koch et al. (2018) found evidence for two lineages in this complex, they could not assign valid names due to the cryptic nature of the bees and the original descriptions	Koch et al. (2018)
<i>cockerelli</i> Franklin, 1913 (but this species status is still uncertain)	was considered a conspecific of <i>B. vagans</i> Smith, 1854	Yanega (2013)
<i>interacti</i> Martinet, Brasero and Rasmont, 2019 (but this species is now considered to be a synonym)	not included (new species) but now considered as conspecific of <i>B. johanseni</i> Sladen, 1919 by Sheffield et al. (2020)	Martinet et al. (2019)
<i>johanseni</i> Sladen, 1919	not included	Sheffield et al. (2020)
<i>kirbiellus</i> Dahlbom, 1832	was considered a conspecific of <i>B. balteatus</i> Dahlbom, 1832	Williams et al. (2015)
<i>mckayi</i> Ashmead, 1902 STAT. REV.	was considered a subspecies of <i>B. occidentalis</i> s. str. now split to be a separate species (as had originally been described)	Williams et al. (2021)
<i>natvigii</i> Richards, 1931	not included	Williams et al. (2015)

unnamed species =	not included (new species)	Williams et al. (2015)
<i>kluanensis</i> Williams and Cannings, 2016		Williams et al. (2016)
<i>vancouverensis</i> Cresson, 1878	<i>B. bifarius</i> was listed with two possible subspecies; it was split into two species by Ghisbain et al. (2020), and then one, <i>B. nearcticus</i> was then itself split into two subspecies, <i>B. vancouverensis vancouverensis comb.n.</i> and <i>B. vancouverensis nearcticus</i>	Ghisbain et al. (2020)

Table A.S2. The common and scientific names and taxonomic authorities for the 51 species and groups of bumble bees (*Bombus* spp.) found in either the BBNA all years or BBW datasets, as well as their IUCN Red List or NatureServe conservation status for their North American range.

Note: Names and authorities are from Williams et al. (2014) and IUCN North American conservation statuses from IUCN (2020) unless otherwise indicated. Abbreviations: DD, Data Deficient; LC, Least Concern; VU, Vulnerable; EN, Endangered; CR, Critically Endangered; [status] global species conservation status from NatureServe (2021); n.s: no status assigned.

Species	Authority	Common Name	IUCN Status [NatureServe Status]
<i>affinis</i>	Cresson, 1863	Rusty-Patched Bumble Bee	CR
<i>appositus</i>	Cresson, 1878	White-Shouldered Bumble Bee	LC
<i>auricomus</i>	(Robertson, 1903)	Black and Gold Bumble bee	LC
<i>bifarius</i>	Cresson, 1878	Two Form Bumble Bee	LC
<i>bimaculatus</i>	Cresson, 1863	Two-spotted Bumble Bee	LC
<i>bohemicus</i>	Seidl, 1838	Ashton Cuckoo Bumble Bee	DD ⁺
<i>borealis</i>	Kirby, 1837	Northern Amber Bumble Bee	LC
<i>caliginosus</i>	(Frison, 1927)	Obscure Bumble Bee	VU
<i>centralis</i>	Cresson, 1864	Central Bumble Bee	LC
<i>citrinus</i>	(Smith, 1854)	Lemon Cuckoo Bumble Bee	LC
<i>cockerelli</i> *	Franklin, 1913	Cockerell's Bumble Bee	[CR]

Species	Authority	Common Name	IUCN Status [NatureServe Status]
<i>crotchii</i>	Cresson, 1878	Crotch Bumble Bee	EN
<i>cryptarum</i>	(Fabricius, 1775)	Cryptic Bumble Bee	DD
<i>distinguendus</i>	Morawitz, 1869	Northern Yellow Bumble Bee	DD
<i>fervidus</i>	(Fabricius, 1798)	Yellow Bumble Bee	VU
<i>flavidus</i>	Eversmann, 1852	Fernald Cuckoo Bumble Bee	DD
<i>flavifrons</i>	Cresson, 1963	Yellow Head Bumble Bee	LC
<i>franklini</i>	(Frison, 1921)	Franklin Bumble Bee	CR
<i>fraternus</i>	(Smith, 1854)	Southern Plains Bumble Bee	EN
<i>frigidus</i>	Smith, 1854	Frigid Bumble Bee	LC
<i>griseocollis</i>	(DeGeer, 1773)	Brown-belted Bumble Bee	LC
<i>huntii</i>	Greene, 1860	Hunt Bumble Bee	LC
<i>impatiens</i>	Cresson, 1863	Common Eastern Bumble Bee	LC
<i>insularis</i>	(Smith, 1861)	Indiscriminate Cuckoo Bumble Bee	LC
<i>jonellus</i>	(Kirby, 1802)	White Tail Bumble Bee	DD
<i>kirbiellus</i>	Curtis, 1835	High Country Bumble Bee (<i>B. balteatus</i> Dahlbom, 1832 in Williams et al. 2014)	DD
<i>kluanensis</i> *	Williams and Cannings, 2016	Kluane Bumble Bee	[VU]
<i>melanopygus</i>	Nylander, 1848	Black Tail Bumble Bee	LC
<i>mixtus</i>	Cresson, 1878	Fuzzy-horned Bumble Bee	LC
<i>morrisoni</i>	Cresson, 1878	Morrison Bumble Bee	VU
<i>natvigi</i> *	Richards, 1931	High Arctic Bumble Bee	DD [VU]
<i>neoboreus</i>	Sladen, 1919	Active Bumble Bee	DD
<i>nevadensis</i>	Cresson, 1874	Nevada Bumble Bee	LC
<i>occidentalis</i>	Greene, 1858	Western Bumble Bee	VU
<i>pensylvanicus</i>	(DeGeer, 1773)	American Bumble Bee	VU
<i>perplexus</i>	Cresson, 1863	Confusing Bumble Bee	LC
<i>polaris</i>	Curtis, 1835	Polar Bumble Bee	DD
<i>rufocinctus</i>	Cresson, 1863	Red-belted Bumble Bee	LC
<i>sandersoni</i>	Franklin, 1913	Sanderson Bumble Bee	LC
<i>sitkensis</i>	Nylander, 1848	Sitka Bumble Bee	LC
<i>sp.</i>	n/a	Unknown Bumble Bee	n.s. depends on the species
<i>suckleyi</i>	Greene, 1860	Suckley Cuckoo Bumble Bee	CR
<i>syvicola</i>	Kirby, 1837	Forest Bumble Bee	LC
<i>ternarius</i>	Say, 1837	Tri-colored Bumble Bee	LC
<i>terricola</i>	Kirby, 1837	Yellow-banded Bumble Bee	VU
<i>vagans</i>	Smith, 1854	Half-black Bumble Bee	LC

Species	Authority	Common Name	IUCN Status [NatureServe Status]
<i>vagans</i> , <i>perplexus</i> , or <i>sandersoni</i>	n/a	Two-striped Yellow Bumble Bee Group	n.s. but species are LC
<i>vandykei</i>	(Frison, 1927)	Van Dyke Bumble Bee	LC
<i>variabilis</i>	Cresson, 1872	Variable Cuckoo Bumble Bee	CR
<i>vosnesenskii</i>	Radoszkowski, 1862	Vosnesensky Bumble Bee	LC
<i>vosnesenskii</i> or <i>caliginosus</i>	n/a	Yellow-faced Bumble Bee Group	n.s. but species are LC or VU

*Authority, name, and global status from NatureServe (2021)

+ Although ranked as DD by the IUCN, *B. bohemicus* has been assessed as Endangered in Canada by COSEWIC (2014) and in Ontario by COSSARO (Committee on the Status of Species at Risk in Ontario and COSSARO 2014)

Table A.S3. The number of total and unique bumble bee species (including three species groups: "sp", "*vagans*, *sandersoni* or *perplexus*", and "*vosnesenskii* or *caliginosus*") per province, state, and territory, by dataset.

Province, State, Territory	# species in BBNA all years	# species in BBNA 2010-2020	# species in BBW	# species in BBW and not in BBNA all years?	# species in BBW and not in BBNA 2010-2020?	# species found in this region
Alabama	9	0	6	1	6	10
Alaska	27	24	9	1	2	28
Alberta	29	26	27	3	15	32
Arizona	17	14	6	1	5	18
Arkansas	8	4	6	1	5	9
British Columbia	34	26	26	2	12	36
California	25	21	20	2	8	27
Colorado	26	21	20	2	17	28
Connecticut	16	10	4	1	2	17
Delaware	10	6	4	1	1	11
District of Columbia	10	7	3	0	1	10
Florida	6	4	6	1	2	7

Province, State, Territory	# species in BBNA all years	# species in BBNA 2010-2020	# species in BBW	# species in BBW and not in BBNA all years?	# species in BBW and not in BBNA 2010-2020?	# species found in this region
Georgia	15	6	6	1	5	16
Idaho	22	16	20	1	16	23
Illinois	17	10	11	1	3	18
Indiana	14	9	10	2	8	16
Iowa	14	3	12	2	9	16
Kansas	12	0	8	1	4	13
Kentucky	10	3	6	1	6	11
Louisiana	6	0	4	1	1	7
Maine	18	12	15	3	4	21
Manitoba	27	8	15	3	6	30
Maryland	14	11	10	2	5	16
Massachusetts	18	13	11	2	9	20
Michigan	21	15	14	2	4	23
Minnesota	20	11	20	3	13	23
Mississippi	8	0	5	1	5	9
Missouri	10	4	9	2	5	12
Montana	28	27	16	1	12	29
Nebraska	17	8	11	1	4	18
Nevada	18	8	5	0	1	18
New Brunswick	18	15	14	2	2	20
New Hampshire	18	13	7	2	5	20
New Jersey	17	9	6	2	2	19
New Mexico	18	6	5	2	5	20
New York	19	15	13	2	11	21
Newfoundland and Labrador	19	12	14	2	5	21
North Carolina	15	11	10	2	10	17
North Dakota	24	1	11	1	7	25
Northwest Territories	21	16	6	1	6	22
Nova Scotia	16	13	12	2	2	18
Nunavut	10	5	2	1	2	11
Ohio	20	8	12	2	3	22
Oklahoma	9	4	5	1	4	10
Ontario	27	16	23	2	6	29
Oregon	25	16	24	2	21	27

Province, State, Territory	# species in BBNA all years	# species in BBNA 2010-2020	# species in BBW	# species in BBW and not in BBNA all years?	# species in BBW and not in BBNA 2010-2020?	# species found in this region
Pennsylvania	16	10	10	2	4	18
Prince Edward Island	14	10	14	2	12	16
Quebec	25	17	20	2	14	27
Rhode Island	10	7	7	3	3	13
Saskatchewan	24	18	20	4	18	28
South Carolina	12	3	6	1	6	13
South Dakota	28	13	15	2	8	30
Tennessee	16	8	7	1	1	17
Texas	12	4	7	1	5	13
Utah	23	13	13	1	10	24
Vermont	17	13	12	2	7	19
Virginia	17	14	13	2	12	19
Washington	26	21	25	3	13	29
West Virginia	14	12	8	2	8	16
Wisconsin	20	7	18	3	2	23
Wyoming	23	18	15	1	15	24
Yukon	26	20	3	0	3	26
Total # species	48	45	44	3	3	51

Table A.S4. The total number of bumble bee records (all species combined) per province, state, and territory by dataset.

Province, State, Territory	# BBNA records all years	# BBNA records 2010- 2020	#BBW records	total # records (BBNA all years & BBW)
Alabama	188	0	60	248
Alaska	40,468	20,310	48	40,516
Alberta	16,251	10,727	1,821	18,072
Arizona	6,431	388	10	6,441
Arkansas	204	19	41	245
British Columbia	12,522	1,410	1,257	13,779
California	61,101	2,200	481	61,582
Colorado	26,259	779	217	26,476

Province, State, Territory	# BBNA records all years	# BBNA records 2010- 2020	#BBW records	total # records (BBNA all years & BBW)
Connecticut	6,639	1,281	26	6,665
Delaware	382	48	21	403
District of Columbia	640	369	9	649
Florida	2,239	15	48	2,287
Georgia	1,339	68	47	1,386
Idaho	4,601	316	4,644	9,245
Illinois	10,176	392	212	10,388
Indiana	4,028	1,035	112	4,140
Iowa	1,367	5	198	1,565
Kansas	1,731	0	47	1,778
Kentucky	724	24	33	757
Louisiana	123	0	15	138
Maine	2,490	1,258	324	2,814
Manitoba	2,475	46	352	2,827
Maryland	4,738	3,066	85	4,823
Massachusetts	14,758	8,001	156	14,914
Michigan	9,512	669	400	9,912
Minnesota	12,899	584	2,662	15,561
Mississippi	1,871	0	11	1,882
Missouri	3,037	8	128	3,165
Montana	14,554	5,567	191	14,745
Nebraska	3,166	25	1,555	4,721
Nevada	2,926	43	15	2,941
New Brunswick	1,424	923	575	1,999
New Hampshire	6,842	1,400	54	6,896
New Jersey	10,464	5,057	46	10,510
New Mexico	3,484	25	18	3,502
New York	11,142	854	245	11,387
Newfoundland and Labrador	2,857	2,205	240	3,097
North Carolina	4,855	1,578	80	4,935
North Dakota	3,415	1	49	3,464
Northwest Territories	993	110	12	1,005
Nova Scotia	3,115	634	581	3,696
Nunavut	1,089	66	7	1,096
Ohio	4,699	95	274	4,973
Oklahoma	1,030	224	60	1,090
Ontario	36,121	19,322	9,581	45,702
Oregon	19,637	6,773	6,292	25,929

Province, State, Territory	# BBNA records all years	# BBNA records 2010- 2020	#BBW records	total # records (BBNA all years & BBW)
Pennsylvania	6,149	2,910	159	6,308
Prince Edward Island	1,519	149	187	1,706
Quebec	5,043	2,899	1,168	6,211
Rhode Island	377	161	45	422
Saskatchewan	1,598	557	314	1,912
South Carolina	532	4	27	559
South Dakota	3,475	675	138	3,613
Tennessee	800	293	42	842
Texas	4,060	827	223	4,283
Utah	10,110	374	52	10,162
Vermont	15,503	12,123	135	15,638
Virginia	4,997	3,675	151	5,148
Washington	13,473	1,588	7,143	20,616
West Virginia	5,375	3,824	33	5,408
Wisconsin	4,560	82	895	5,455
Wyoming	8,214	1,419	79	8,293
Yukon	8,368	2,521	3	8,371
Total # records	475,159	132,001	44,134	519,293

Table A.S5. A comparison of the mean numbers of bee records, species richness, Menhinick's Index, and Shannon-Weiner species diversity index values in BBW as compared to BBNA all years and BBNA 2010-2010 at three scales: province (including states and territories)(n=63), 100km x 100km grids (n=1485), and 10km x 10km grids (n=19314). The means were based on the individual calculation for all species within each scale variable (e.g. for each province or state) and dataset using only provinces or grids where there was at least one record amongst all databases. Values presented here are mean $\pm$ standard error (SE); see Tables S6, S7, S8 for the individual values for each scale variable. Average Species Richness is calculated as the total number of species, Average Menhinick's Index is the total number species divided by the square-root of the total number of individuals, and the Average Shannon-Weiner Index (species diversity) is calculated as $-1 \cdot \sum(\pi_i \cdot \ln \pi_i)$, where π_i is the proportion of each species. Statistical tests conducted were either Independent samples T-tests (T) or Mann-Whitney U-tests (U).

Dataset comparison	Variable	Scale	Dataset	Mean	SE	Statistical test results
BBW vs BBNA all years	# bee records	Province	BBNA_allyears	86.241	26.605	U = 1,047.000, p-value $\leq$ 0.001
			BBW	127.732	21.474	
BBW vs BBNA 2010-2020	# bee records	Province	BBNA 2010-2020	158.32	32.637	U = 1,576.500, p-value = 0.047
			BBW	127.732	21.474	
BBW vs BBNA all years	species richness	Province	BBNA_allyears	17.857	0.814	U = 3,031.500, p-value $\leq$ 0.001
			BBW	11.460	0.795	
BBW vs BBNA 2010-2020	species richness	Province	BBNA 2010-2020	11.032	0.85	U = 1,946.000, p-value = 0.853
			BBW	11.460	0.795	
BBW vs BBNA all years	Menhinick's Index	Province	BBNA_allyears	0.306	0.018	U = 199.000, p-value $\leq$ 0.001
			BBW	0.95	0.048	
BBW vs BBNA 2010-2020	Menhinick's Index	Province	BBNA 2010-2020	0.299	0.028	U = 242.500, p-value $\leq$ 0.001
			BBW	0.95	0.048	

Dataset comparison	Variable	Scale	Dataset	Mean	SE	Statistical test results
BBW vs BBNA all years	species diversity	Province	BBNA_allyears	1.959	0.062	U = 2,401.000, p-value = 0.177
			BBW	1.789	0.061	
BBW vs BBNA 2010-2020	species diversity	Province	BBNA 2010-2020	1.434	0.089	T = -3.296, p-value = 0.001
			BBW	1.789	0.061	
BBW vs BBNA all years	# bee records	100km x 100km	BBNA_allyears	319.972	22.51	U = 1,835,000.000, p-value ≤ 0.001
			BBW	29.72	3.338	
BBW vs BBNA 2010-2020	# bee records	100km x 100km	BBNA 2010-2020	88.89	10.918	U = 1,020,000.000, p-value ≤ 0.001
			BBW	29.72	3.338	
BBW vs BBNA all years	species richness	100km x 100km	BBNA_allyears	7.253	0.139	U = 1,710,000.000, p-value ≤ 0.001
			BBW	2.923	0.109	
BBW vs BBNA 2010-2020	species richness	100km x 100km	BBNA_2010_2020	2.255	0.098	U = 951,213.000, p-value ≤ 0.001
			BBW	2.923	0.109	
BBW vs BBNA all years	Menhinick's Index	100km x 100km	BBNA_allyears	0.835	0.011	U = 2,114,000.000, p-value ≤ 0.001
			BBW	0.04	0.005	
BBW vs BBNA 2010-2020	Menhinick's Index	100km x 100km	BBNA_2010_2020	0.024	0.004	U = 1,099,000.000, p-value = 0.625
			BBW	0.04	0.005	
BBW vs BBNA all years	species diversity	100km x 100km	BBNA_allyears	1.209	0.019	U = 1,582,000.000, p-value ≤ 0.001
			BBW	0.601	0.02	
BBW vs BBNA 2010-2020	species diversity	100km x 100km	BBNA_2010_2020	0.061	0.008	U = 678,257.500, p-value ≤ 0.001
			BBW	0.601	0.02	
BBW vs BBNA all years	# bee records	10km x 10km	BBNA_allyears	2.36	0.094	U = 21,260,000,000.000, p-value ≤ 0.001
			BBW	0.219	0.011	
BBW vs BBNA 2010-2020	# bee records	10km x 10km	BBNA_2010-2020	0.655	0.05	U = 20,010,000,000.000, p-value ≤ 0.001
			BBW	0.219	0.011	
BBW vs BBNA all years	species richness	10km x 10km	BBNA_allyears	2.444	0.019	U = 285,700,000.000, p-value ≤ 0.001
			BBW	0.766	0.012	
BBW vs BBNA 2010-2020	species richness	10km x 10km	BBNA_2010-2020	0.56	0.011	U = 162,900,000.000, p-value ≤ 0.001
			BBW	0.766	0.012	

Dataset comparison	Variable	Scale	Dataset	Mean	SE	Statistical test results
BBW vs BBNA all years	Menhinic k's Index	10km x 10km	BBNA_allyears BBW	1.302 0.376	0.006 0.004	U = 296,500,000.000, p-value $\leq$ 0.001
BBW vs BBNA 2010-2020	Menhinic k's Index	10km x 10km	BBNA_2010-2020 BBW	0.295 0.376	0.005 0.004	U = 165,000,000.000, p-value $\leq$ 0.001
BBW vs BBNA all years	species diversity	10km x 10km	BBNA_allyears BBW	0.517 0.171	0.004 0.003	U = 247,300,000.000, p-value $\leq$ 0.001
BBW vs BBNA 2010-2020	species diversity	10km x 10km	BBNA_2010-2020 BBW	0.119 0.171	0.003 0.003	U = 178,300,000.000, p-value $\leq$ 0.001

Table A.S6. The total Menhinick's and Shannon-Weiner diversity indices (all species combined) per province, state, and territory, by dataset. Menhinick's index is the number of species divided by the square-root of the total number of individuals. Shannon-Weiner diversity index is $\pi \cdot \ln \pi$ where π = relative individual species density.

Province, State, Territory	Menhinick's index			Shannon-Weiner diversity index		
	BBNA all years	BBNA 2010-2020	BBW	BBNA all years	BBNA 2010-2020	BBW
Alabama	0.66	n/a	0.77	1.33	n/a	1.23
Alaska	0.13	0.17	1.30	2.47	2.36	1.86
Alberta	0.23	0.25	0.63	2.63	2.13	2.71
Arizona	0.21	0.71	1.90	1.43	1.96	1.61
Arkansas	0.56	0.92	0.94	1.40	1.01	1.50
British Columbia	0.30	0.69	0.73	2.45	2.43	2.61
California	0.10	0.45	0.91	2.21	1.89	2.07
Colorado	0.16	0.75	1.36	2.77	2.56	2.26
Connecticut	0.20	0.28	0.78	1.95	1.05	0.94
Delaware	0.51	0.87	0.87	1.55	1.12	0.96
District of Columbia	0.40	0.36	1.00	1.47	0.79	1.06
Florida	0.13	1.03	0.87	1.27	1.06	1.36
Georgia	0.41	0.73	0.88	1.61	1.08	1.41
Idaho	0.32	0.90	0.29	2.46	1.58	2.58
Illinois	0.17	0.51	0.76	1.97	1.80	1.75
Indiana	0.22	0.28	0.94	1.92	1.60	1.80
Iowa	0.38	1.34	0.85	1.66	1.05	1.81
Kansas	0.29	n/a	1.17	1.68	n/a	1.84
Kentucky	0.37	0.61	1.04	0.95	0.46	1.57
Louisiana	0.54	n/a	1.03	1.33	n/a	1.18
Maine	0.36	0.34	0.83	2.09	1.53	2.23
Manitoba	0.54	1.18	0.80	2.50	1.68	2.10
Maryland	0.20	0.20	1.08	1.64	1.34	1.78
Massachusetts	0.15	0.15	0.88	1.84	1.14	1.35
Michigan	0.22	0.58	0.70	2.38	2.10	1.74
Minnesota	0.18	0.46	0.39	2.48	1.48	2.27
Mississippi	0.18	n/a	1.51	1.39	n/a	1.52
Missouri	0.18	1.41	0.80	1.70	1.26	1.95
Montana	0.23	0.36	1.16	2.65	2.63	2.29
Nebraska	0.30	1.60	0.28	1.90	1.71	1.53
Nevada	0.33	1.22	1.29	2.32	1.70	1.43

Province, State, Territory	Menhinick's index			Shannon-Weiner diversity index		
	BBNA all years	BBNA 2010-2020	BBW	BBNA all years	BBNA 2010-2020	BBW
New Brunswick	0.48	0.49	0.58	2.23	2.28	1.99
New Hampshire	0.22	0.35	0.95	2.09	1.53	1.38
New Jersey	0.17	0.13	0.88	1.48	1.12	1.43
New Mexico	0.30	1.20	1.18	2.31	1.46	1.35
New York	0.18	0.51	0.83	2.40	2.08	1.89
Newfoundland and Labrador	0.36	0.26	0.90	1.50	0.96	2.21
North Carolina	0.22	0.28	1.12	2.08	1.40	1.89
North Dakota	0.41	1.00	1.57	2.00	0.00	2.14
Northwest Territories	0.67	1.53	1.73	2.38	2.51	1.54
Nova Scotia	0.29	0.52	0.50	2.30	2.32	2.03
Nunavut	0.30	0.62	0.76	1.23	1.18	0.41
Ohio	0.29	0.82	0.72	2.23	0.56	1.60
Oklahoma	0.28	0.27	0.65	1.12	0.76	1.43
Ontario	0.14	0.12	0.23	2.37	2.04	1.98
Oregon	0.18	0.19	0.30	2.35	1.34	2.54
Pennsylvania	0.20	0.19	0.79	1.54	0.78	1.75
Prince Edward Island	0.36	0.82	1.02	2.03	1.65	1.95
Quebec	0.35	0.32	0.59	2.57	2.13	2.27
Rhode Island	0.52	0.55	1.04	1.98	1.48	1.51
Saskatchewan	0.60	0.76	1.13	2.66	2.35	2.40
South Carolina	0.52	1.50	1.15	1.47	1.04	1.61
South Dakota	0.47	0.50	1.28	2.47	1.58	2.23
Tennessee	0.57	0.47	1.08	2.07	1.08	1.57
Texas	0.19	0.14	0.47	0.57	0.45	1.05
Utah	0.23	0.67	1.80	2.34	1.76	2.32
Vermont	0.14	0.12	1.03	2.01	1.75	1.86
Virginia	0.24	0.23	1.06	1.74	1.47	1.93
Washington	0.22	0.53	0.30	2.66	2.46	2.76
West Virginia	0.19	0.19	1.39	1.32	1.05	1.62
Wisconsin	0.30	0.77	0.60	1.74	0.54	2.30
Wyoming	0.25	0.48	1.69	2.31	2.35	2.36
Yukon	0.28	0.40	1.73	2.44	2.32	1.10
All data combined	0.07	0.12	0.21	3.31	2.87	3.07

Table A.S7. The total number of records, species, and the Menhinick's and Shannon-Weiner diversity indices (all species combined) per 100km x 100km grid, by dataset. Menhinick's index is the number of species divided by the square-root of the total number of individuals. Shannon-Weiner diversity index is $\pi * \ln \pi$ where π = relative individual species density.

See separate Excel file for Table A.S7 (40pp; not included in page counts)

Table A.S8. The total number of records, species, and the Menhinick's and Shannon-Weiner diversity indices (all species combined) per 10km x 10km grid, by dataset. Menhinick's index is the number of species divided by the square-root of the total number of individuals. Shannon-Weiner diversity index is $\pi * \ln \pi$ where π = relative individual species density.

See separate Excel file (537pp; not included in page counts)

Table A.S9. A comparison of the Extent of Occurrence (EOO) geographic range area and difference in EOO areas per species between BBW dataset and the BBNA all years or BBNA 2010-2020 datasets. See the text for discussion about constraints with interpreting these values as areas of usable range (e.g. the inclusion of areas in the EOO that are not suitable habitat).

Species	EOO area (km ²)			Difference in EOO area (km ²) (BBW less BBNA)	
	BBNA all years	BBNA 2010-2020	BBW	BBW vs BBNA all years	BBW vs BBNA 2010-2020
<i>affinis</i>	2,695,720	447,577	1,284,220	-1,411,500	836,643
<i>appositus</i>	3,099,020	1,824,600	1,172,080	-1,926,940	-652,520
<i>auricomus</i>	4,240,090	2,591,170	2,433,400	-1,806,690	-157,770
<i>bifarius</i>	9,424,620	6,278,810	2,834,600	-6,590,020	-3,444,210
<i>bimaculatus</i>	5,787,300	3,834,660	5,336,340	-450,960	1,501,680
<i>bohemicus</i>	13,678,200	5,195,400	2,792,900	-10,885,300	-2,402,500
<i>borealis</i>	12,107,600	8,991,360	5,169,280	-6,938,320	-3,822,080
<i>caliginosus</i>	551,953	96,711	322,515	-229,438	225,804
<i>centralis</i>	8,611,140	4,958,690	2,518,260	-6,092,880	-2,440,430
<i>citrinus</i>	5,510,460	5,074,500	3,127,740	-2,382,720	-1,946,760
<i>cockerelli</i>	1,297	0	no records	n/a	n/a
<i>crotchii</i>	357,698	2,433	84,010	-273,688	81,577
<i>cryptarum</i>	6,548,630	2,256,180	4,962,840	-1,585,790	2,706,660
<i>distinguendus</i>	409,904	no records	no records	n/a	n/a
<i>fervidus</i>	17,952,500	13,776,700	8,705,000	-9,247,500	-5,071,700
<i>flavidus</i>	18,436,000	15,396,100	7,187,510	-11,248,490	-8,208,590
<i>flavifrons</i>	15,877,600	6,706,140	3,734,950	-12,142,650	-2,971,190
<i>franklini</i>	19,589	no records	no records	n/a	n/a
<i>fraternus</i>	4,545,830	1,937,690	2,141,730	-2,404,100	204,040
<i>frigidus</i>	15,756,600	12,405,800	5,614,210	-10,142,390	-6,791,590
<i>griseocollis</i>	9,462,960	6,635,110	7,403,930	-2,059,030	768,820
<i>huntii</i>	5,446,530	2,807,540	3,412,950	-2,033,580	605,410
<i>impatiens</i>	9,944,970	5,983,250	9,304,660	-640,310	3,321,410
<i>insularis</i>	15,523,800	13,186,400	6,698,170	-8,825,630	-6,488,230
<i>jonellus</i>	4,145,690	2,043,470	0	-4,145,690	-2,043,470
<i>kirbiellus</i>	16,069,500	6,066,480	1,884,860	-14,184,640	-4,181,620
<i>kluanensis</i>	11,114	8,415	no records	n/a	n/a
<i>melanopygus</i>	18,102,600	11,398,200	11,077,400	-7,025,200	-320,800
<i>mixtus</i>	16,760,700	5,564,230	2,863,910	-13,896,790	-2,700,320
<i>morrisoni</i>	2,999,980	1,008,850	1,304,430	-1,695,550	295,580

Species	EOO area (km ²)			Difference in EOO area (km ²) (BBW less BBNA)	
	BBNA all years	BBNA 2010- 2020	BBW	BBW vs BBNA all years	BBW vs BBNA 2010- 2020
<i>natvigi</i>	7,790,570	4,132,230	no records	n/a	n/a
<i>neoboreus</i>	4,062,620	905,351	no records	n/a	n/a
<i>nevadensis</i>	6,337,480	4,118,470	4,662,030	-1,675,450	543,560
<i>occidentalis</i>	10,346,600	5,282,160	5,895,740	-4,450,860	613,580
<i>pensylvanicus</i>	9,180,680	6,813,980	5,762,510	-3,418,170	-1,051,470
<i>perplexus</i>	10,668,500	8,795,900	3,994,910	-6,673,590	-4,800,990
<i>polaris</i>	13,735,400	8,260,170	0	-13,735,400	-8,260,170
<i>rufocinctus</i>	14,327,000	11,602,000	7,611,200	-6,715,800	-3,990,800
<i>sandersoni</i>	8,832,360	7,416,070	3,581,700	-5,250,660	-3,834,370
<i>sitkensis</i>	5,680,490	2,236,540	1,182,750	-4,497,740	-1,053,790
<i>sp.</i>	no records	no records	22,812,300	n/a	n/a
<i>suckleyi</i>	13,958,500	8,292,670	3	-13,958,497	-8,292,667
<i>sylvicola</i>	23,973,300	23,973,300	12,311,800	-11,661,500	-11,661,500
<i>ternarius</i>	10,445,900	6,800,730	7,123,760	-3,322,140	323,030
<i>terricola</i>	13,094,000	7,910,660	6,933,690	-6,160,310	-976,970
<i>vagans</i>	14,299,700	7,175,190	7,991,690	-6,308,010	816,500
<i>vagans</i> , <i>sandersoni</i> or <i>perplexus</i>	no records	no records	6,055,720	n/a	n/a
<i>vandykei</i>	748,521	505,566	240,012	-508,509	-265,554
<i>variabilis</i>	5,944,340	no records	no records	n/a	n/a
<i>vosnesenskii</i>	1,428,890	557,806	1,014,040	-414,850	456,234
<i>vosnesenskii</i> or <i>caliginosus</i>	no records	no records	831,586	n/a	n/a
all species combined	31,862,000	26,323,600	25,840,000	-6,022,000	-483,600

Table A.S10. A comparison of the number of 100km x 100km grids: with records per species per dataset; where BBW confirms the presence of a species in BBNA all years (i.e. in both BBNA and BBW); where BBW shows novel recent persistence (i.e. present historically in BBNA all years but only found in the last decade through BBW); with unique grids over the combined all years and 2010-2020 datasets due to the BBW dataset; and the total number of grids in the combined BBNA all years + BBW and BBNA 2010-2020 + BBW datasets. This latter measure can also be used to calculate the total range size by multiplying the number of grids per combined dataset by 100km x 100km.

Comparison of 100km x 100km grids being tested per <i>Bombus</i> species	total # grids per dataset			# grids where BBW confirms presence*	# grids where BBW shows novel recent persistence*	# unique grids due to BBW over all years	# unique grids due to BBW over 2010-2020	# grids with any records in combined all years data	# grids with any records in combined 2010-2020 data
Datasets being compared	BBNA all years	BBNA 2010-2020	BBW	BBW in same grid as BBNA all years	BBW in same grid as BBNA all years, when no BBNA 2010-2020 present	BBW only vs BBNA all years	BBW only vs BBNA 2010-2020	BBW or BBNA all years	BBW or BBNA 2010-2020
<i>affinis</i>	178	23	30	23	7	7	14	185	37
<i>appositus</i>	173	46	67	59	41	8	49	181	95
<i>auricomus</i>	221	31	63	52	43	11	54	232	85
<i>bifarius</i>	292	99	111	99	50	12	62	304	161
<i>bimaculatus</i>	325	130	217	163	78	54	132	379	262
<i>bohemicus</i>	263	22	5	2	1	3	4	266	26
<i>borealis</i>	277	104	151	126	72	25	97	302	201
<i>caliginosus</i>	44	7	20	18	15	2	17	46	24
<i>centralis</i>	243	78	90	71	47	19	66	262	144
<i>citrinus</i>	189	64	46	29	15	17	32	206	96

Comparison of 100km x 100km grids being tested per <i>Bombus</i> species	total # grids per dataset			# grids where BBW confirms presence*	# grids where BBW shows novel recent persistence*	# unique grids due to BBW over all years	# unique grids due to BBW over 2010-2020	# grids with any records in combined all years data	# grids with any records in combined 2010-2020 data
Datasets being compared	BBNA all years	BBNA 2010-2020	BBW	BBW in same grid as BBNA all years	BBW in same grid as BBNA all years, when no BBNA 2010-2020 present	BBW only vs BBNA all years	BBW only vs BBNA 2010-2020	BBW or BBNA all years	BBW or BBNA 2010-2020
<i>cockerelli</i>	2	1	0	0	0	0	0	2	1
<i>crotchii</i>	35	3	9	9	6	0	6	35	9
<i>cryptarum</i>	104	57	28	16	4	12	16	116	73
<i>distinguendus</i>	3	0	0	0	0	0	0	3	0
<i>fervidus</i>	587	169	187	167	106	20	126	607	295
<i>flavidus</i>	311	97	57	35	24	22	46	333	143
<i>flavifrons</i>	350	123	97	79	49	18	67	368	190
<i>franklini</i>	7	0	0	0	0	0	0	7	0
<i>fraternus</i>	214	15	33	28	21	5	26	219	41
<i>frigidus</i>	253	83	16	8	1	8	9	261	92
<i>griseocollis</i>	501	170	299	256	161	43	204	544	374
<i>huntii</i>	269	81	126	101	69	25	94	294	175
<i>impatiens</i>	400	171	326	265	126	61	187	461	358
<i>insularis</i>	361	105	90	64	41	26	67	387	172
<i>jonellus</i>	95	38	1	1	1	0	1	95	39
<i>kirbiellus</i>	113	34	7	3	1	4	5	117	39
<i>kluanensis</i>	5	4	0	0	0	0	0	5	4
<i>melanopygus</i>	283	102	104	71	42	33	75	316	177
<i>mixtus</i>	308	117	89	75	37	14	51	322	168
<i>morrisoni</i>	183	10	37	29	25	8	33	191	43
<i>natvigi</i>	50	10	0	0	0	0	0	50	9
<i>neoboreus</i>	41	12	0	0	0	0	0	41	12

Comparison of 100km x 100km grids being tested per <i>Bombus</i> species	total # grids per dataset			# grids where BBW confirms presence*	# grids where BBW shows novel recent persistence*	# unique grids due to BBW over all years	# unique grids due to BBW over 2010-2020	# grids with any records in combined all years data	# grids with any records in combined 2010-2020 data
Datasets being compared	BBNA all years	BBNA 2010-2020	BBW	BBW in same grid as BBNA all years	BBW in same grid as BBNA all years, when no BBNA 2010-2020 present	BBW only vs BBNA all years	BBW only vs BBNA 2010-2020	BBW or BBNA all years	BBW or BBNA 2010-2020
<i>nevadensis</i>	250	64	120	86	64	34	98	284	162
<i>occidentalis</i>	369	131	98	93	45	5	50	374	181
<i>pennsylvanicus</i>	558	100	134	124	88	10	98	568	198
<i>perplexus</i>	252	138	127	84	30	43	73	295	211
<i>polaris</i>	113	30	1	0	0	1	1	114	30
<i>rufocinctus</i>	402	142	191	145	79	46	125	448	267
<i>sandersoni</i>	184	85	20	11	8	9	17	193	102
<i>sitkensis</i>	114	26	29	29	19	0	19	114	45
<i>sp.</i>	0	0	419	0	0	419	419	419	419
<i>suckleyi</i>	202	11	2	2	2	0	2	202	13
<i>sylvicola</i>	309	84	36	19	12	17	29	326	112
<i>ternarius</i>	300	149	235	178	75	57	132	357	281
<i>terricola</i>	383	135	155	127	50	28	78	411	213
<i>vagans</i>	406	200	179	140	57	39	96	445	296
<i>vagans, sandersoni or perplexus</i>	0	0	149	0	0	149	149	149	149
<i>vandykei</i>	56	16	18	15	8	3	11	59	27
<i>variabilis</i>	94	0	0	0	0	0	0	94	0
<i>vosnesenskii</i>	98	31	73	60	34	13	47	111	78
<i>vosnesenskii or caliginosus</i>	0	0	49	0	0	49	49	49	49

Comparison of 100km x 100km grids being tested per <i>Bombus</i> species	total # grids per dataset			# grids where BBW confirms presence*	# grids where BBW shows novel recent persistence*	# unique grids due to BBW over all years	# unique grids due to BBW over 2010-2020	# grids with any records in combined all years data	# grids with any records in combined 2010-2020 data
Datasets being compared	BBNA all years	BBNA 2010-2020	BBW	BBW in same grid as BBNA all years	BBW in same grid as BBNA all years, when no BBNA 2010-2020 present	BBW only vs BBNA all years	BBW only vs BBNA 2010-2020	BBW or BBNA all years	BBW or BBNA 2010-2020
all species	1434	619	842	792 ⁺ 717 ^{..}	384 ⁺ 543 ^{..}	50 ⁺ 604 ^{..}	398 ⁺ 764 ^{..}	1484	1017

* Number of grids out of the 100km x 100km grids in BBNA all years (excluding grids unique to BBW)

⁺ Number of grids overall (grids compared with all species combined)

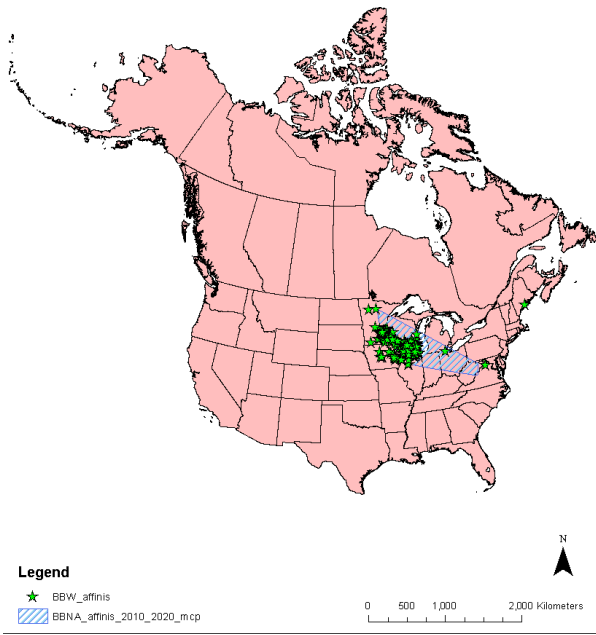
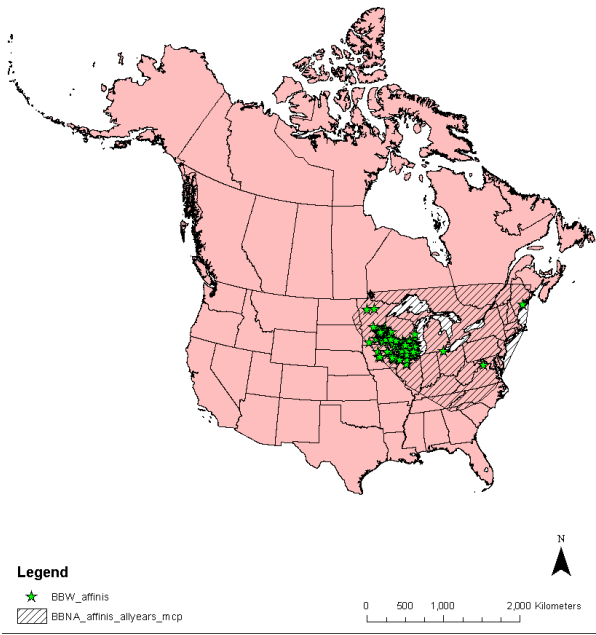
^{..} Number of grids for at least one species (grids compared for each species separately)

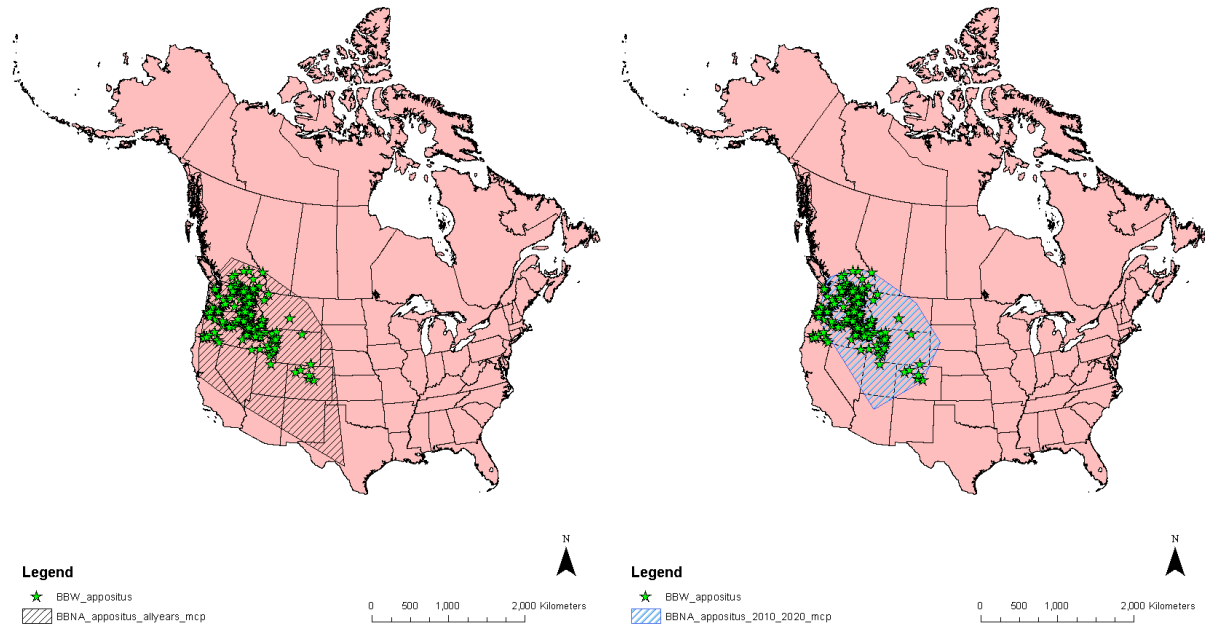
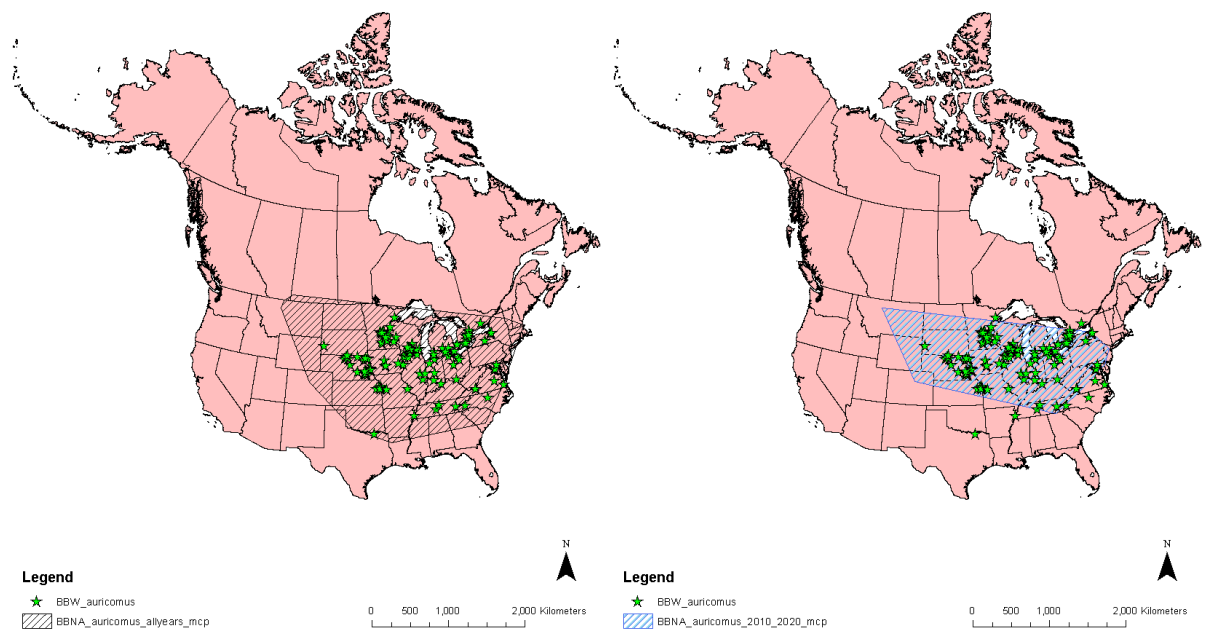
Table A.S11. Total number of bumble bee records per plant species (lowest level of identification), per bumble bee (*Bombus*) species (including BBNA all years, BBNA 2010-2020, BBW databases) Note: plant "species" in brackets are not actually plant species but descriptions; these were not included in analyses.

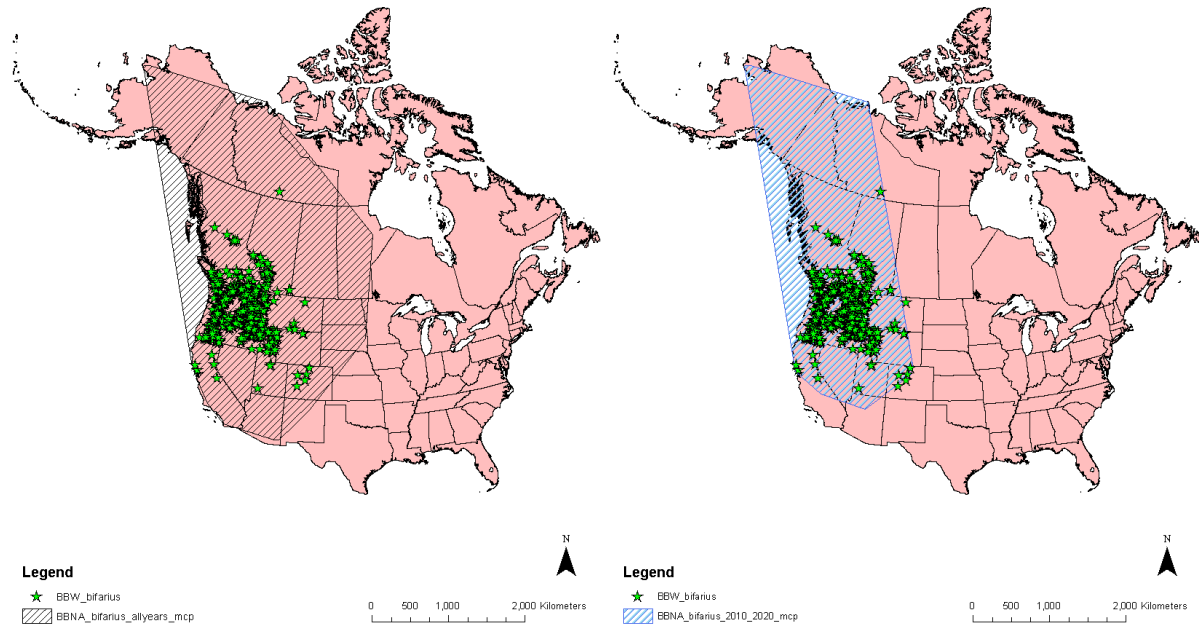
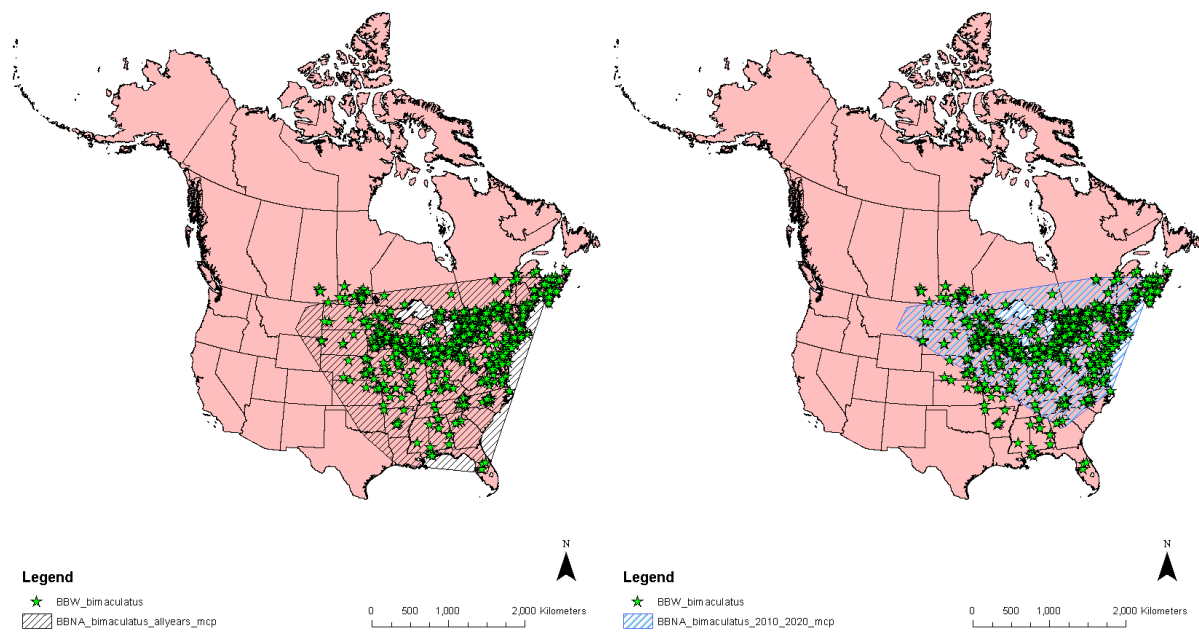
See separate Excel file (432pp; not included in page counts)

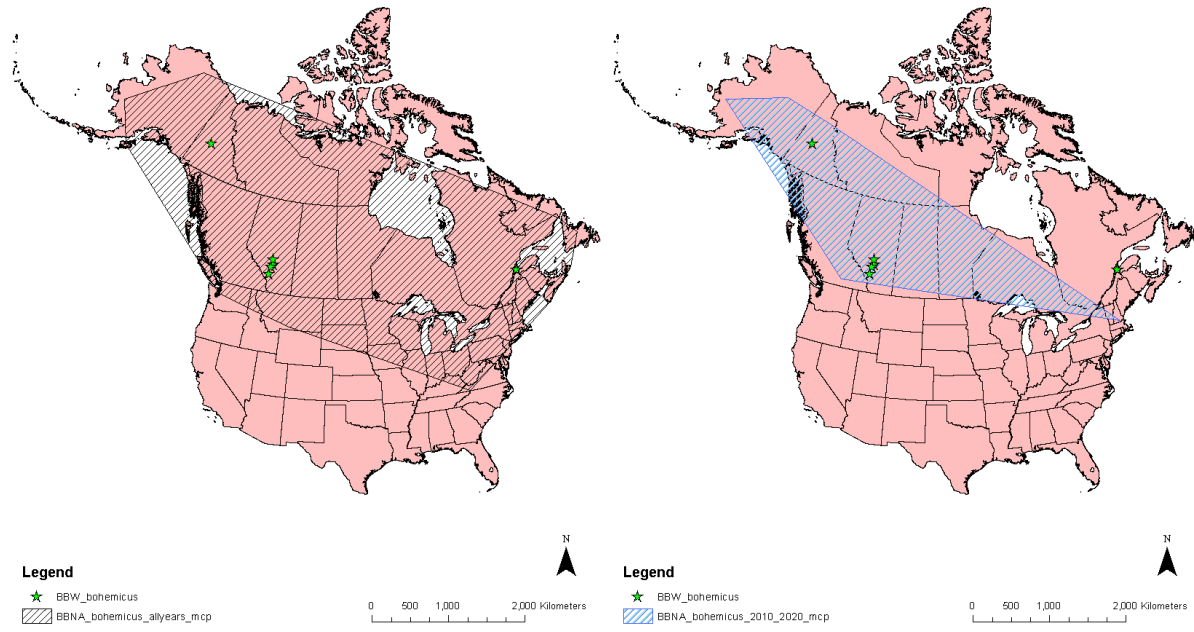
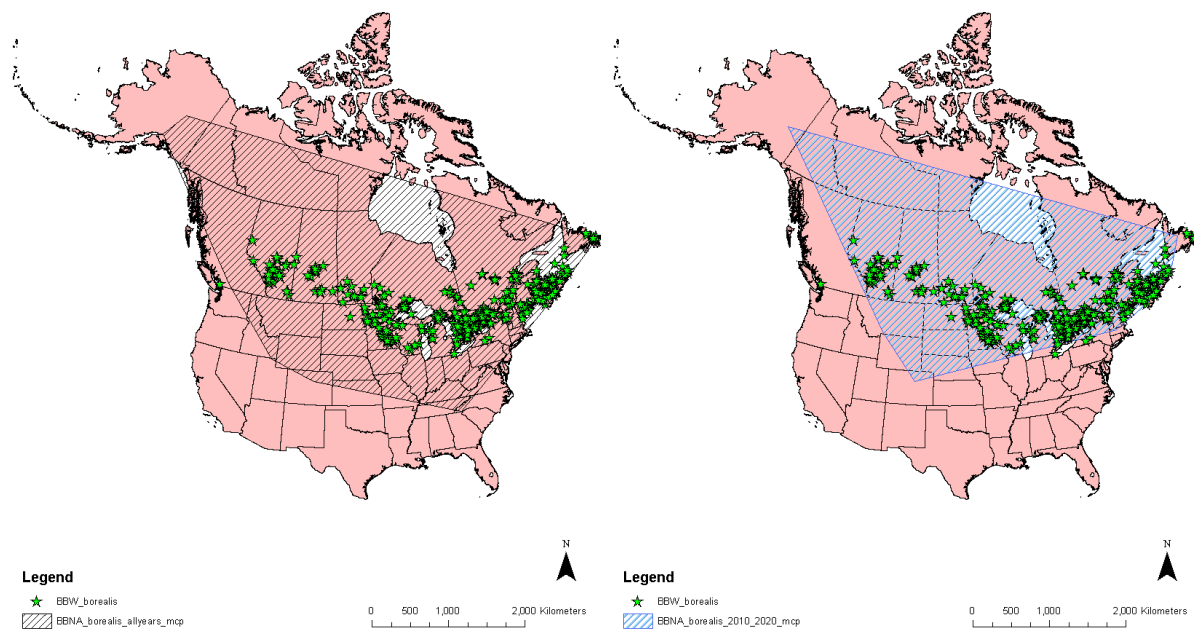
Figure A.S1.

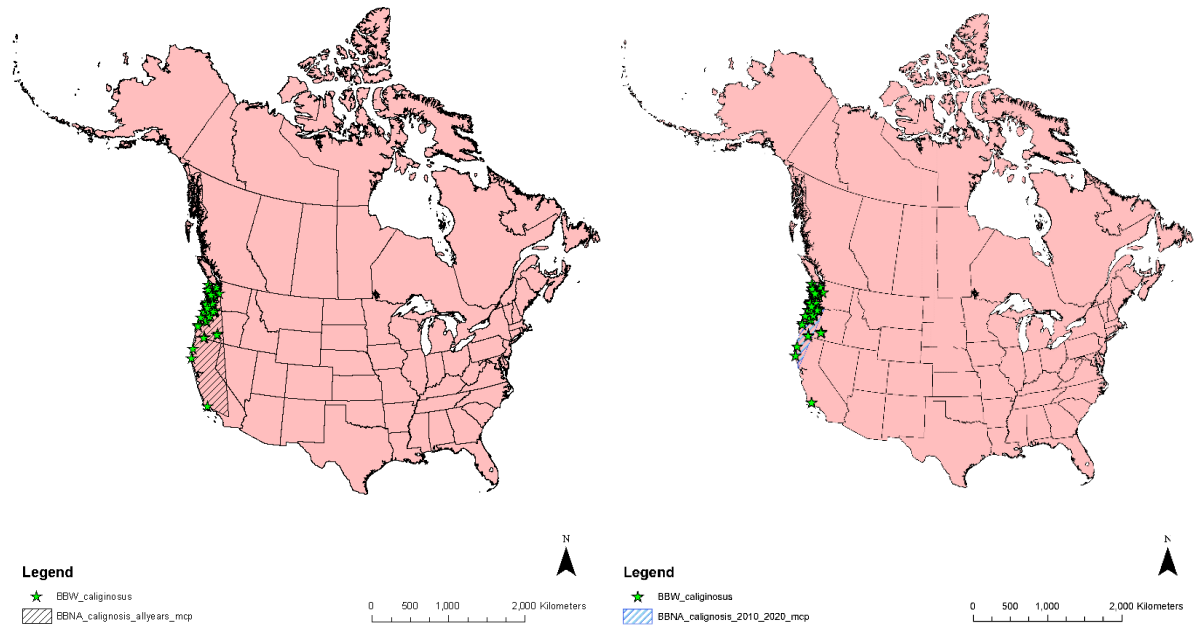
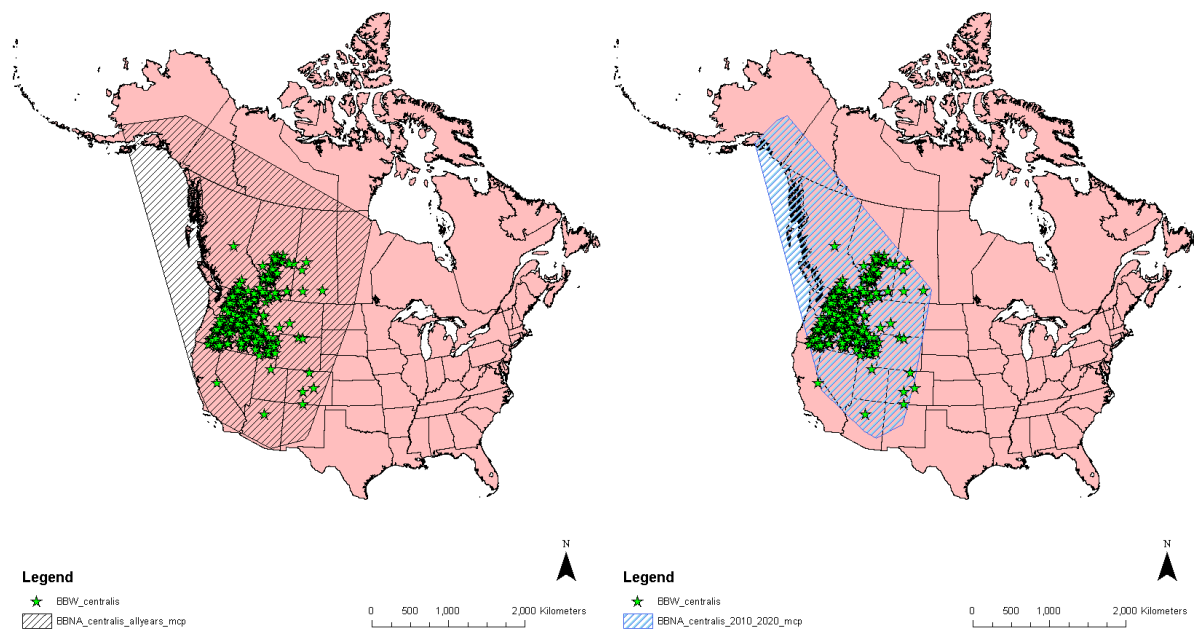
a) *Bombus affinis*

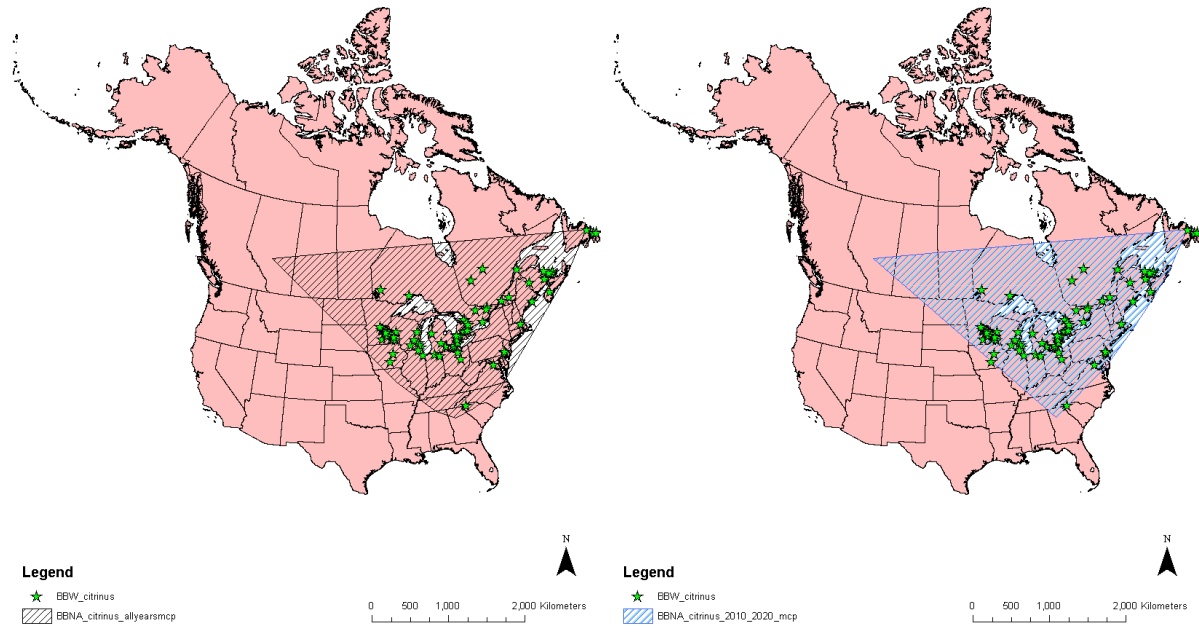
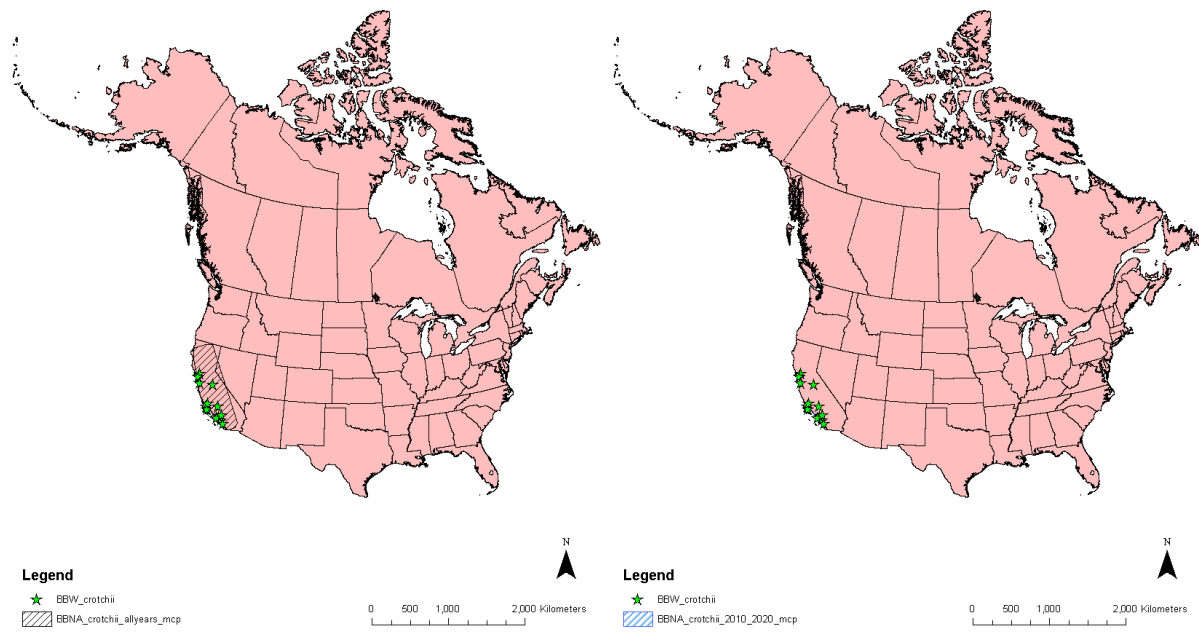


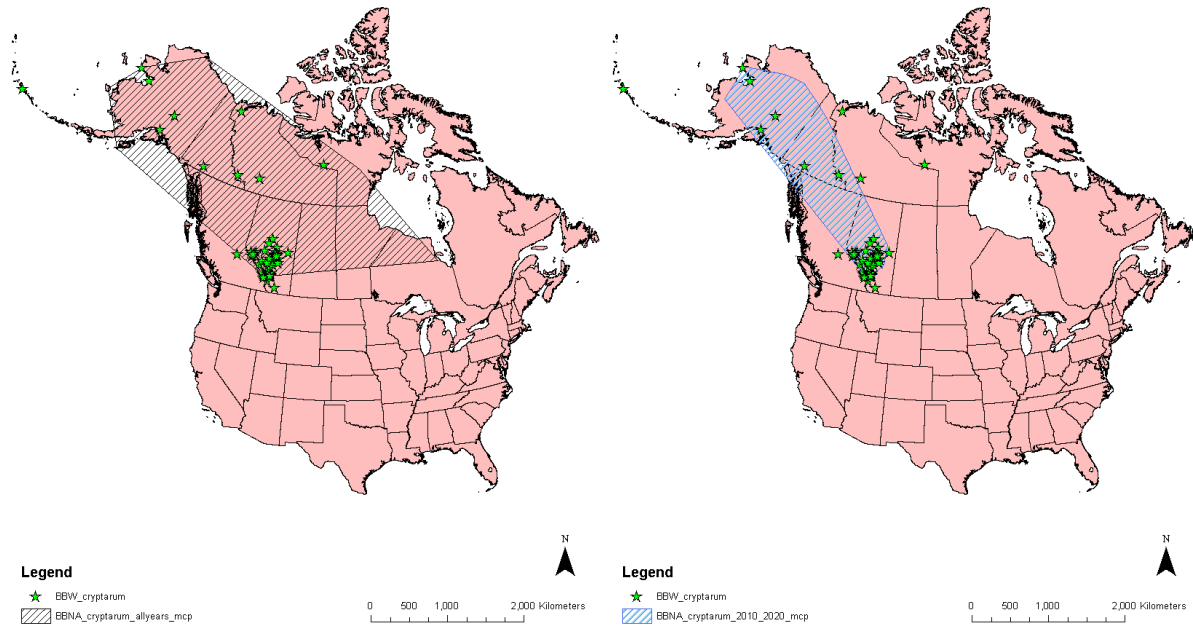
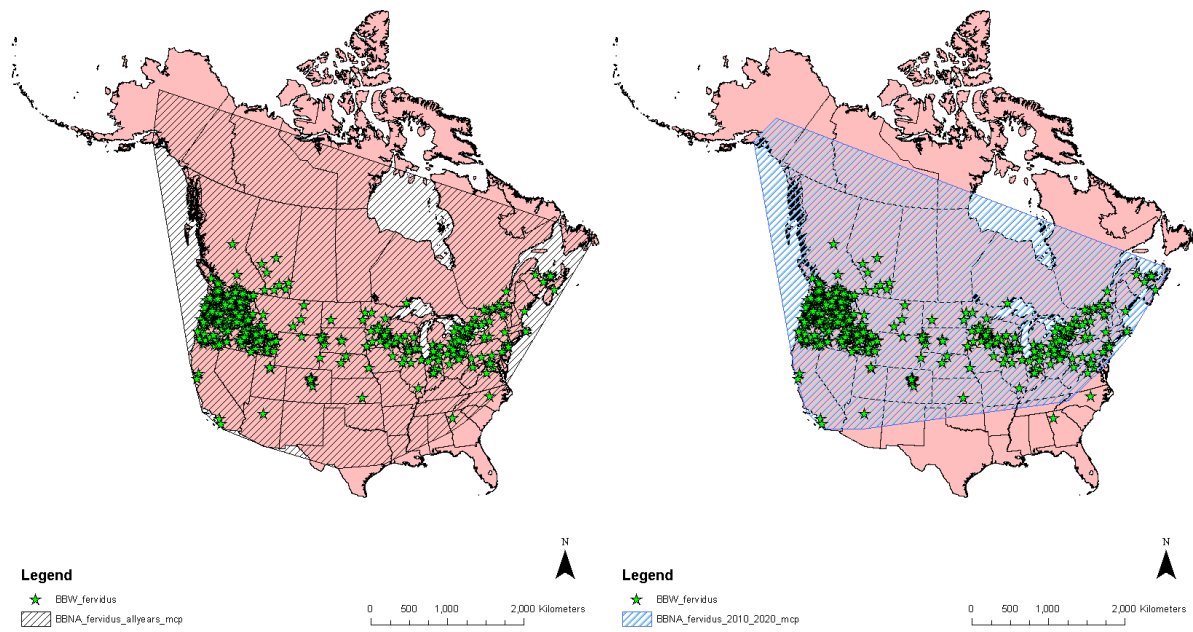
b) *Bombus appositus*c) *Bombus auricomus*

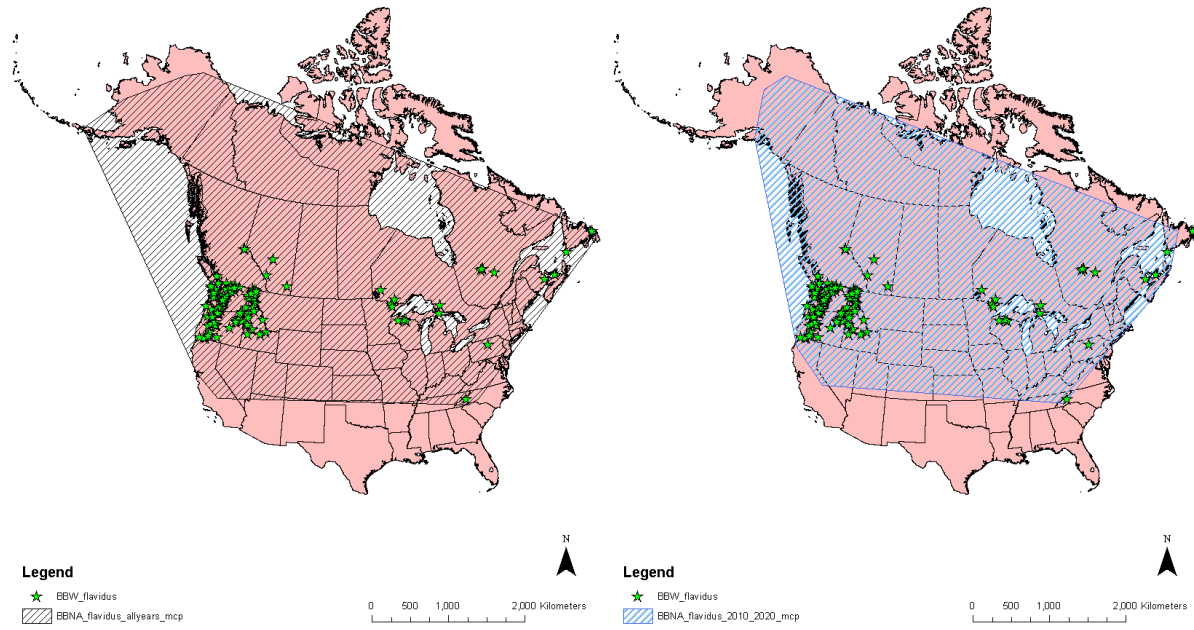
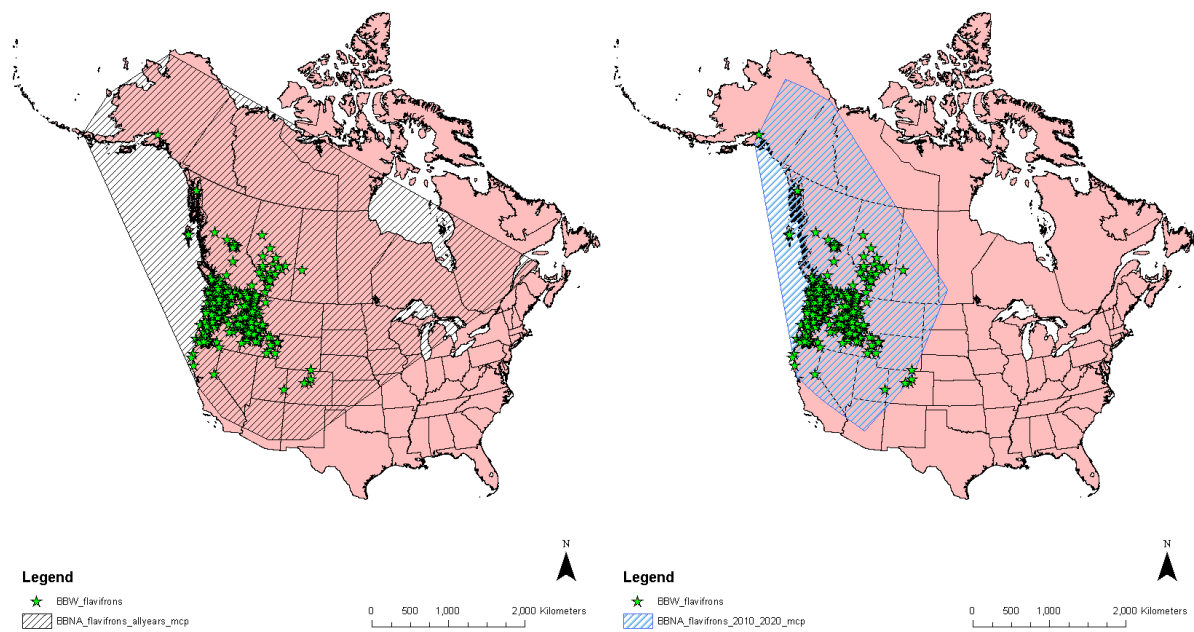
d) *Bombus bifarius*e) *Bombus bimaculatus*

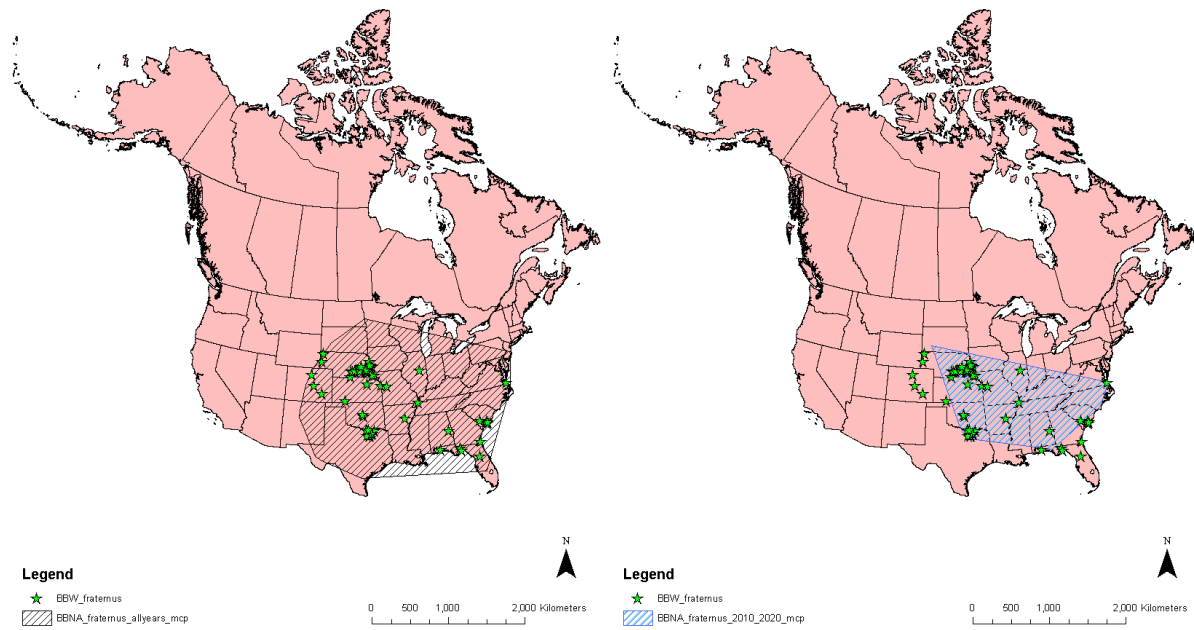
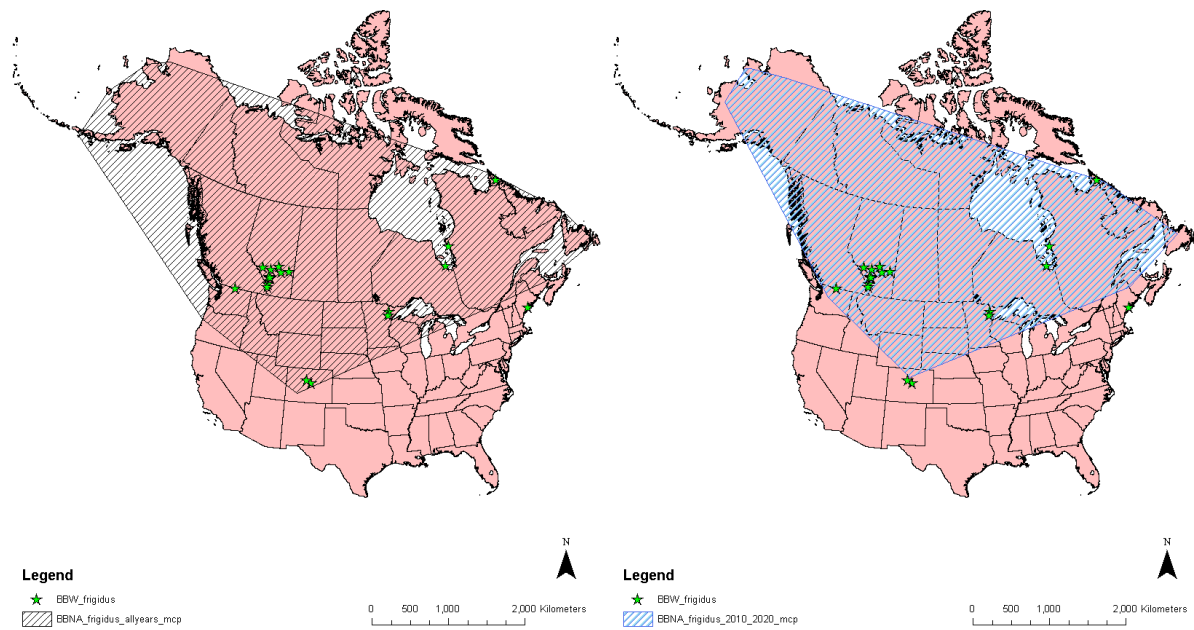
f) *Bombus bohemicus*g) *Bombus borealis*

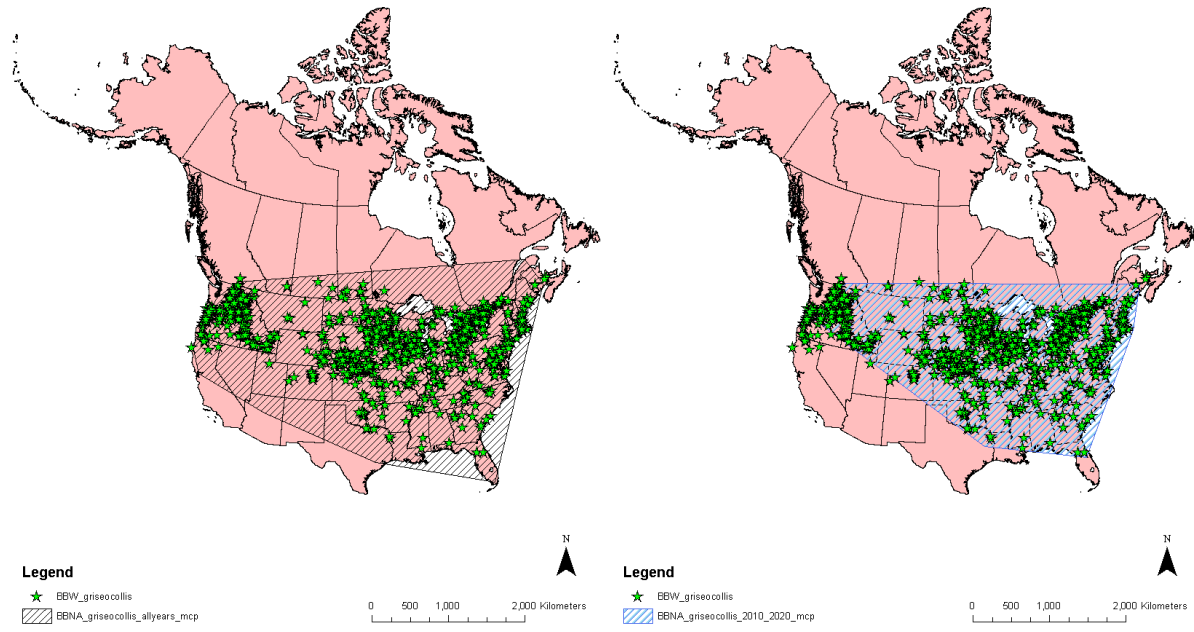
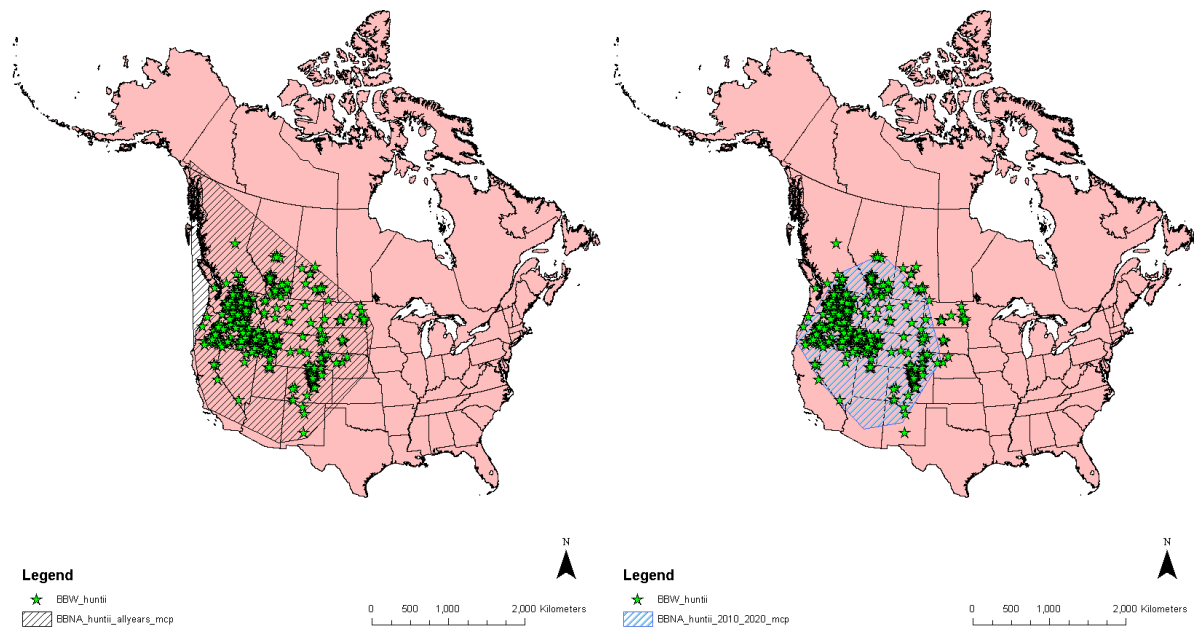
h) *Bombus caliginosus*i) *Bombus centralis*

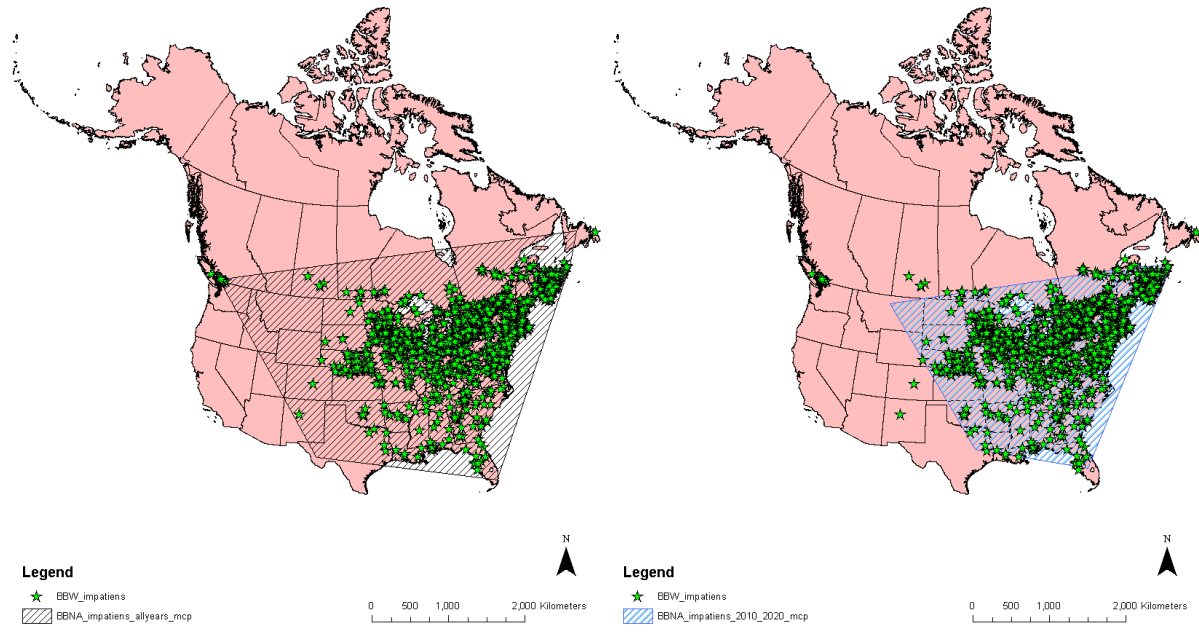
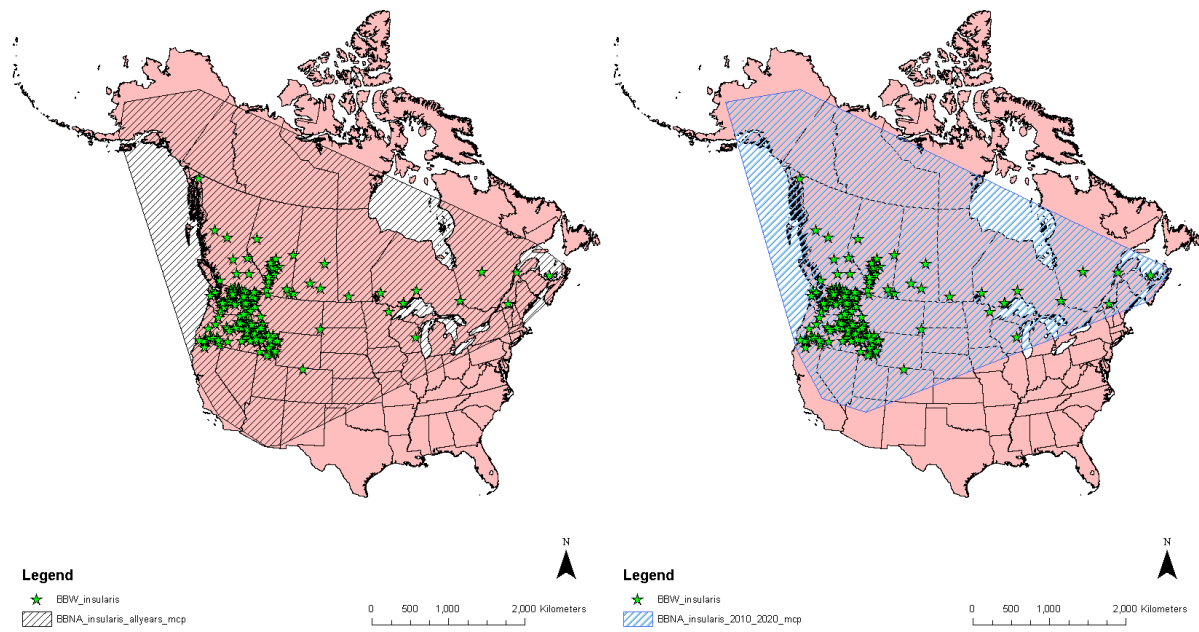
j) *Bombus citrinus*k) *Bombus crotchii*

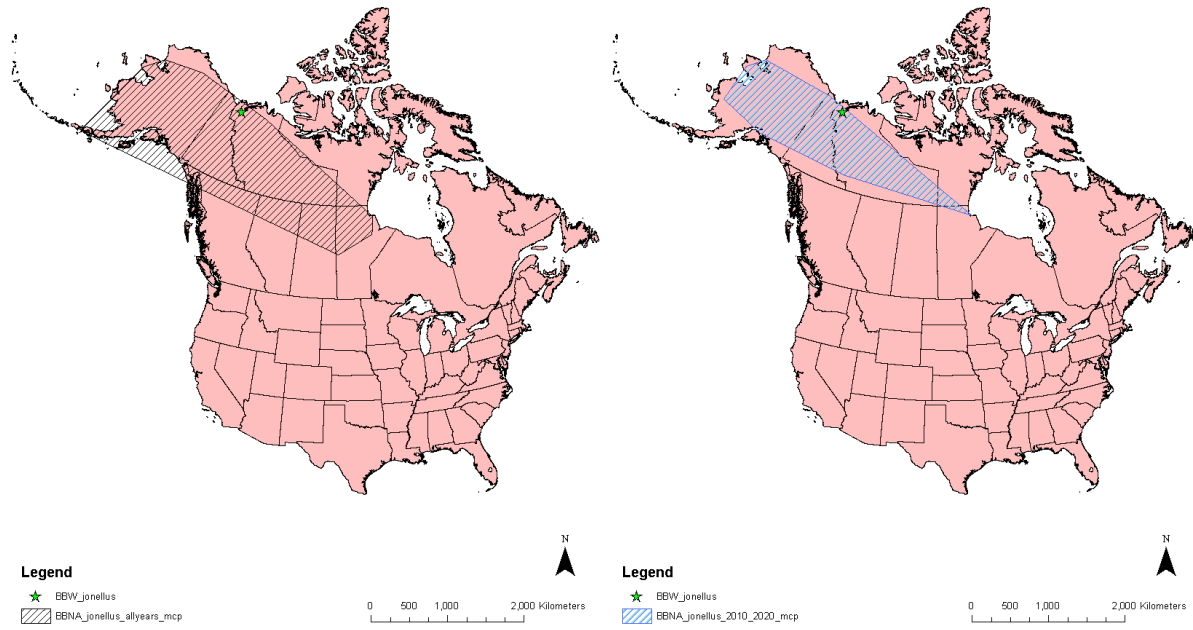
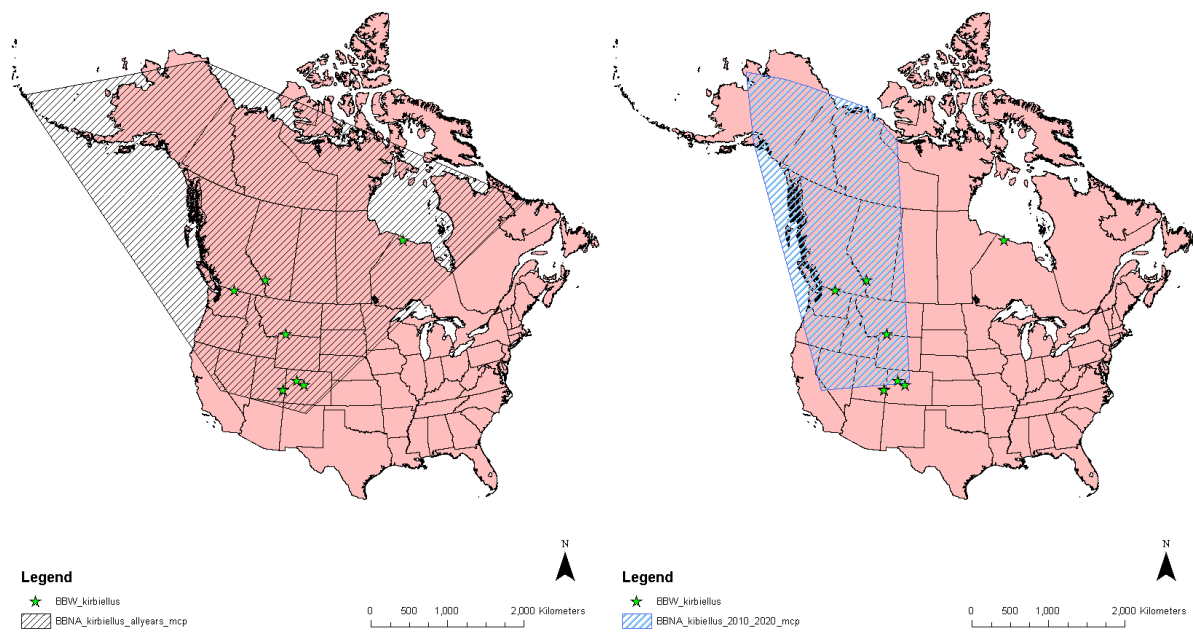
l) *Bombus cryptarum*m) *Bombus fervidus*

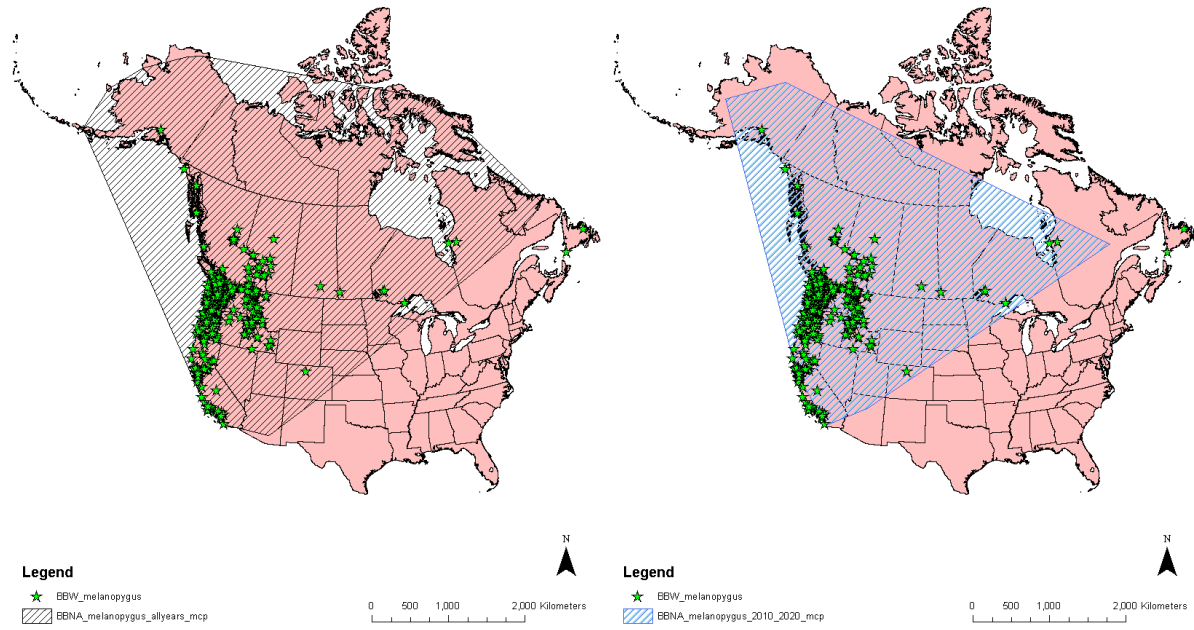
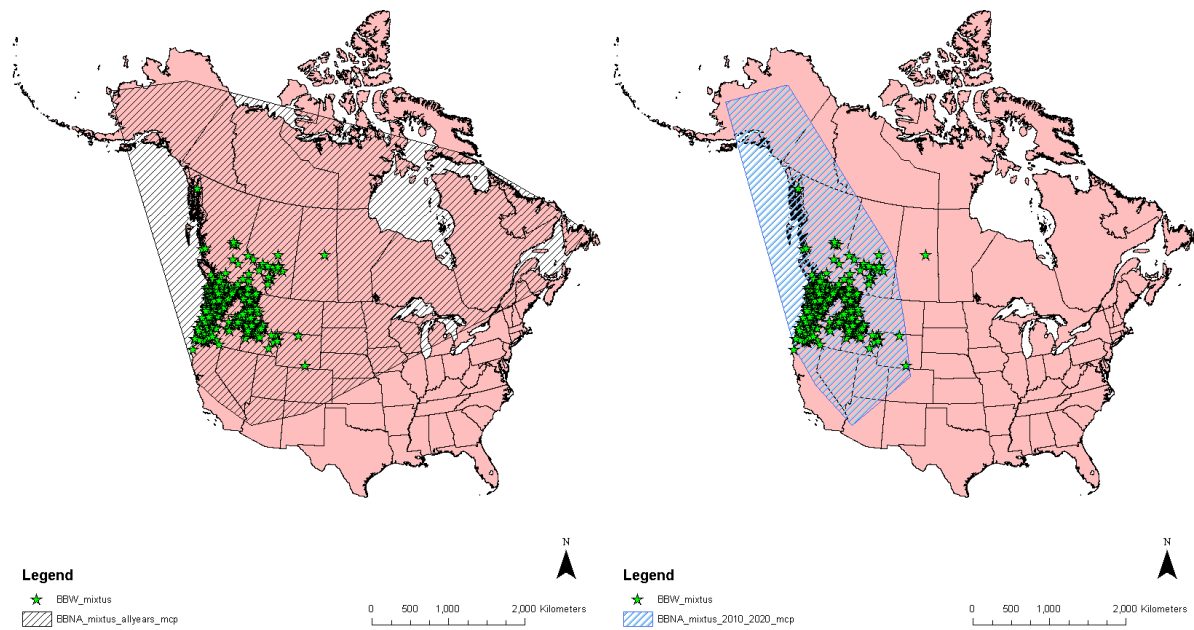
n) *Bombus flavidus*o) *Bombus flavifrons*

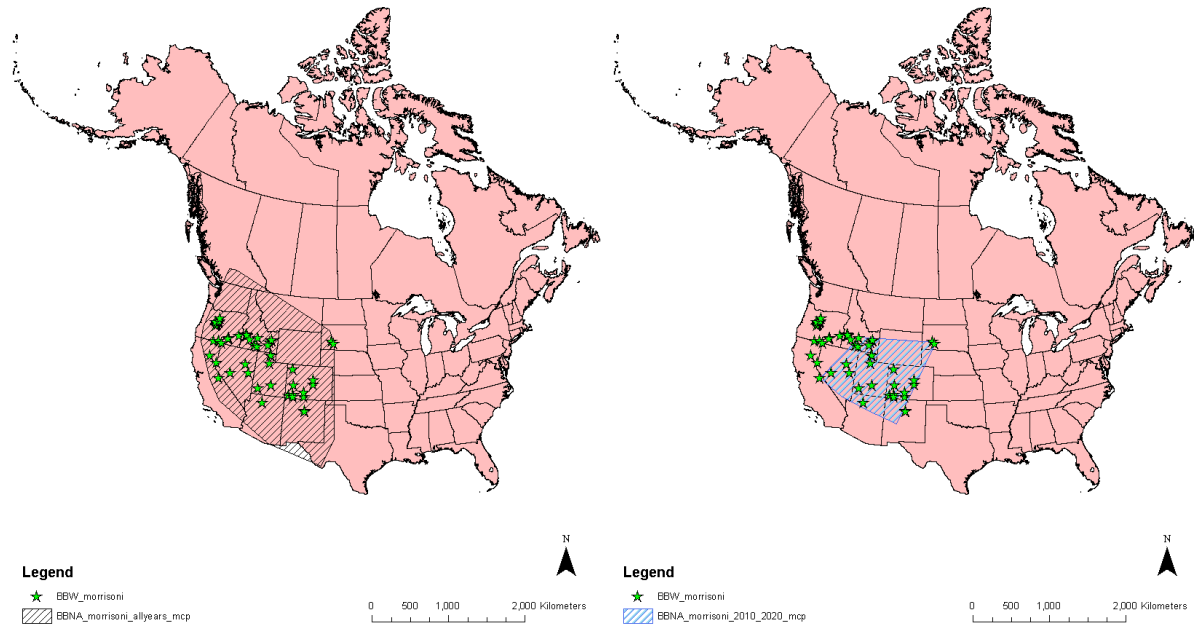
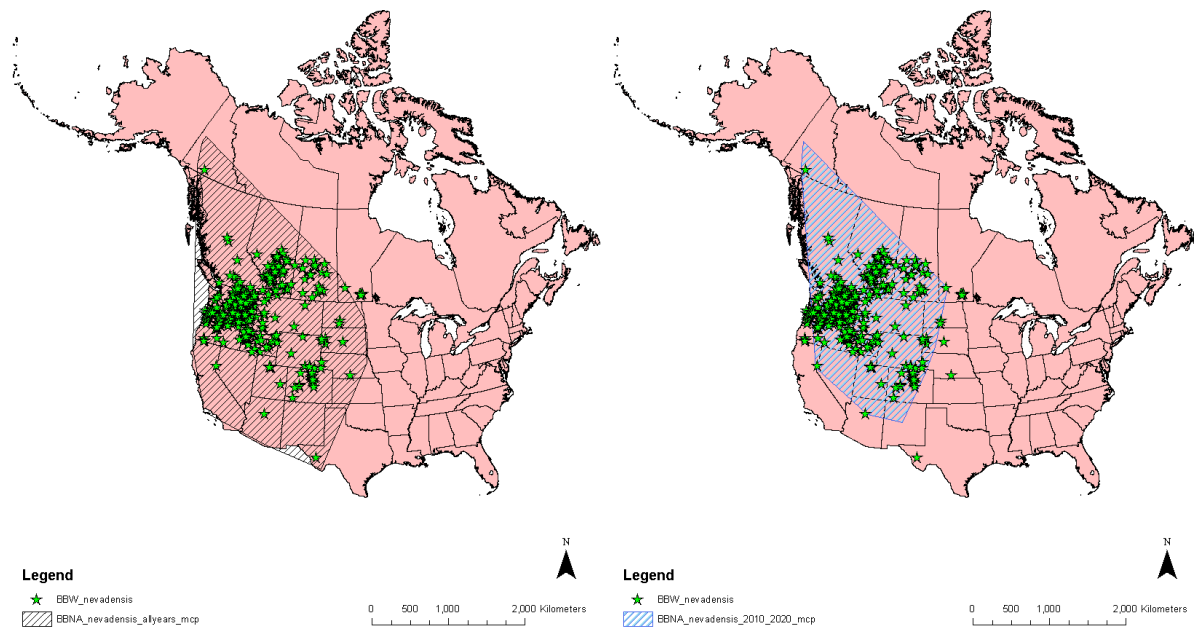
p) *Bombus fraternus*q) *Bombus frigidus*

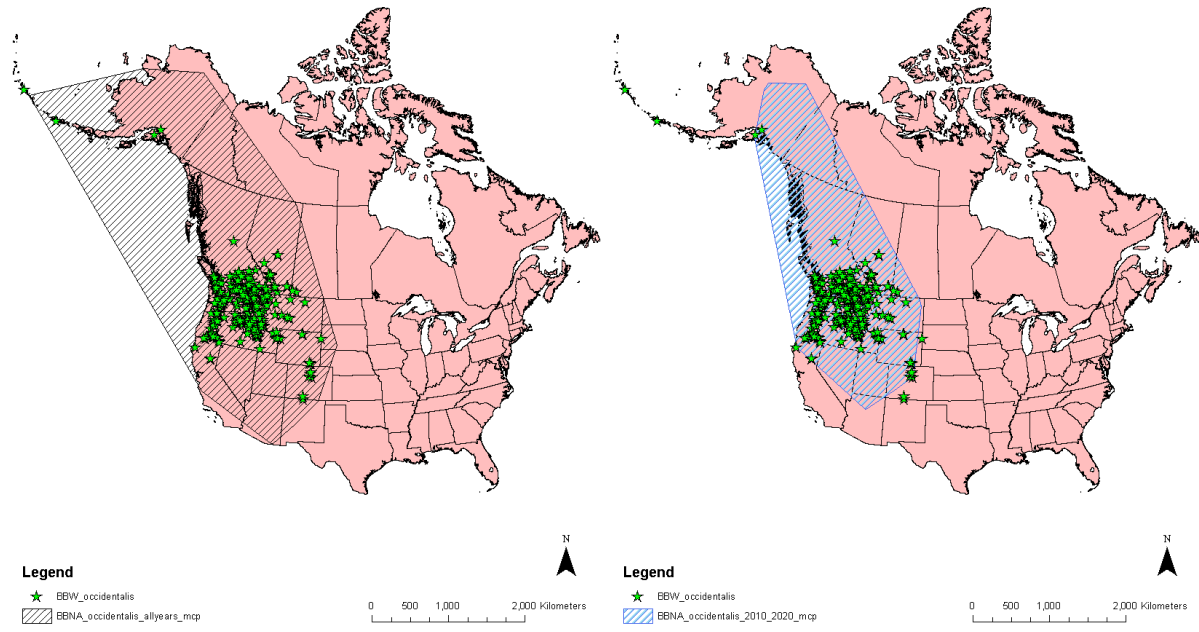
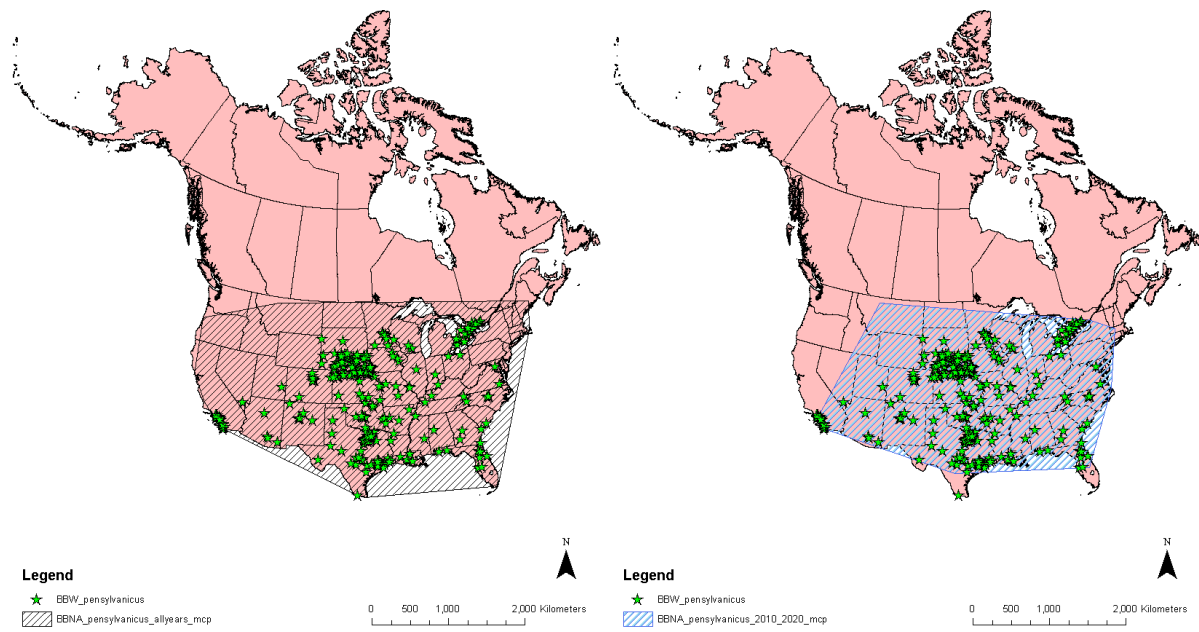
r) *Bombus griseocollis*s) *Bombus huntii*

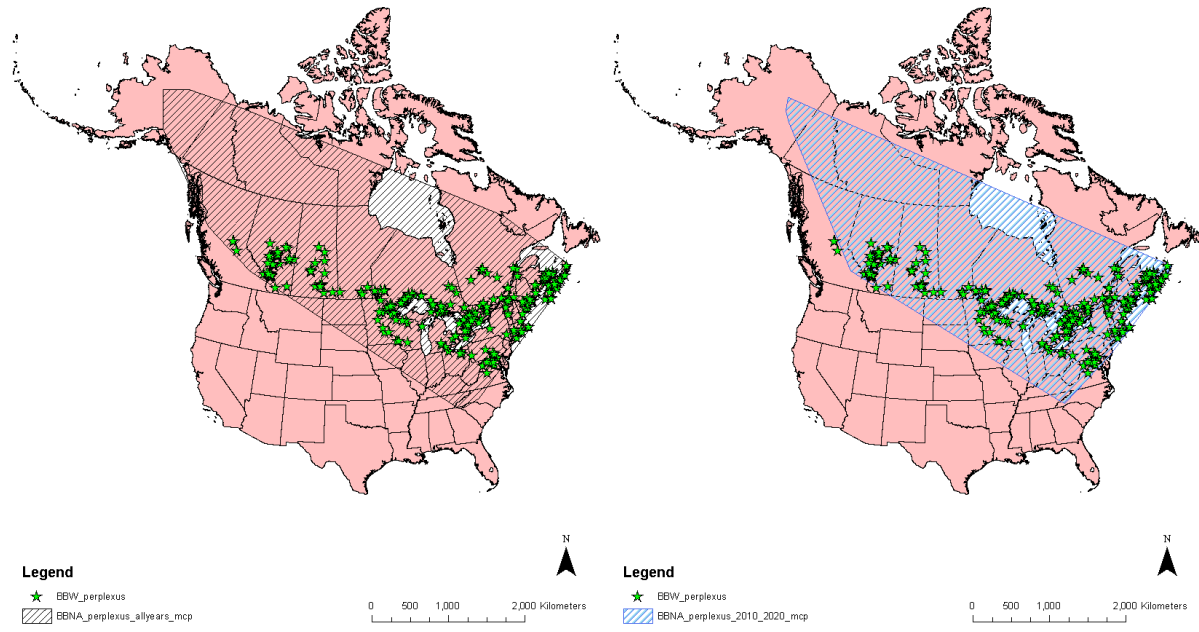
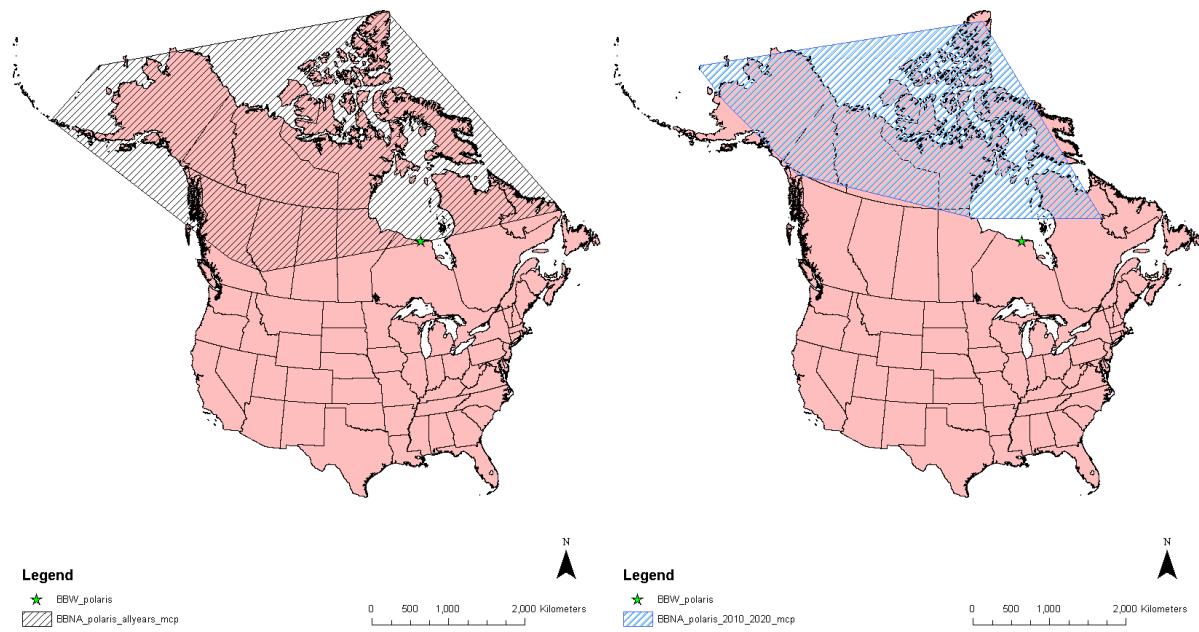
t) *Bombus impatiens*u) *Bombus insularis*

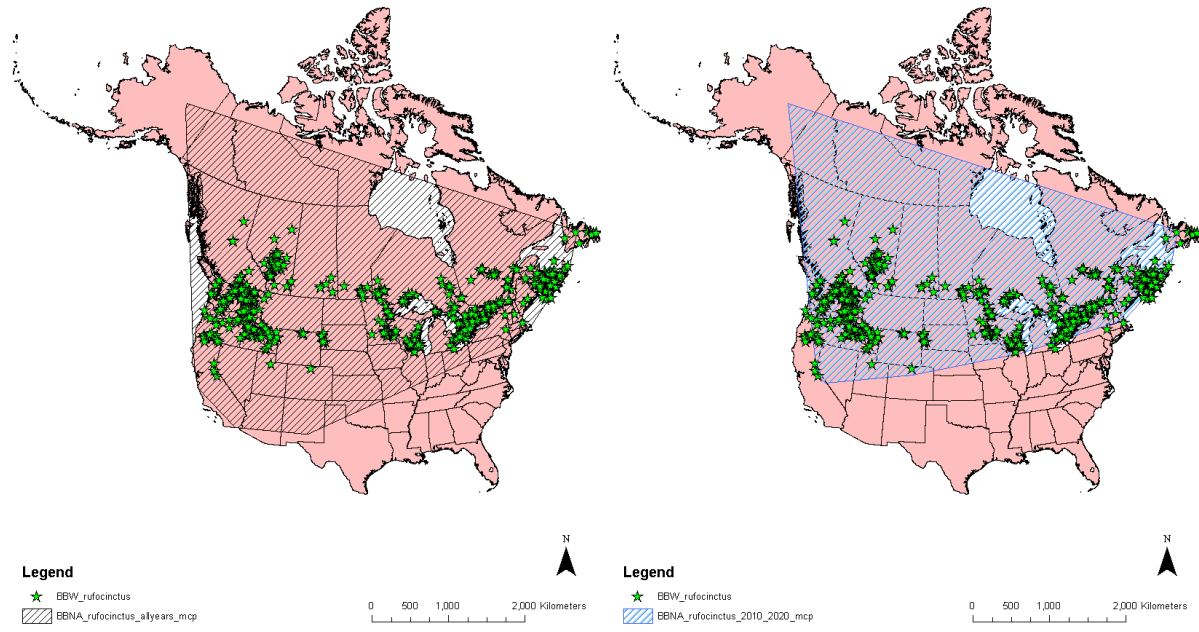
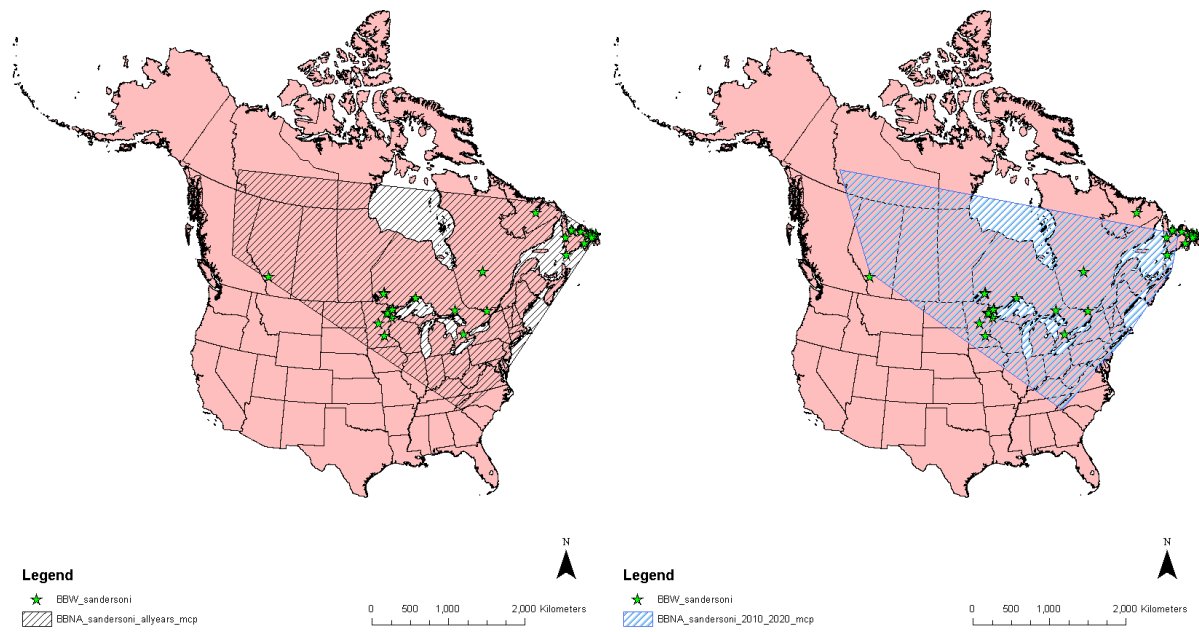
v) *Bombus jonellus*w) *Bombus kirbiellus*

x) *Bombus melanopygus*y) *Bombus mixtus*

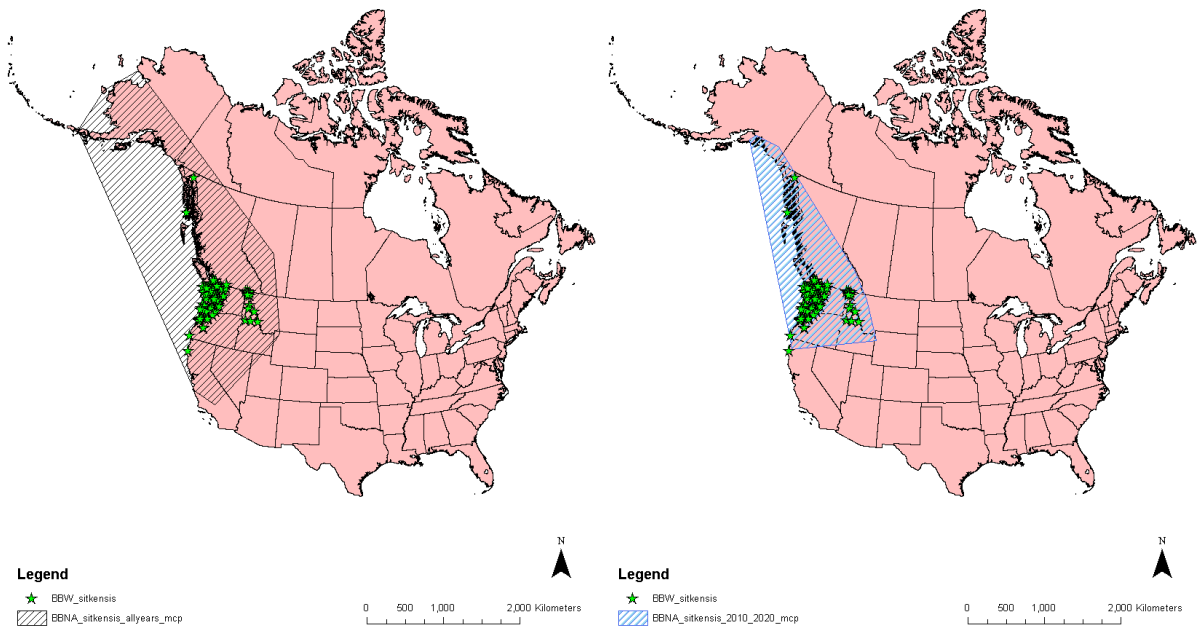
z) *Bombus morrisoni*aa) *Bombus nevadensis*

bb) *Bombus occidentalis*cc) *Bombus pensylvanicus*

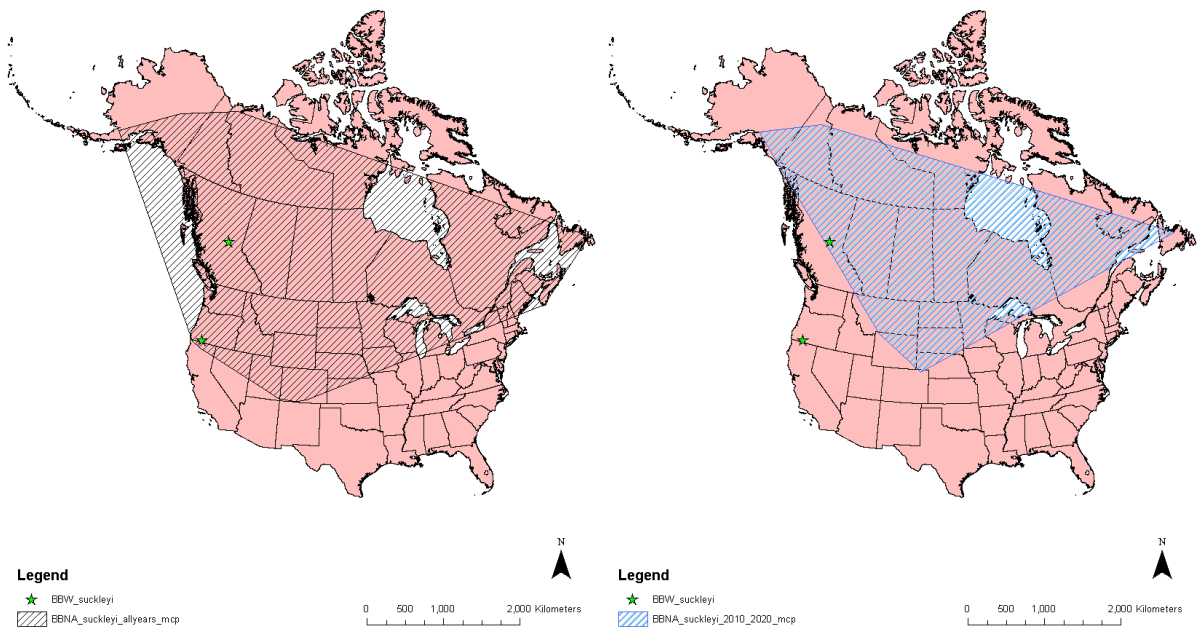
dd) *Bombus perplexus*ee) *Bombus polaris*

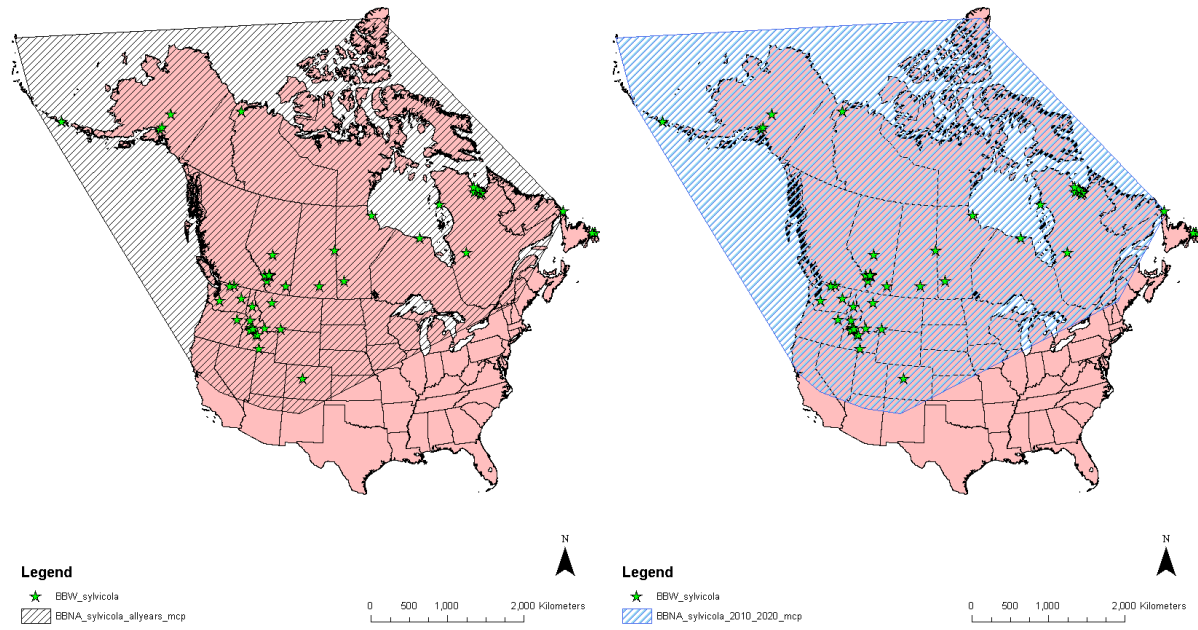
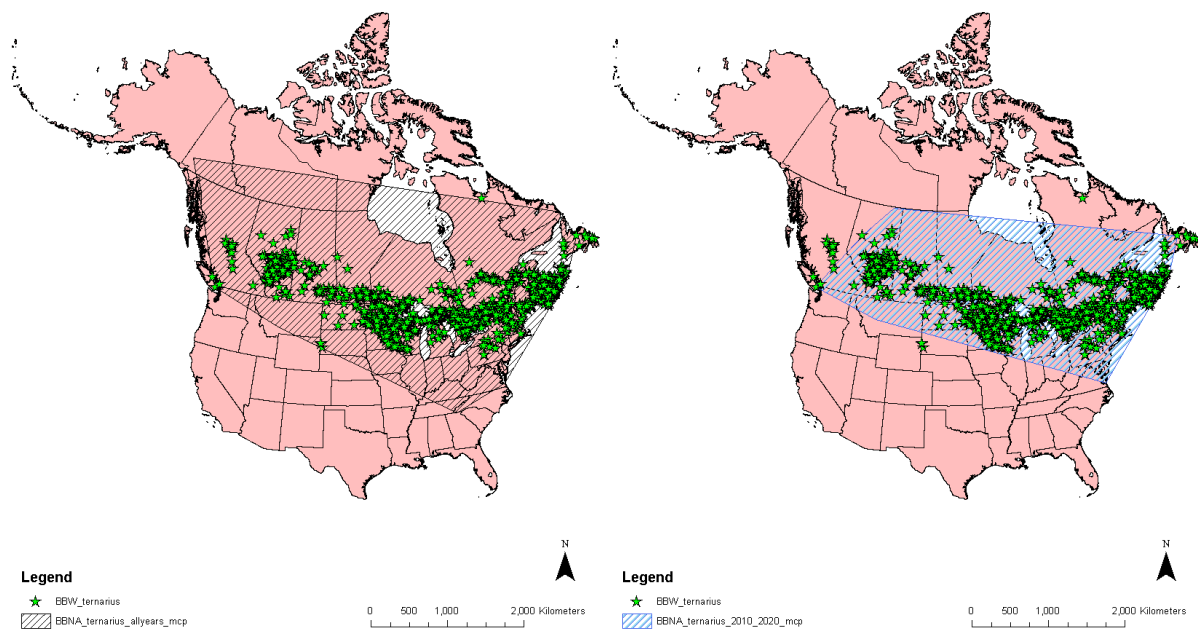
ff) *Bombus rufocinctus*gg) *Bombus sandersoni*

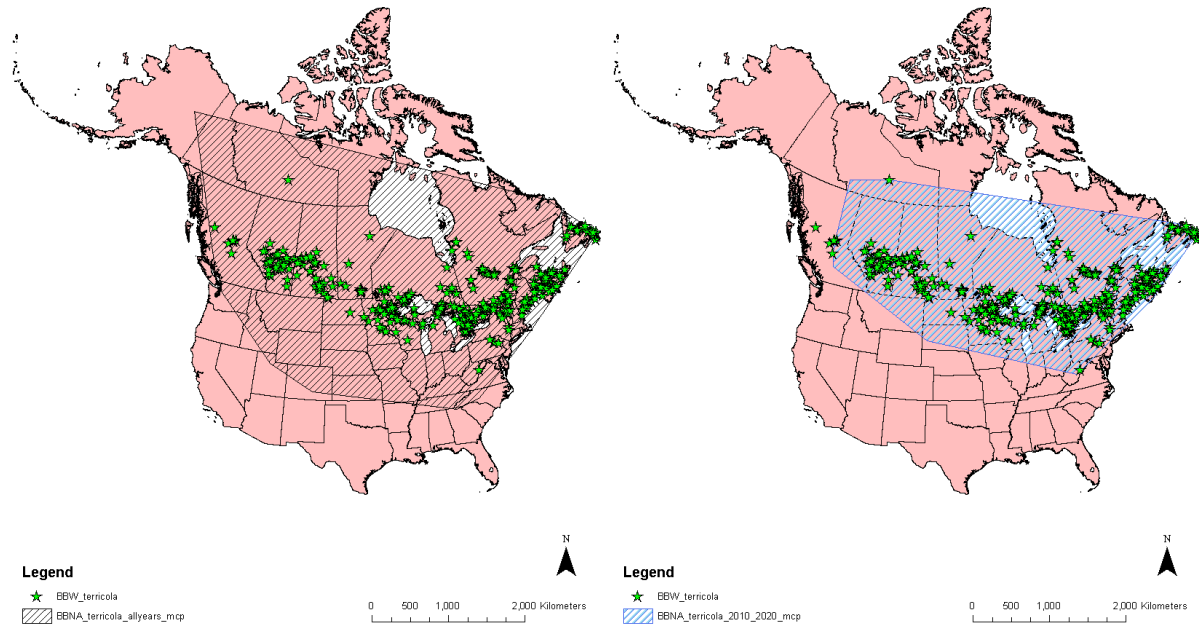
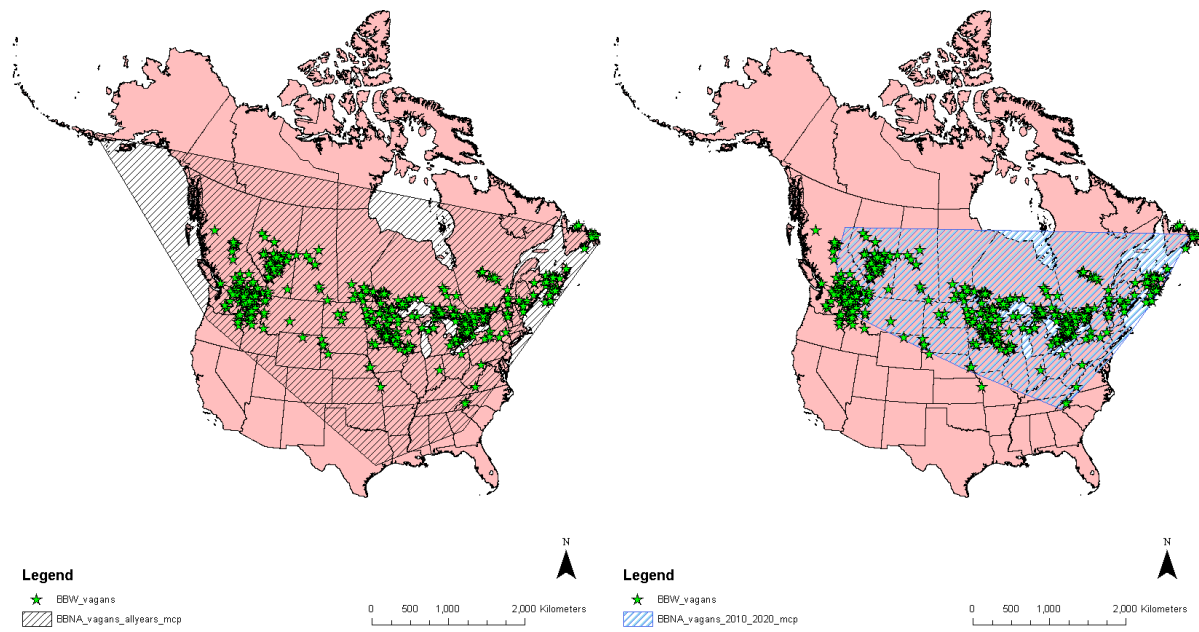
hh) *Bombus sitkensis*

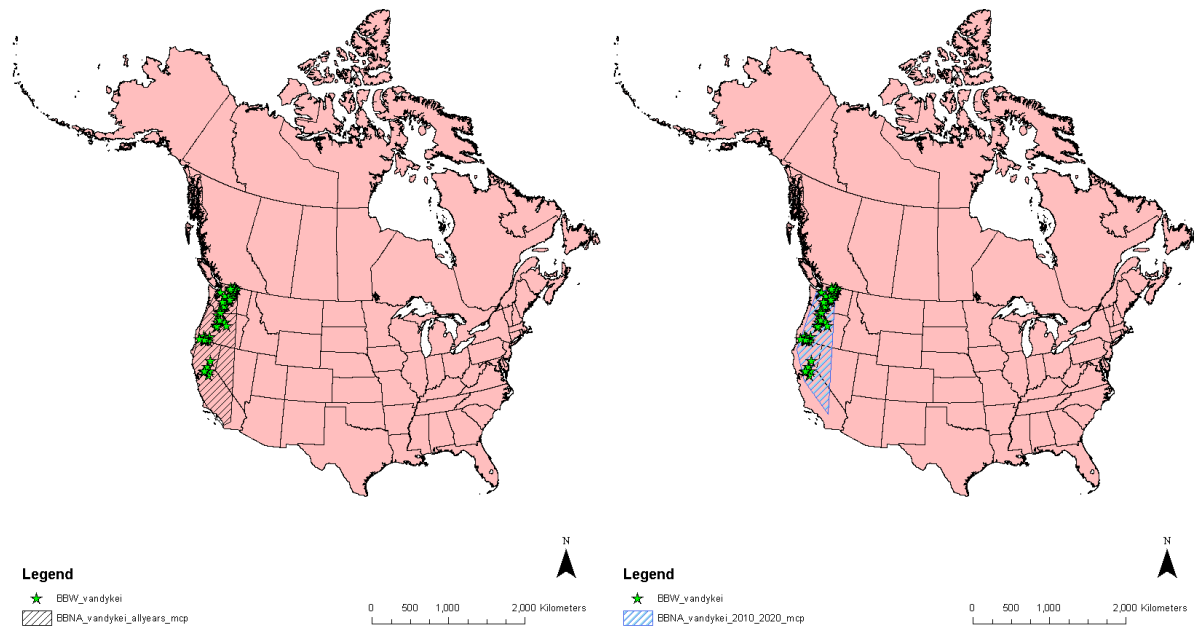
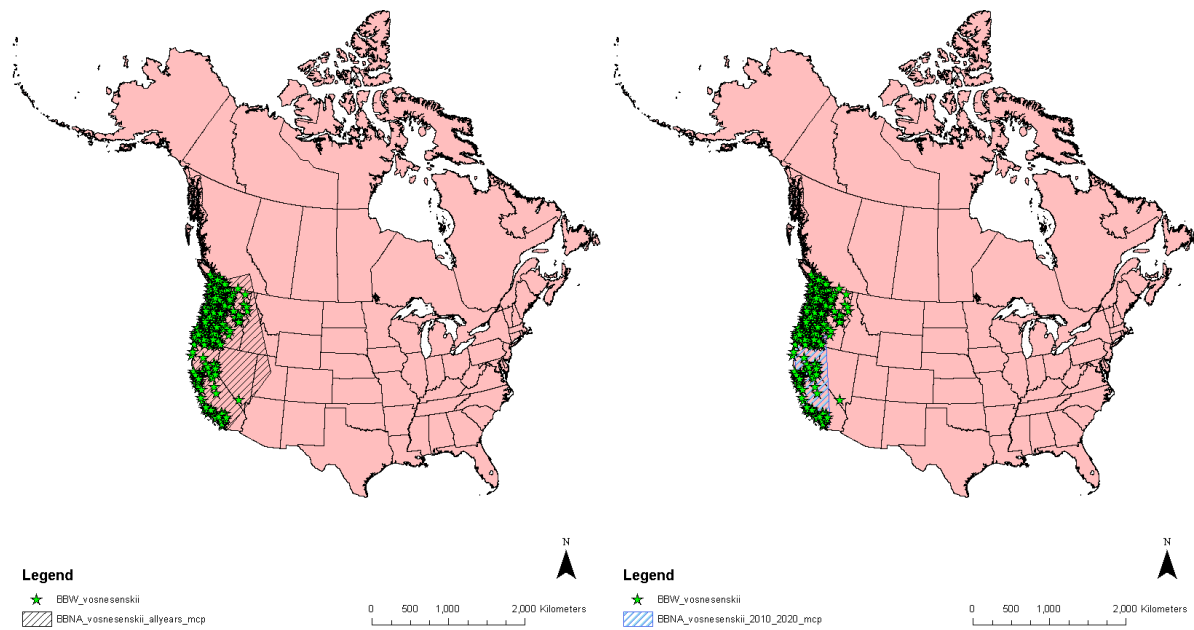


ii) *Bombus suckleyi*



jj) *Bombus sylvicola*kk) *Bombus ternarius*

ll) *Bombus terricola*mm) *Bombus vagans*

nn) *Bombus vandykei*oo) *Bombus vosnesenskii*

pp) *all Bombus species combined*

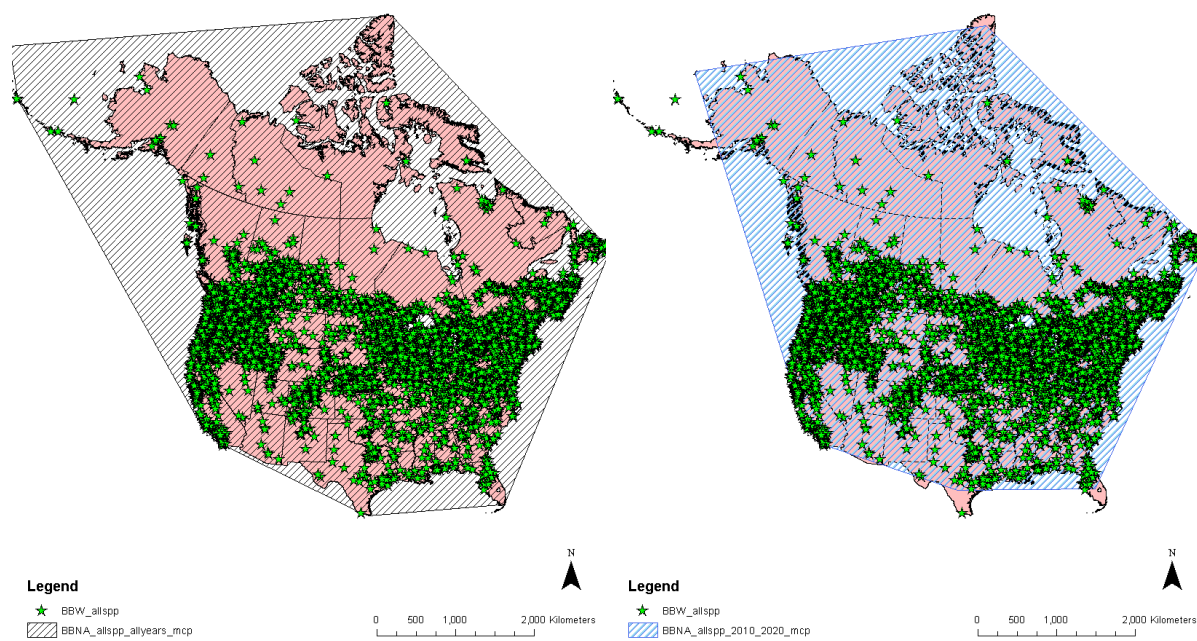


Figure A.S1. Location of individual BBW records (green stars) as compared to the Extent of Occurrence area (EOO) for BBNA all years (black grid, left map) and BBNA 2010-2020 (blue grid, right map), for each of the 41 bumble bee (*Bombus*) species (Figs A.S1:a-pp) that were present in all three datasets.

Figure A.S2 (following page). A comparison of A) the total number of plant genera recorded per bumble bee species in BBNA all years (black bars), BBNA 2010-2020 (yellow bars), and BBW (green bars) datasets, and B) the percent unique plant genera recorded from BBW as compared to BBNA all years (blue bars) and BBNA 2010-2020 (orange bars).

Figure A.S3 (following pages). A comparison of A) the total number of plant species recorded per bumble bee species in BBNA all years (black bars), BBNA 2010-2020 (yellow bars), and BBW (green bars) datasets, and B) the percent unique plant species recorded from BBW as compared to BBNA all years (blue bars) and BBNA 2010-2020 (orange bars)

Figure A.S2

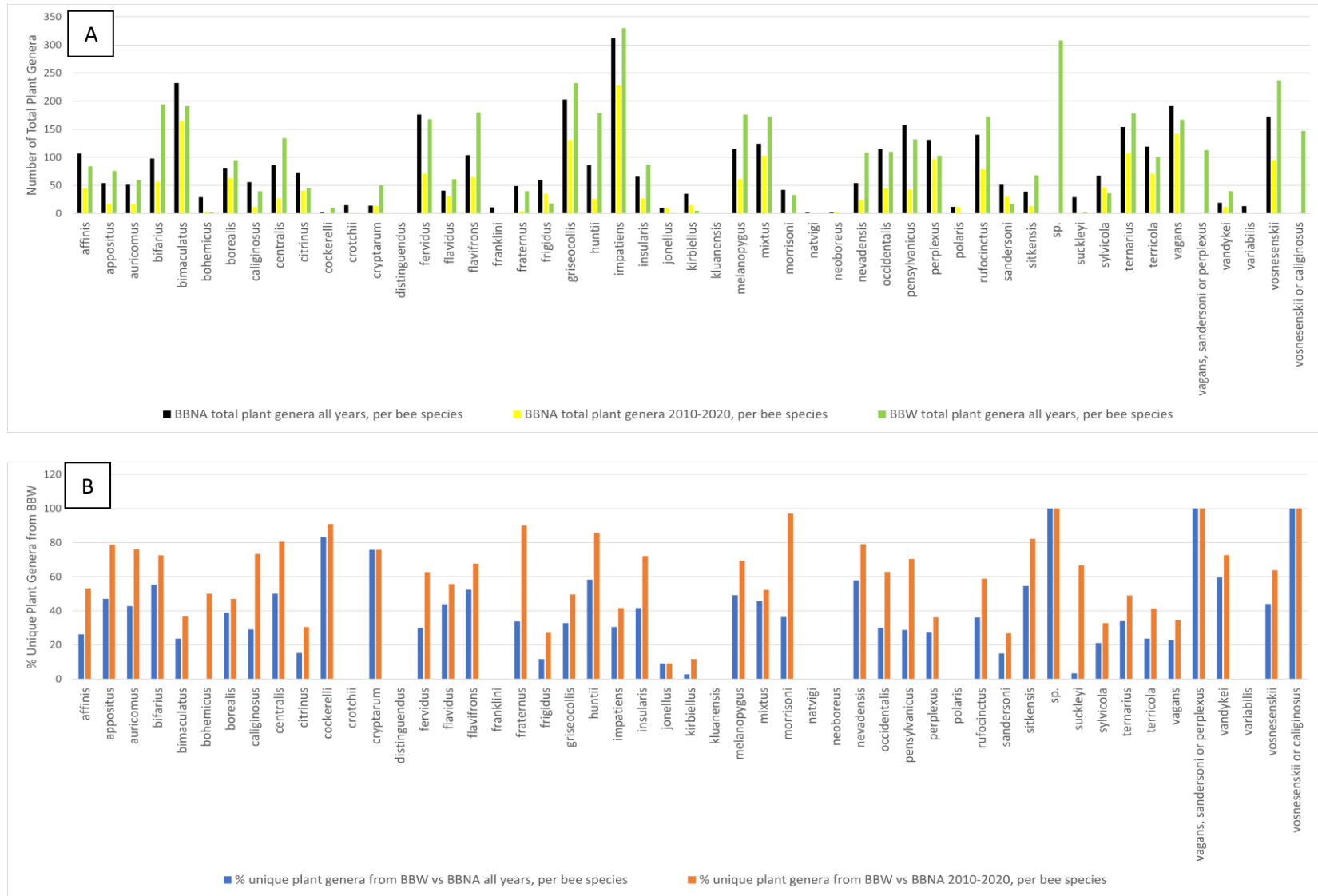
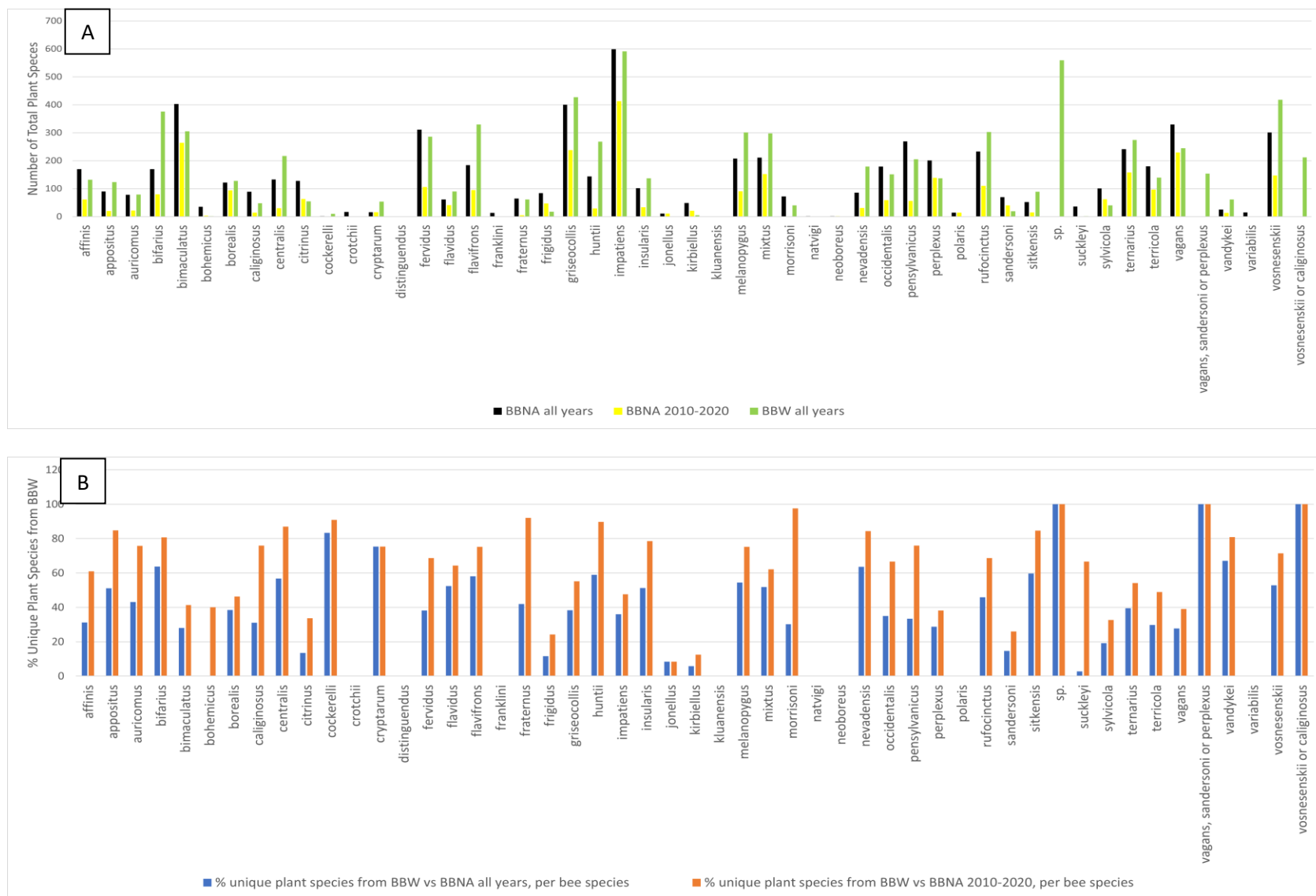


Figure A. S3.



Appendix B. Supplementary Information for Chapter 4

Table B.S1. Bumble bee (*Bombus* spp.) related field survey data collected by authors and colleagues across Ontario and Quebec, from 1907-2016, not already incorporated into the *Bumble Bees of North America* database.

Data Source	Number of records	Notes
Erika Nardone 2013 MSc thesis, as shared with V. MacPhail March 2017 (Nardone 2013)	353	Surveys in Algonquin Park as part of a study on impact of logging on bees, 2010-2011
Sheila Colla 2016 surveys	306	Targeted <i>B. affinis</i> and general <i>Bombus</i> surveys in 2016
Victoria MacPhail and Mariya Cheryomina 2013 surveys	50	Remainder of the summer habitat and parasites <i>Bombus</i> study survey data for 2013 not previously incorporated into the <i>Bumble Bees of North America</i> database
Victoria MacPhail 2007 MSc thesis (MacPhail 2007)	23	Observations as part of a study of insect visitors to wild roses, <i>Rosa</i> spp., 2004-2007
Victoria MacPhail 2013 American Water Willow surveys	65	Observations as part of a study of insect visitors to American Water Willow (<i>Justicia americana</i>) in 2013
Victoria MacPhail 2013 Colicroot surveys	110	Observations as part of a study of insect visitors to Colicroot (<i>Aletris farinosa</i>) in 2013
Victoria MacPhail 2013 Dense Blazing Star surveys	110	Observations as part of a study of insect visitors to Dense Blazing Star (<i>Liatris spicata</i>) in 2013
Victoria MacPhail 2013 Hoary Mountain Mint surveys	137	Observations as part of a study of insect visitors to Hoary Mountain Mint (<i>Pycnanthemum incanum</i>) in 2013
Victoria MacPhail 2013 White Wood Aster surveys	20	Observations as part of a study of insect visitors to White Wood Aster (<i>Eurybia divaricata</i>) in 2013
Victoria MacPhail 2014 surveys	3453	Includes targeted <i>B. terricola</i> spring queen surveys, targeted <i>B. affinis</i> surveys, summer habitat and parasites <i>Bombus</i> study surveys, general <i>Bombus</i> summer surveys
Victoria MacPhail 2015 surveys	1911	Includes targeted <i>B. terricola</i> spring queen surveys, targeted <i>B. affinis</i> surveys, and general <i>Bombus</i> summer surveys
Cont'd.		

Data Source	Number of records	Notes
Victoria MacPhail 2016 surveys	5267	Includes targeted <i>B. terricola</i> and <i>B. bohemicus</i> spring and summer surveys, targeted <i>B. affinis</i> surveys, and general <i>Bombus</i> summer surveys
Grand Total	11805	

Table B.S2. A comparison of the number of observations of *B. pensylvanicus* in Ontario and Quebec between historic (1907-2006) and recent (2007-2016) periods as found in each of three data sets. BBNA is the Bumble Bees of North America database maintained by LLR. See the text for more details on the data sources. Note that 20 of the 32 *B. pensylvanicus* observations by MacPhail and Colla were from three visits to a single site in 2016.

Data source	# historic <i>B. pensylvanicus</i> 1907-2006	# recent <i>B. pensylvanicus</i> 2007-2016
BBNA	279	8
Bumble Bee Watch	0	10
MacPhail and Colla	0	32
Total	279	50

Table B.S3. A comparison of the Extent of Occurrence (EOO) for *B. pensylvanicus* from historic (1907-2006) to recent (2007-2016) periods in Ontario and Quebec using three different techniques as described in the text: the GeoCat program (which automatically included the Great Lakes area), ArcGIS including the Great Lakes area, and ArcGIS clipping to the land area of Ontario and Quebec (thus excluding the Great Lakes area).

	EOO Historic period, 1907-2006 (279 records) (km²)	EOO Recent period, 2007-2016 (50 records) (km²)	Change in EOO between periods (km²)	EOO Combined , 1907- 2016 (339 records) (km²)	Change between Historic and Recent periods (%)	Amount of Historic Range still Occupied (%)
GeoCat - incl Great Lakes	103,084.97	64,821.53	38,263.45	108,552.63	37.12	62.88
ArcGIS - incl Great Lakes	107,732.47	67,579.84	40,152.62	113,353.49	40.38	59.62
ArcGIS - clipped to land	90,458.52	60,282.09	30,176.43	95,378.76	36.80	63.20
difference in GeoCat vs ArcGis incl Great Lakes	-4,647.49	-2,758.32	-1,889.18	-4,800.86	-3.26	3.26
difference in GeoCat vs ArcGis clipped to land	12,626.46	4,539.44	8,087.02	13,173.87	0.32	-0.32
difference in ArcGIS incl Great Lakes vs clipped to land	17,273.95	7,297.75	9,976.20	17,974.74	3.58	-3.58

Table B.S4. A comparison of the results of a series of Z-tests evaluating the difference in proportion of *B. pensylvanicus* to all other *Bombus* spp. on a per decade basis from 1907 to 2016 in Ontario and Quebec. N = sample size; P is significant (*) if <0.05.

Decades	1907 vs 1917	1917 vs 1927	1927 vs 1937	1937 vs 1947	1947 vs 1957	1957 vs 1967	1967 vs 1977	1977 vs 1987	1987 vs 1997	1997 vs 2007
N	738	528	223	493	1013	1279	1353	1425	2753	13883
Z value	1.636	2.570	4.026	1.665	2.462	0.482	0.253	3.378	0.881	1.136
P value	0.102	0.01*	0.00*	0.096	0.014*	0.63	0.801	0.001*	0.379	0.256

Table B.S5. A comparison of the number of *B. pensylvanicus* individuals per caste found in Ontario and Quebec from 1907-2016. Only records with a known caste were included (n=314).

Caste	Number of bees	Percent of Total
Queen or Worker	3	1.0
Male	41	13.1
Queen	93	29.6
Worker	177	56.4

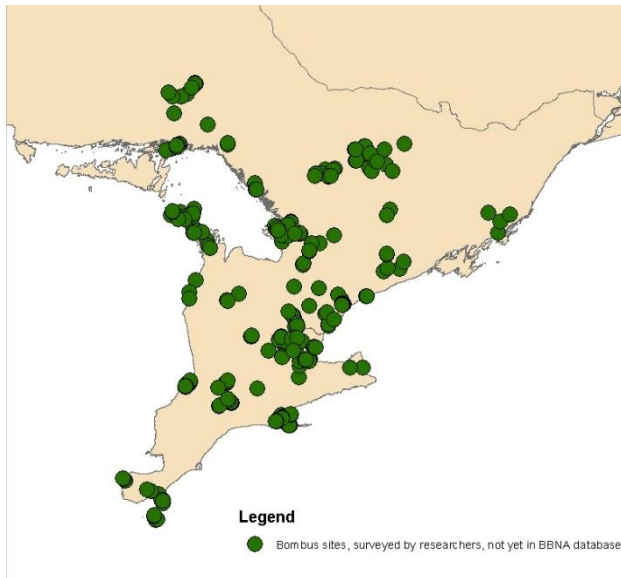


Figure B.S1. Field survey data collected by authors and colleagues across Ontario and Quebec, from 1907-2016, not already incorporated into the *Bumble Bees of North America* database.

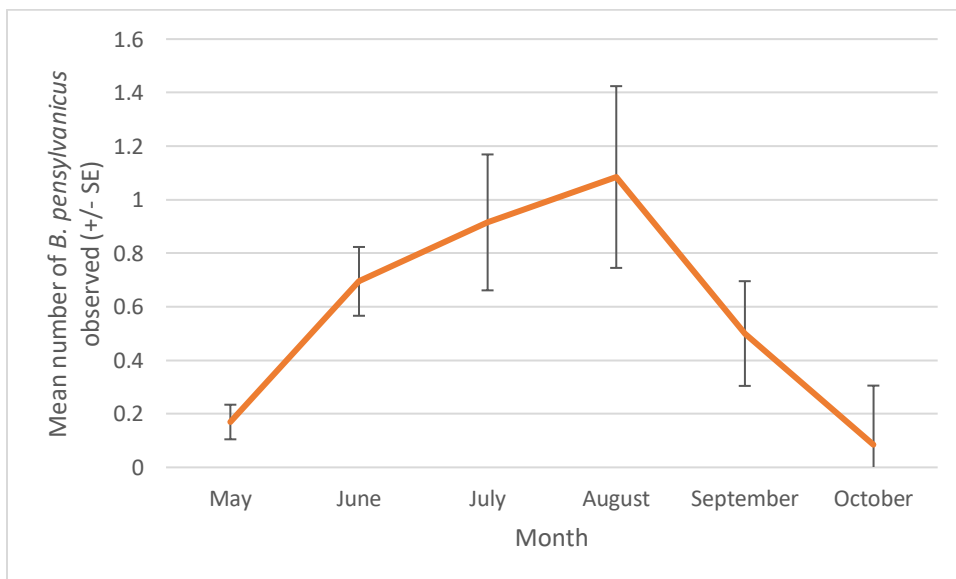


Figure B.S2. The mean number of *B. pensylvanicus* bees (all castes combined) observed per month (+/- SE) from 1907-2016 in Ontario and Quebec. Only records with a known month of observation were included (n=325).

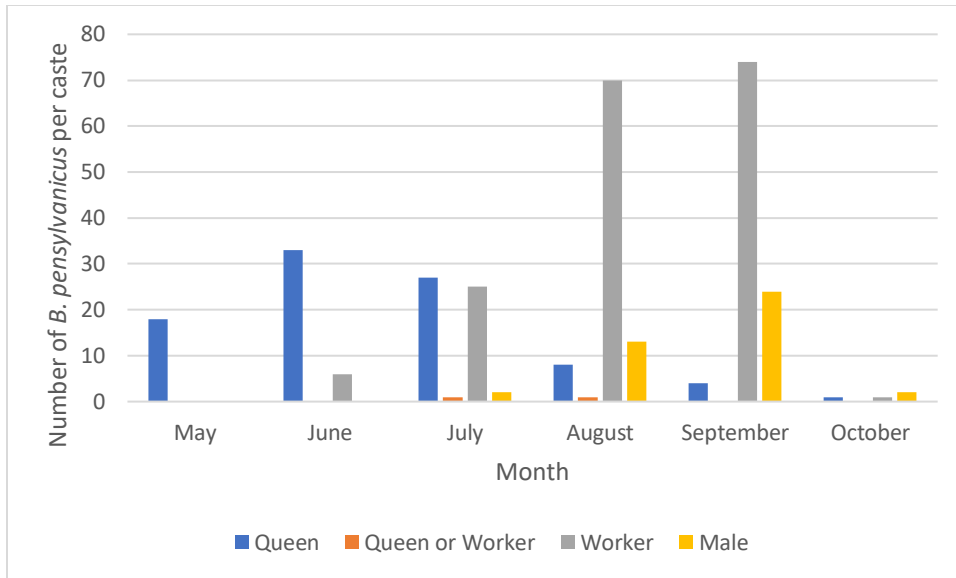


Figure B.S3. The number of *B. pensylvanicus* bees observed per month and per caste from 1907-2016 in Ontario and Quebec. Only records with both month of observation and caste available were included (n=310)(i.e. three records with no months were not included here).

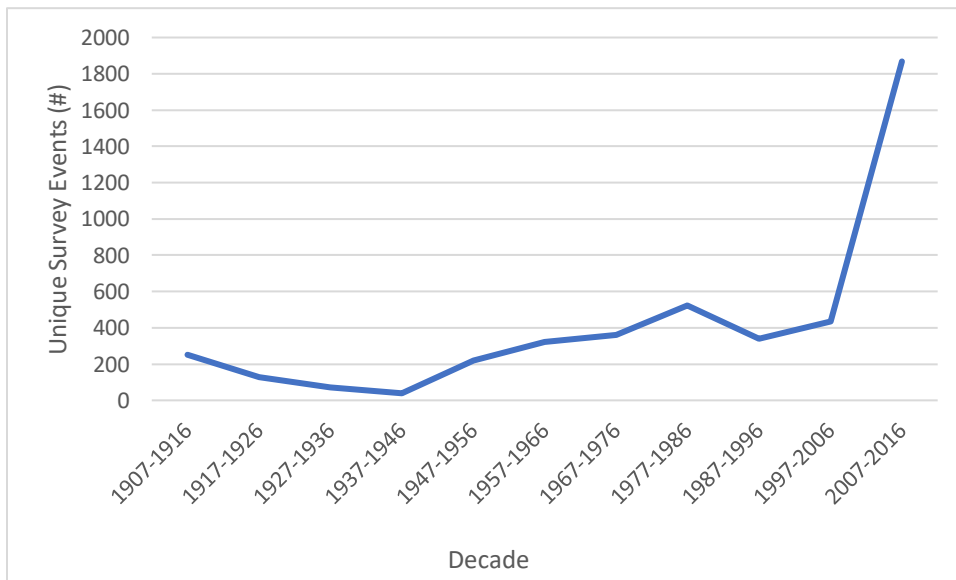


Figure B.S4. The number of unique *Bombus* survey events that occurred per decade in Ontario and Quebec within the range of *B. pensylvanicus*. One unique event includes all observations from the same observer at the same site and on the same date.

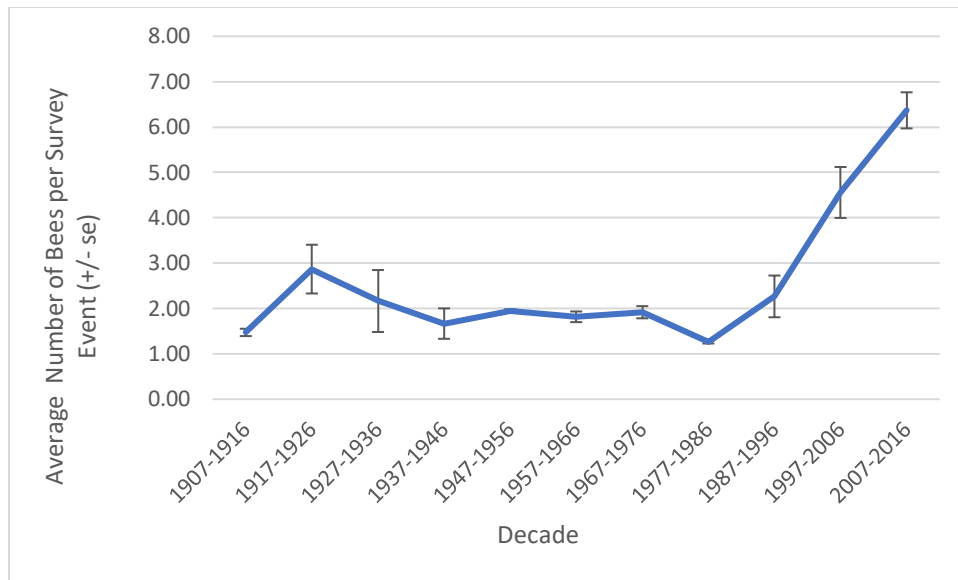


Figure B.S5. The average number ($\pm$ se) of *Bombus* counted per unique survey event that occurred per decade in Ontario and Quebec within the range of *B. pensylvanicus*.

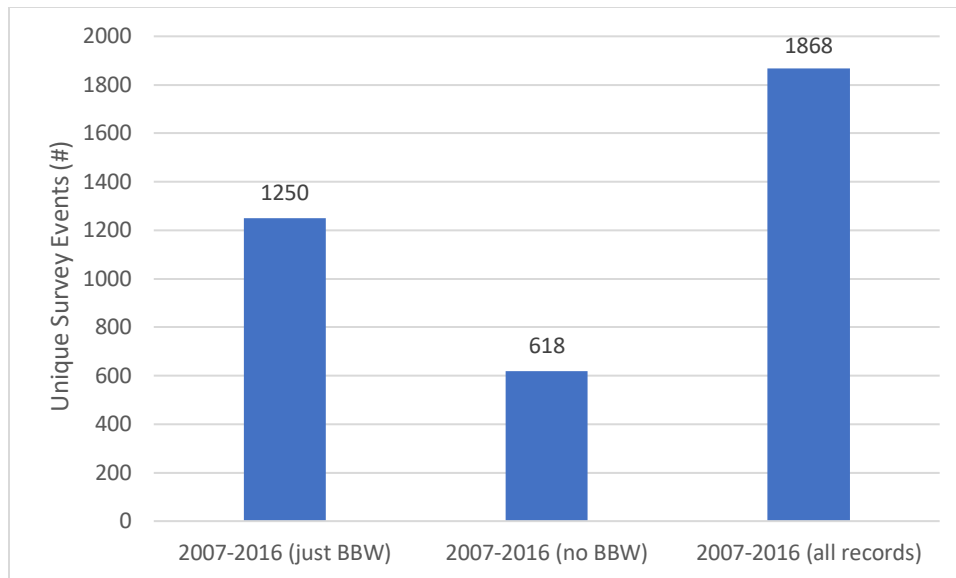


Figure B.S6. A comparison amongst data sets of the number of unique *Bombus* survey events that occurred in the 2007-2016 decade in Ontario and Quebec within the range of *B. pensylvanicus*. The first column only includes records from the citizen science program Bumble Bee Watch, the second includes all other records (various sources), and the third shows all records combined. One unique event includes all observations from the same observer at the same site and on the same date.

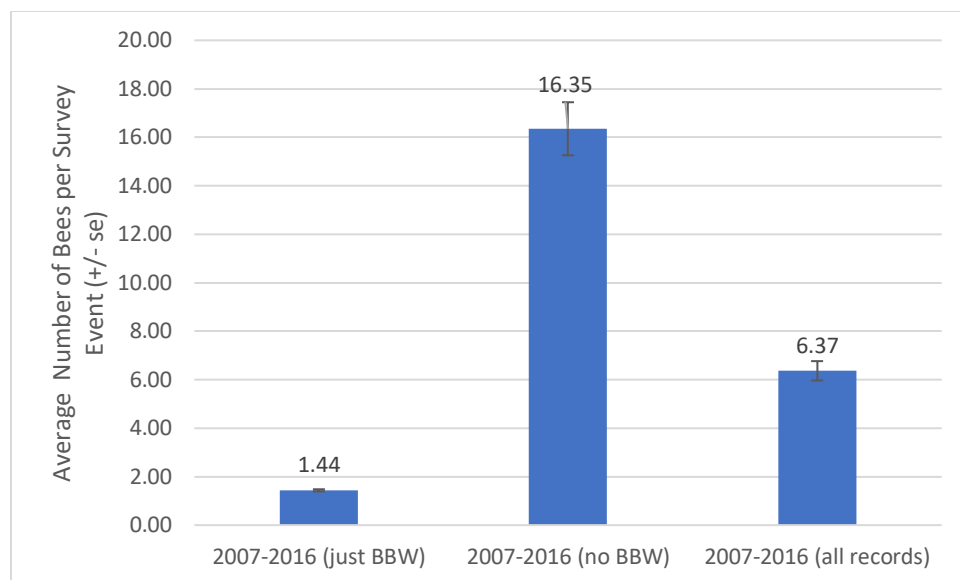


Figure B.S7. A comparison amongst data sets of the average number ($\pm$ se) of *Bombus* counted per unique survey event that occurred in the 2007-2016 decade in Ontario and Quebec within the range of *B. pensylvanicus*. The first column only includes records from the citizen science program Bumble Bee Watch, the second includes all other records (various sources), and the third shows all records combined.

Appendix C. Supplementary Information for Chapter 5

Table C.S1. The number and relative percent abundance of bumble bee (*Bombus* spp) records, and their expert review status per province, territory, or state, as used in our analyses of user accuracy. Ranks relate the standing of each jurisdiction regarding the relative percent of records submitted from that jurisdiction, with a higher relative abundance yielding a higher rank; tied ranks indicate identical percentages.

Province, State, Territory	# Invalid Records	# Verified Records	Total # Records	Relative Percent Abundance	Rank
Alabama	43	13	56	0.25	30
Alaska	0	2	2	0.01	58
Alberta	63	1077	1140	5.14	6
Arizona	9	3	12	0.05	50
Arkansas	3	3	6	0.03	51
British Columbia	36	474	510	2.30	8
California	167	217	384	1.73	9
Colorado	11	60	71	0.32	26
Connecticut	4	2	6	0.03	51
Delaware	1	14	15	0.07	47
District of Columbia	0	3	3	0.01	58
Florida	28	11	39	0.18	34
Georgia	25	16	41	0.19	32
Idaho	68	2234	2302	10.39	4
Illinois	22	102	124	0.56	17
Indiana	22	32	54	0.24	31
Iowa	8	74	82	0.37	24
Kansas	8	6	14	0.06	48
Kentucky	7	7	14	0.06	48
Louisiana	4	1	5	0.02	56
Maine	6	82	88	0.40	19
Manitoba	17	222	239	1.08	12
Maryland	20	50	70	0.32	26
Massachusetts	19	68	87	0.39	21
Michigan	34	154	188	0.85	15
Minnesota	96	1458	1554	7.01	5
Mississippi	5	2	7	0.03	51
Missouri	16	23	39	0.18	34

Province, State, Territory	# Invalid Records	# Verified Records	Total # Records	Relative Percent Abundance	Rank
Montana	10	29	39	0.18	34
Nebraska	6	33	39	0.18	34
Nevada	13	5	18	0.08	44
New Brunswick	10	179	189	0.85	15
New Hampshire	7	29	36	0.16	38
New Jersey	12	22	34	0.15	39
New Mexico	3	4	7	0.03	51
New York	16	74	90	0.41	18
Newfoundland and Labrador	13	59	72	0.32	26
North Carolina	19	41	60	0.27	29
North Dakota	1	16	17	0.08	44
Northwest Territories	4	2	6	0.03	51
Nova Scotia	19	324	343	1.55	11
Ohio	60	150	210	0.95	13
Oklahoma	4	14	18	0.08	44
Ontario	611	5536	6147	27.74	1
Oregon	190	2347	2537	11.45	3
Pennsylvania	26	60	86	0.39	21
Prince Edward Island	0	43	43	0.19	32
Quebec	20	360	380	1.71	10
Rhode Island	1	3	4	0.02	56
Saskatchewan	15	192	207	0.93	14
South Carolina	15	14	29	0.13	40
South Dakota	1	2	3	0.01	58
Tennessee	11	11	22	0.10	42
Texas	49	28	77	0.35	25
Utah	8	16	24	0.11	41
Vermont	2	82	84	0.38	23
Virginia	26	63	89	0.40	19
Washington	115	3310	3425	15.46	2
West Virginia	1	1	2	0.01	58
Wisconsin	33	616	649	2.93	7
Wyoming	3	16	19	0.09	43
Yukon	0	2	2	0.01	58
Grand Total	2066	20093	22159	100.00	

Table C.S2. Results of Chi-Square (χ^2) or Fisher's Exact Tests (FET) and Cohen's Kappa values investigating the agreement between user submitted and expert identifications for all records in the Bumble Bee Watch citizen science program, as evaluated on a per species basis. When the Chi-square test assumption of expected values being >0 and 80% of records being >5 were not met, FET were conducted to provide the significance (p) values. No statistic value is provide by the FET in these instances. As there were no verified records of *B. variabilis* despite user-submitted identifications, no Chi-Square or Kappa values could be calculated. The degrees of freedom associated with the Chi-Square and FET statistic was 1 for each species when considered separately and 1681 for all species together. Significance levels for Kappa were <0.0001 except for *B. bohemicus*, which was 0.96. Cohen's Kappa values as per Landis and Koch (1977): < 0 : no observer agreement; 0–0.20: slight observer agreement; 0.21-0.40: fair observer agreement; 0.41-0.60: moderate observer agreement; 0.61-0.80: substantial observer agreement; 0.81-1: almost perfect observer agreement.

<i>Bombus</i> species	χ^2 or FET test?	Chi-Square (χ^2) Value	Sig. Value for χ^2 or FET	Kappa Value
<i>affinis</i>	χ^2	9,144.64	<0.0001	0.59
<i>appositus</i>	FET	n/a	<0.0001	0.47
<i>auricomus</i>	FET	n/a	<0.0001	0.49
<i>bifarius</i>	χ^2	12,117.38	<0.0001	0.74
<i>bimaculatus</i>	χ^2	8,479.12	<0.0001	0.62
<i>bohemicus</i>	FET	n/a	1.00	0.00
<i>borealis</i>	FET	n/a	<0.0001	0.69
<i>caliginosus</i>	FET	n/a	<0.0001	0.29
<i>centralis</i>	χ^2	10,162.21	<0.0001	0.67
<i>citrinus</i>	FET	n/a	<0.0001	0.44
<i>crotchii</i>	FET	n/a	<0.0001	0.57
<i>cryptarum</i>	FET	n/a	<0.0001	0.54
<i>fervidus</i>	χ^2	7,999.26	<0.0001	0.60
<i>flavidus</i>	FET	n/a	<0.0001	0.54

<i>Bombus</i> species	χ^2 or FET test?	Chi-Square (χ^2) Value	Sig. Value for χ^2 or FET	Kappa Value
<i>flavifrons</i>	χ^2	7,436.08	<0.0001	0.57
<i>franklini</i>	χ^2	7,374.49	<0.0001	0.57
<i>fraternus</i>	FET	n/a	<0.0001	0.63
<i>frigidus</i>	FET	n/a	<0.0001	0.37
<i>griseocollis</i>	χ^2	8,985.17	<0.0001	0.63
<i>huntii</i>	χ^2	12,375.80	<0.0001	0.74
<i>impatiens</i>	χ^2	9,755.90	<0.0001	0.65
<i>insularis</i>	FET	n/a	<0.0001	0.32
<i>kirbiellus</i>	FET	n/a	<0.0001	0.04
<i>melanopygus</i>	χ^2	6,553.95	<0.0001	0.54
<i>mixtus</i>	χ^2	11,561.33	<0.0001	0.71
<i>morrisoni</i>	FET	n/a	<0.0001	0.60
<i>nevadensis</i>	χ^2	11,989.26	<0.0001	0.74
<i>occidentalis</i>	FET	n/a	<0.0001	0.71
<i>pensylvanicus</i>	FET	n/a	<0.0001	0.41
<i>perplexus</i>	χ^2	9,995.50	<0.0001	0.67
<i>rufocinctus</i>	χ^2	4,183.46	<0.0001	0.43
<i>sandersoni</i>	FET	n/a	<0.0001	0.05
<i>sitkensis</i>	FET	n/a	<0.0001	0.42
sp.	n/a	n/a	n/a	n/a
<i>suckleyi</i>	FET	n/a	0.002	0.04
<i>sylvicola</i>	FET	n/a	<0.0001	0.22
<i>ternarius</i>	χ^2	12,490.63	<0.0001	0.74
<i>terricola</i>	FET	n/a	<0.0001	0.72
Unknown (Non- <i>Bombus</i>)	n/a	n/a	n/a	n/a
<i>vagans</i>	χ^2	4,287.25	<0.0001	0.44
<i>vagans</i> , <i>sandersoni</i> or <i>perplexus</i>	n/a	n/a	n/a	n/a
<i>vandykei</i>	FET	n/a	<0.0001	0.43
<i>variabilis</i>	n/a	n/a	n/a	n/a
<i>vosnesenskii</i>	χ^2	10,642.80	<0.0001	0.69
<i>vosnesenskii</i> or <i>caliginosus</i>	FET	n/a	0.017	0.01
Grand Total	FET	n/a	<0.0001	0.50

Table C.S3. Results of pair-wise Bonferroni-corrected post-hoc tests investigating the relationship between the percent agreement and veracity for each bumble bee species (*Bombus* spp.) submitted to Bumble Bee Watch as compared to the IUCN Red List value for the species. The IUCN red list status is for each species across its North American range, as per a July 30, 2019 export (IUCN 2019). IUCN ranks are as follows: 1 – Least Concern; 2 – Vulnerable; 3 – Endangered; 4 – Critically Endangered. Species that are considered Data Deficient by the IUCN are not presented here. *Bombus variabilis* and *B. franklini* were removed from analyses involving veracity there were no verified records in the dataset. Marginal mean difference refers to the difference in marginal means between each associated IUCN Red List pair.

IUCN Red List	IUCN Red List	Percent Agreement (total n= 37)			Veracity (total n= 35)		
		Marginal Mean Difference	Std. Error	Sig.	Marginal Mean Difference	Std. Error	Sig.
1	2	18.95	10.230	.384	-15.33	5.802	0.049
	3	18.02	4.943	.002	-40.50	4.845	<0.001
	4	46.19	12.669	.002	-44.50	3.078	<0.001
2	1	-18.95	10.230	.384	15.33	5.802	0.049
	3	-.93	9.081	1.000	-25.17	6.359	<0.001
	4	27.24	14.783	.392	-29.17	5.142	<0.001
3	1	-18.02	4.943	.002	40.50	4.845	<0.001
	2	.93	9.081	1.000	25.17	6.359	<0.001
	4	28.17	11.761	.100	-4.00	4.031	1.000
4	1	-46.19	12.669	.002	44.50	3.078	<0.001
	2	-27.24	14.783	.392	29.17	5.142	<0.001
	3	-28.17	11.761	.100	4.00	4.031	1.000

Table C.S4. A comparison of the means and estimates of the marginal means resulting from descriptive statistics and pair-wise Bonferroni-corrected post-hoc tests investigating the relationship between the percent agreement and veracity for each bumble bee species (*Bombus* spp.) submitted to Bumble Bee Watch as compared to the IUCN Red List value for the species. The IUCN red list status is for each species across its North American range, as per a July 30, 2019 export (IUCN 2019). IUCN ranks are as follows: 1 – Least Concern; 2 – Vulnerable; 3 – Endangered; 4 – Critically Endangered. Species that are considered Data Deficient by the IUCN are not presented here. *Bombus variabilis* and *B. franklini* were removed from analyses involving veracity there were no verified records in the dataset.

IUCN Red List	Variable	Standard Mean			Estimated Marginal Means	
		Mean	Std. Deviation	N	Mean	Std. Error
1	Percent Agreement	61.5224	24.5961	25	61.52	4.828
2	Percent Agreement	42.5514	25.81192	7	42.57	9.019
3	Percent Agreement	43.78	2.36174	2	43.50	1.061
4	Percent Agreement	15.1967	24.70269	3	15.33	11.713
1	Veracity	53.9892	14.71108	25	54.00	2.889
2	Veracity	69.34	13.36435	6	69.33	5.031
3	Veracity	94.445	7.85596	2	94.50	3.889
4	Veracity	98.26	2.46073	2	98.50	1.061

Table C.S5. A comparison of the species names as submitted by users to those species names later assigned by experts. The original user submitted species names are along the first row, and the expert identifications are down the first column. Numbers in each cell relate to the total numbers of records that match both the user-submitted species name in the first row and the expert-reviewed species name (or category) in the first columns of the table.

See separate Excel file (3pp; not included in page counts)

Table C.S6. The number of unique users who submitted records for each expert-reviewed species, and summary statistics related to the number of observations per person and per species.

The number of minimum records per user excluded zeros.

Verified Species	# Verified Records	# Unique Users	Mean # Records /User	SE Mean	Max # Records Per User	Min # Records Per User	Relative Percent Max Records Per User
<i>affinis</i>	345	136	2.54	0.36	31	1	8.99
<i>appositus</i>	198	82	2.41	0.29	19	1	9.60
<i>auricomus</i>	105	61	1.72	0.26	13	1	12.38
<i>bifarius</i>	1387	213	6.51	0.89	134	1	9.66
<i>bimaculatus</i>	1340	281	4.77	0.34	77	1	5.75
<i>bohemicus</i>	2	1	2.00		2	2	100.00
<i>borealis</i>	328	180	1.82	0.18	23	1	7.01
<i>caliginosus</i>	60	22	2.73	0.65	11	1	18.33
<i>centralis</i>	476	175	2.72	0.31	31	1	6.51
<i>citrinus</i>	94	54	1.74	0.26	11	1	11.70
<i>crotchii</i>	9	5	1.80	0.58	4	1	44.44
<i>cryptarum</i>	107	70	1.53	0.19	12	1	11.21
<i>fervidus</i>	563	273	2.06	0.16	32	1	5.68
<i>flavidus</i>	125	45	2.78	0.48	16	1	12.80
<i>flavifrons</i>	919	219	4.20	0.55	76	1	8.27
<i>fraternus</i>	20	12	1.67	0.25	5	1	25.00
<i>frigidus</i>	20	12	1.67	0.58	8	1	40.00
<i>griseocollis</i>	1520	268	5.67	0.24	84	1	5.53
<i>huntii</i>	659	267	2.47	0.20	27	1	4.10
<i>impatiens</i>	4205	1447	2.91	0.33	271	1	6.73
<i>insularis</i>	240	87	2.76	0.44	25	1	10.42
<i>kirbiellus</i>	3	3	1.00	0.00	1	1	33.33
<i>melanopygus</i>	599	263	2.28	0.17	33	1	5.51
<i>mixtus</i>	731	217	3.37	0.43	54	1	7.39
<i>morrisoni</i>	46	34	1.35	0.11	3	1	6.52
<i>nevadensis</i>	442	241	1.83	0.14	20	1	4.52
<i>occidentalis</i>	242	96	2.52	0.32	22	1	9.09
<i>pensylvanicus</i>	93	72	1.29	0.11	6	1	6.45
<i>perplexus</i>	297	153	1.94	0.24	28	1	9.43
<i>rufocinctus</i>	937	256	3.66	0.19	32	1	3.42
<i>sandersoni</i>	21	17	1.24	0.14	3	1	14.29
<i>sitkensis</i>	113	40	2.83	0.55	16	1	14.16

Verified Species	# Verified Records	# Unique Users	Mean # Records /User	SE Mean	Max # Records Per User	Min # Records Per User	Relative Percent Max Records Per User
<i>suckleyi</i>	1	1	1.00		1	1	100.00
<i>sylvicola</i>	46	15	3.07	1.17	14	1	30.43
<i>ternarius</i>	1154	250	4.62	0.28	100	1	8.67
<i>terricola</i>	279	136	2.05	0.26	21	1	7.53
Unknown/non - <i>Bombus</i>	2037	248	8.21	0.03	20	1	0.98
<i>vagans</i>	539	200	2.70	0.28	28	1	5.19
<i>vagans</i> , <i>sandersoni</i> or <i>perplexus</i>	292	187	1.56	0.16	22	1	7.53
<i>vandykei</i>	69	19	3.63	0.76	11	1	15.94
<i>vosnesenskii</i>	1112	243	4.58	0.25	53	1	4.77
<i>vosnesenskii</i> or <i>caliginosus</i>	384	241	1.59	0.09	11	1	2.86
totals overall all species combined	22159	4912	4.51	0.27	448	1	2.02

Article C.S1. Excerpt of the Bumble Bee Watch citizen science user survey sent to participants in the Bumble Bee Watch program in Winter 2018 to gain input into their demographics, motivations for participating, perceptions of the program, and perceived ease of identification (or difficulty) for identifying bumble bees from photos.

2/28/2018

Bumble Bee Watch - User Survey

Bumble Bee Watch - User Survey

The purpose of this survey is to help build an understanding of the application of citizen science in biodiversity conservation. As Bumble Bee Watch.org has generated a remarkable database of bumble bee records, researchers would like to know more about the website's users. Learning about participants demographics, motives, and confidence with bumble bee identification is highly useful for researchers who wish to understand the possibly wide-ranging application of citizen science in the future.

* Required

Informed Consent to Participate in Research

Please read the informed consent form and indicate your consent below.

1. **By checking the box below you indicate that you have read the form, below, and consent to participate in the BumbleBeeWatch.org survey conducted by York University research team. ***

Check all that apply.

☐ I consent.

2/28/2018

Bumble Bee Watch - User Survey



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ore@yorku.ca
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Informed Consent Form

Date: September 26, 2017

Study Name: Assessing the Quality of BumbleBeeWatch.org Data

Researcher name:

Faculty of Environmental Studies
York University
Health, Nursing and Environmental Studies Building
4700 Keele St, Toronto, ON
M3J 1P3

Principal Investigator: Dr. Sheila Colla, PhD, srcolla@yorku.ca

Student Researchers: Shelby Gibson, MES candidate, sgibs94@yorku.ca, Madeleine Lavin,
MES candidate, mlavin@yorku.ca, Victoria MacPhail, PhD candidate, vmacphail@gmail.com

Purpose of the Research:

You are being asked to participate in a short (5-10 min) survey because you are a user of BumbleBeeWatch.org. York University is a partner on the BumbleBeeWatch program, and are interested in assessing the quality of data collected through citizen science programs, such as BumbleBeeWatch. Part of this research requires an understanding of who is submitting observations to the database, as well as their motives for doing so. We do not foresee any risks or discomfort from your participation in the research. The benefit of participation is that the participant is able to contribute to a greater understanding of the application of citizen science research in biodiversity conservation. There is no requirement to complete the survey, and once a participant has begun the survey they reserve the right to quit at any point. The survey responses remain anonymous unless permission is given otherwise. As this survey is being administered online, we are relying on this informed consent letter (as opposed to a signature form) to fulfill the duty of informed consent. Further, the data collected may be used in a peer-reviewed publication and conference presentations in the future.

Voluntary Participation and Withdrawal:

Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the nature of the ongoing relationship you may have with the researchers or study staff, or the nature of your relationship with York University either now, or in the future. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete.

Confidentiality:

The method of documentation is through an online Google Survey, which will have an Student Version 08.09.17

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2/28/2018

Bumble Bee Watch - User Survey



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option to export the data collected in to an Excel spreadsheet. The data will be stored on a locked laptop for two years. After this, it may be added to an online data repository. This will allow for the data to be used in future research which may look at citizen science in biodiversity conservation.

Unless you choose otherwise, all information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. Your data will be safely stored on a locked laptop, and only the research team will have access to this information. By September 2019, the data will either be destroyed or added to an online data repository. Confidentiality will be provided to the fullest extent possible by law.

The data collected in this research project may be used – in an anonymized form - by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project. If data is added to a repository, it will be done so in an anonymized manner.

The researcher(s) acknowledge that the host of the online survey (e.g., Qualtrix, Survey Monkey etc.) may automatically collect participant data without their knowledge (i.e., IP addresses.) Although this information may be provided or made accessible to the researchers, it will not be used or saved without participant's consent on the researcher's system. Further, "Because this project employs e-based collection techniques, data may be subject to access by third parties as a result of various security legislation now in place in many countries and thus the confidentiality and privacy of data cannot be guaranteed during web-based transmission."

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact me at sgibs94@yorku.ca, or my supervisor, Dr. Sheila Colla at srcolla@yorku.ca. You may also contact the Graduate Program in Faculty of Environmental Studies at York University, (416)-736-5252.

This research has received ethics review and approval by the Delegated Ethics Review Committee, which is delegated authority to review research ethics protocols by the Human Participants Review Sub-Committee, York University's Ethics Review Board, and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).

Legal Rights and Signatures:

I _____ consent to participate in the BumbleBeeWatch.org survey conducted by York University research team. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature

Student Version 08.09.17

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research ethics UNIVERSITÉ UNIVERSITY U below indicates my consent. <u>Signature</u> _____ Participant  _____ Principal Investigator <u>Date</u> _____ November 28, 2017 _____	Office of Research Ethics York University Kaneff Tower, Fifth Floor – 4700 Keele Street, Toronto, Ontario, Canada, M3J 1P3 ore@yorku.ca research.info@yorku.ca Additional consent: 1. Consent to waive anonymity I _____ consent to the use of my name in the publications arising from this research. <u>Signature</u> _____ Participant Name: <u>Date</u> _____

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3

Biogeographic Region

2/28/2018

Bumble Bee Watch - User Survey

Species Identification Difficulty (from photo)

Please only answer the question for your biogeographic region (East/West).

Species are to be ranked from 1 to 5, where 1 is considered easy to identify and 5 is considered difficult to identify from a photograph.

Easy - you are able to spot one or two characteristics that allow you to quickly identify the species without consulting any reference materials.

Medium - you spend time looking for key characteristics to help you identify the species, and may or may not consult reference materials.

Difficult - you spend a considerable amount of time searching for key characteristics and consult reference materials to help identify the species.

2/28/2018

Bumble Bee Watch - User Survey

19. EASTERN REGION ONLY. (For the Western region, please skip to the following question). Please identify the level of difficulty in identifying the following species from a photograph; 1 is easy and 5 is difficult.

Mark only one oval per row.

	1 - Easy	2 - Somewhat Easy	3 - Medium	4 - Somewhat Difficult	5 - Difficult	6 - N/A
Rusty-patched Bumble Bee (<i>affinis</i>)	☐	☐	☐	☐	☐	☐
Black and Gold Bumble Bee (<i>auricomus</i>)	☐	☐	☐	☐	☐	☐
Two-spotted Bumble Bee (<i>bimaculatus</i>)	☐	☐	☐	☐	☐	☐
Gypsy Cuckoo Bumble Bee (<i>bohemicus</i>)	☐	☐	☐	☐	☐	☐
Northern Amber Bumble Bee (<i>borealis</i>)	☐	☐	☐	☐	☐	☐
Lemon Cuckoo Bumble Bee (<i>citrinus</i>)	☐	☐	☐	☐	☐	☐
Yellow Bumble Bee (<i>fervidus</i>)	☐	☐	☐	☐	☐	☐
Fernald Cuckoo Bumble Bee (<i>flavidus</i>)	☐	☐	☐	☐	☐	☐
Southern Plains Bumble Bee (<i>fraternus</i>)	☐	☐	☐	☐	☐	☐
Frigid Bumble Bee (<i>frigidus</i>)	☐	☐	☐	☐	☐	☐
Brown-belted Bumble Bee (<i>griseocollis</i>)	☐	☐	☐	☐	☐	☐
Common Eastern Bumble Bee (<i>impatiens</i>)	☐	☐	☐	☐	☐	☐
Indiscriminate Cuckoo Bumble Bee (<i>insularis</i>)	☐	☐	☐	☐	☐	☐
High Country Bumble Bee (<i>kirbiellus</i>)	☐	☐	☐	☐	☐	☐
Morrison Bumble Bee (<i>morrisoni</i>)	☐	☐	☐	☐	☐	☐
Nevada Bumble Bee (<i>nevadensis</i>)	☐	☐	☐	☐	☐	☐
American Bumble Bee (<i>pensylvanicus</i>)	☐	☐	☐	☐	☐	☐
Confusing Bumble Bee (<i>perplexus</i>)	☐	☐	☐	☐	☐	☐
Red-belted Bumble Bee (<i>rufocinctus</i>)	☐	☐	☐	☐	☐	☐
Sanderson Bumble Bee (<i>sandersoni</i>)	☐	☐	☐	☐	☐	☐
Tri-coloured Bumble Bee (<i>ternarius</i>)	☐	☐	☐	☐	☐	☐
Yellow-banded Bumble Bee (<i>terricola</i>)	☐	☐	☐	☐	☐	☐

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	1 - Easy	2 - Somewhat Easy	3 - Medium	4 - Somewhat Difficult	5 - Difficult	6 - N/A
Half-black Bumble Bee (vagans)	☐	☐	☐	☐	☐	☐
Variable Cuckoo Bumble Bee (variabilis)	☐	☐	☐	☐	☐	☐

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Bumble Bee Watch - User Survey

20. WESTERN REGION ONLY. (For the Eastern region, please return to the previous question). Please identify the level of difficulty in identifying the following species from a photograph; 1 is easy and 5 is difficult.

Mark only one oval per row.

	1 - Easiest	2 - Easy	3 - Medium	4 - Difficult	5 - Most Difficult	6 - N/A
White-shouldered Bumble Bee (appositus)	☐	☐	☐	☐	☐	☐
Black and Gold Bumble Bee (auricomus)	☐	☐	☐	☐	☐	☐
Gypsy Cuckoo Bumble Bee (bohemicus)	☐	☐	☐	☐	☐	☐
Two Form Bumble Bee (bifarius)	☐	☐	☐	☐	☐	☐
Northern Amber Bumble Bee (borealis)	☐	☐	☐	☐	☐	☐
Obscure Bumble Bee (caliginosus)	☐	☐	☐	☐	☐	☐
Central Bumble Bee (centralis)	☐	☐	☐	☐	☐	☐
Lemon Cuckoo Bumble Bee (citrinus)	☐	☐	☐	☐	☐	☐
Crotch Bumble Bee (crotchii)	☐	☐	☐	☐	☐	☐
Cryptic Bumble Bee (cryptarum)	☐	☐	☐	☐	☐	☐
Yellow Bumble Bee (fervidus)	☐	☐	☐	☐	☐	☐
Yellow-headed Bumble Bee (flavifrons)	☐	☐	☐	☐	☐	☐
Franklin Bumble Bee (franklini)	☐	☐	☐	☐	☐	☐
Southern Plains Bumble Bee (fraternus)	☐	☐	☐	☐	☐	☐
Frigid Bumble Bee (frigidus)	☐	☐	☐	☐	☐	☐
Brown-belted Bumble Bee (griseocollis)	☐	☐	☐	☐	☐	☐
Common Eastern Bumble Bee (impatiens)	☐	☐	☐	☐	☐	☐
Indiscriminate Cuckoo Bumble Bee (insularis)	☐	☐	☐	☐	☐	☐
White-tailed Bumbled Bee (jonellus)	☐	☐	☐	☐	☐	☐
Black-tailed Bumble Bee (melanopygus)	☐	☐	☐	☐	☐	☐
Fuzzy-horned Bumble Bee (mixtus)	☐	☐	☐	☐	☐	☐
Morrison Bumble Bee (morrisoni)	☐	☐	☐	☐	☐	☐
Nevada Bumble Bee (nevadensis)	☐	☐	☐	☐	☐	☐
Western Bumble Bee (occidentalis)	☐	☐	☐	☐	☐	☐
American Bumble Bee (pennsylvanicus)	☐	☐	☐	☐	☐	☐

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Bumble Bee Watch - User Survey

	1 - Easiest	2 - Easy	3 - Medium	4 - Difficult	5 - Most Difficult	6 - N/A
Confusing Bumble Bee (perplexus)	☐	☐	☐	☐	☐	☐
Red-belted Bumble Bee (rufocinctus)	☐	☐	☐	☐	☐	☐
Sanderson Bumble Bee (sandersoni)	☐	☐	☐	☐	☐	☐
Suckley Cuckoo Bumble Bee (suckleyi)	☐	☐	☐	☐	☐	☐
Forest Bumble Bee (sylvicola)	☐	☐	☐	☐	☐	☐
Tri-coloured Bumble Bee (ternarius)	☐	☐	☐	☐	☐	☐
Half-black Bumble Bee (vagans)	☐	☐	☐	☐	☐	☐
Van Dyke Bumble Bee (vandykei)	☐	☐	☐	☐	☐	☐
Vosnesensky Bumble Bee (vosnesenski)	☐	☐	☐	☐	☐	☐

Final Thoughts

21. Please feel free to leave any additional comments about this survey or about Bumble Bee Watch in general.

Thank you!

Thanks very much for taking the time to participate in the Bumble Bee Watch User Survey!

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Article C.S2. Excerpt of the Bumble Bee Watch citizen science expert survey sent to selected experts in Winter 2018 and Fall 2019 to gain input into their demographics, motivations for participating, perceptions of the program, and perceived ease of identification (or difficulty) for identifying bumble bees from photos.

Bumble Bee Watch - Expert Survey

You have been selected as an individual with expertise in bumble bee identification.

We are attempting to build an understanding of the application of citizen science in biodiversity conservation. As Bumble Bee Watch.org has generated a remarkable database of bumble bee records, researchers would like to know more about the website's users. Learning about participants demographics, motives, and confidence with bumble bee identification is highly useful for researchers who wish to understand the possibly wide-ranging application of citizen science in the future.

As a complement to a separate survey of Bumble Bee Watch users, we are asking for your participation in our expert survey. (If you are interested in taking the user survey, please follow the link at the end of this survey). We are interested in your feedback regarding the ease or difficulty of identifying various species in the eastern and/or western regions of North America, whether you have verified submissions for us in the past or if you are interested in verifying submissions for us in the future, and your thoughts on the kinds of research questions that we might ask with the data collected through Bumble Bee Watch.

* Required

Informed Consent to Participate in Research

Please read the informed consent form and indicate your consent below.

1. **By checking the box below you indicate that you have read the form, below, and consent to participate in the BumbleBeeWatch.org survey conducted by York University research team. ***

Check all that apply.

☐ I consent.

Additional Consent

Consent to waive anonymity

2. **Please indicate your consent below to the use of your name in the publications arising from this research. ***

Mark only one oval.

☐ Waive anonymity
☐ Remain anonymous

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Bumble Bee Watch - Expert Survey



Office of Research Ethics
York University
Kaneff Tower, Fifth Floor – 4700 Keele Street,
Toronto, Ontario, Canada M3J 1P3
ore@yorku.ca
research.info@yorku.ca

Informed Consent Form

Date: September 26, 2017

Study Name: Assessing the Quality of BumbleBeeWatch.org Data

Researcher name:

Faculty of Environmental Studies
York University
Health, Nursing and Environmental Studies Building
4700 Keele St, Toronto, ON
M3J 1P3

Principal Investigator: Dr. Sheila Colla, PhD, srcolla@yorku.ca

Student Researchers: Shelby Gibson, MES candidate, sgibs94@yorku.ca, Madeleine Lavin,
MES candidate, mlavin@yorku.ca, Victoria MacPhail, PhD candidate, vmacphail@gmail.com

Purpose of the Research:

You are being asked to participate in a short (5-10 min) survey because you are a user of BumbleBeeWatch.org. York University is a partner on the BumbleBeeWatch program, and are interested in assessing the quality of data collected through citizen science programs, such as BumbleBeeWatch. Part of this research requires an understanding of who is submitting observations to the database, as well as their motives for doing so. We do not foresee any risks or discomfort from your participation in the research. The benefit of participation is that the participant is able to contribute to a greater understanding of the application of citizen science research in biodiversity conservation. There is no requirement to complete the survey, and once a participant has begun the survey they reserve the right to quit at any point. The survey responses remain anonymous unless permission is given otherwise. As this survey is being administered online, we are relying on this informed consent letter (as opposed to a signature form) to fulfill the duty of informed consent. Further, the data collected may be used in a peer-reviewed publication and conference presentations in the future.

Voluntary Participation and Withdrawal:

Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the nature of the ongoing relationship you may have with the researchers or study staff, or the nature of your relationship with York University either now, or in the future. In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete.

Confidentiality:

The method of documentation is through an online Google Survey, which will have an Student Version 08.09.17

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Bumble Bee Watch - Expert Survey



Office of Research Ethics
York University

Kaneff Tower, Fifth Floor – 4700 Keele Street,
Toronto, Ontario, Canada, M3J 1P3

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research.info.yorku.ca

option to export the data collected in to an Excel spreadsheet. The data will be stored on a locked laptop for two years. After this, it may be added to an online data repository. This will allow for the data to be used in future research which may look at citizen science in biodiversity conservation.

Unless you choose otherwise, all information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. Your data will be safely stored on a locked laptop, and only the research team will have access to this information. By September 2019, the data will either be destroyed or added to an online data repository. Confidentiality will be provided to the fullest extent possible by law.

The data collected in this research project may be used – in an anonymized form - by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project. If data is added to a repository, it will be done so in an anonymized manner.

The researcher(s) acknowledge that the host of the online survey (e.g., Qualtrix, Survey Monkey etc.) may automatically collect participant data without their knowledge (i.e., IP addresses.) Although this information may be provided or made accessible to the researchers, it will not be used or saved without participant's consent on the researcher's system. Further, "Because this project employs e-based collection techniques, data may be subject to access by third parties as a result of various security legislation now in place in many countries and thus the confidentiality and privacy of data cannot be guaranteed during web-based transmission."

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact me at sgibs94@yorku.ca, or my supervisor, Dr. Sheila Colla at srcolla@yorku.ca. You may also contact the Graduate Program in Faculty of Environmental Studies at York University, (416)-736-5252.

This research has received ethics review and approval by the Delegated Ethics Review Committee, which is delegated authority to review research ethics protocols by the Human Participants Review Sub-Committee, York University's Ethics Review Board, and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).

Legal Rights and Signatures:

I _____ consent to participate in the BumbleBeeWatch.org survey conducted by York University research team. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature

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Bumble Bee Watch - Expert Survey

research ethics | YORK UNIVERSITY

Office of Research Ethics
York University

Kanell Tower, Fifth Floor – 4700 Keele Street,
Toronto, Ontario, Canada, M3J 1P3

ore@yorku.ca
researchinfo@yorku.ca

below indicates my consent.

Signature _____ **Date** _____
Participant

[Handwritten Signature] _____
Principal Investigator

November 28, 2017

Additional consent:

1. Consent to waive anonymity

I _____ consent to the use of my name in the publications arising from this research.

Signature _____ **Date** _____
Participant Name:

|

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Introductory Questions

Please state your name and biogeographic region.

3. **Please state your name: ***

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Bumble Bee Watch - Expert Survey

13. Comments on using data from Bumble Bee Watch:

Species Identification Difficulty (from photo)

Please note that the following species lists are separated by biogeographic region (East/West). Please feel free to rank the ease or difficulty for the eastern and/or western biogeographic regions.

Species are to be ranked from 1 to 5, where 1 is considered easy to identify and 5 is considered difficult to identify from a photograph.

Easy - you are able to spot one or two characteristics that allow you to quickly identify the species without consulting any reference materials.

Medium - you spend time looking for key characteristics to help you identify the species, and may or may not consult reference materials.

Difficult - you spend a considerable amount of time searching for key characteristics and consult reference materials to help identify the species.

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Bumble Bee Watch - Expert Survey

14. EASTERN REGION ONLY. (For the Western region, please skip to the following question). Please identify the level of difficulty in identifying the following species from a photograph; 1 is easy and 5 is difficult.

Mark only one oval per row.

	1 - Easy	2 - Somewhat Easy	3 - Medium	4 - Somewhat Difficult	5 - Difficult	6 - N/A
Rusty-patched Bumble Bee (<i>affinis</i>)	☐	☐	☐	☐	☐	☐
Black and Gold Bumble Bee (<i>auricomus</i>)	☐	☐	☐	☐	☐	☐
Two-spotted Bumble Bee (<i>bimaculatus</i>)	☐	☐	☐	☐	☐	☐
Gypsy Cuckoo Bumble Bee (<i>bohemicus</i>)	☐	☐	☐	☐	☐	☐
Northern Amber Bumble Bee (<i>borealis</i>)	☐	☐	☐	☐	☐	☐
Lemon Cuckoo Bumble Bee (<i>citrinus</i>)	☐	☐	☐	☐	☐	☐
Yellow Bumble Bee (<i>fervidus</i>)	☐	☐	☐	☐	☐	☐
Fernald Cuckoo Bumble Bee (<i>flavidus</i>)	☐	☐	☐	☐	☐	☐
Southern Plains Bumble Bee (<i>fraternus</i>)	☐	☐	☐	☐	☐	☐
Frigid Bumble Bee (<i>frigidus</i>)	☐	☐	☐	☐	☐	☐
Brown-belted Bumble Bee (<i>griseocollis</i>)	☐	☐	☐	☐	☐	☐
Common Eastern Bumble Bee (<i>impatiens</i>)	☐	☐	☐	☐	☐	☐
Indiscriminate Cuckoo Bumble Bee (<i>insularis</i>)	☐	☐	☐	☐	☐	☐
High Country Bumble Bee (<i>kirbiellus</i>)	☐	☐	☐	☐	☐	☐
Morrison Bumble Bee (<i>morrisoni</i>)	☐	☐	☐	☐	☐	☐
Nevada Bumble Bee (<i>nevadensis</i>)	☐	☐	☐	☐	☐	☐
American Bumble Bee (<i>pensylvanicus</i>)	☐	☐	☐	☐	☐	☐
Confusing Bumble Bee (<i>perplexus</i>)	☐	☐	☐	☐	☐	☐
Red-belted Bumble Bee (<i>rufocinctus</i>)	☐	☐	☐	☐	☐	☐
Sanderson Bumble Bee (<i>sandersoni</i>)	☐	☐	☐	☐	☐	☐
Tri-coloured Bumble Bee (<i>ternarius</i>)	☐	☐	☐	☐	☐	☐
Yellow-banded Bumble Bee (<i>terricola</i>)	☐	☐	☐	☐	☐	☐

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	1 - Easy	2 - Somewhat Easy	3 - Medium	4 - Somewhat Difficult	5 - Difficult	6 - N/A
Half-black Bumble Bee (vagans)	☐	☐	☐	☐	☐	☐
Variable Cuckoo Bumble Bee (variabilis)	☐	☐	☐	☐	☐	☐

2/28/2018

Bumble Bee Watch - Expert Survey

15. WESTERN REGION ONLY. (For the Eastern region, please return to the previous question). Please identify the level of difficulty in identifying the following species from a photograph; 1 is easy and 5 is difficult.

Mark only one oval per row.

	1 - Easiest	2 - Easy	3 - Medium	4 - Difficult	5 - Most Difficult	6 - N/A
White-shouldered Bumble Bee (appositus)	☐	☐	☐	☐	☐	☐
Black and Gold Bumble Bee (auricomus)	☐	☐	☐	☐	☐	☐
Gypsy Cuckoo Bumble Bee (bohemicus)	☐	☐	☐	☐	☐	☐
Two Form Bumble Bee (bifarius)	☐	☐	☐	☐	☐	☐
Northern Amber Bumble Bee (borealis)	☐	☐	☐	☐	☐	☐
Obscure Bumble Bee (caliginosus)	☐	☐	☐	☐	☐	☐
Central Bumble Bee (centralis)	☐	☐	☐	☐	☐	☐
Lemon Cuckoo Bumble Bee (citrinus)	☐	☐	☐	☐	☐	☐
Crotch Bumble Bee (crotchii)	☐	☐	☐	☐	☐	☐
Cryptic Bumble Bee (cryptarum)	☐	☐	☐	☐	☐	☐
Yellow Bumble Bee (fervidus)	☐	☐	☐	☐	☐	☐
Yellow-headed Bumble Bee (flavifrons)	☐	☐	☐	☐	☐	☐
Franklin Bumble Bee (franklini)	☐	☐	☐	☐	☐	☐
Southern Plains Bumble Bee (fraternus)	☐	☐	☐	☐	☐	☐
Frigid Bumble Bee (frigidus)	☐	☐	☐	☐	☐	☐
Brown-belted Bumble Bee (griseocollis)	☐	☐	☐	☐	☐	☐
Common Eastern Bumble Bee (impatiens)	☐	☐	☐	☐	☐	☐
Indiscriminate Cuckoo Bumble Bee (insularis)	☐	☐	☐	☐	☐	☐
White-tailed Bumble Bee (jonellus)	☐	☐	☐	☐	☐	☐
Black-tailed Bumble Bee (melanopygus)	☐	☐	☐	☐	☐	☐
Fuzzy-horned Bumble Bee (mixtus)	☐	☐	☐	☐	☐	☐
Morrison Bumble Bee (morrisoni)	☐	☐	☐	☐	☐	☐
Nevada Bumble Bee (nevadensis)	☐	☐	☐	☐	☐	☐
Western Bumble Bee (occidentalis)	☐	☐	☐	☐	☐	☐
American Bumble Bee (pennsylvanicus)	☐	☐	☐	☐	☐	☐

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Bumble Bee Watch - Expert Survey

	1 - Easiest	2 - Easy	3 - Medium	4 - Difficult	5 - Most Difficult	6 - N/A
Confusing Bumble Bee (perplexus)	☐	☐	☐	☐	☐	☐
Red-belted Bumble Bee (rufocinctus)	☐	☐	☐	☐	☐	☐
Sanderson Bumble Bee (sandersoni)	☐	☐	☐	☐	☐	☐
Suckley Cuckoo Bumble Bee (suckleyi)	☐	☐	☐	☐	☐	☐
Forest Bumble Bee (sylvicola)	☐	☐	☐	☐	☐	☐
Tri-coloured Bumble Bee (ternarius)	☐	☐	☐	☐	☐	☐
Half-black Bumble Bee (vagans)	☐	☐	☐	☐	☐	☐
Van Dyke Bumble Bee (vandykei)	☐	☐	☐	☐	☐	☐
Vosnesensky Bumble Bee (vosnesenski)	☐	☐	☐	☐	☐	☐

Bumble Bee Watch - User Survey

Please click the following link if you'd also like to participate in the Bumble Bee Watch User Survey:

<https://goo.gl/forms/FYlXAn7Jgt4Pca4o2>

Final Thoughts

16. **Please feel free to leave any additional comments about this survey or about Bumble Bee Watch in general.**

Thank you!

Thanks very much for taking the time to participate in the Bumble Bee Watch Expert Survey!

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Appendix D. Supplementary Information for Chapter 6

Table D.S1. Results for a series of Kruskal-Wallis test statistics for the comparisons of user survey respondents' motivations by age of respondent, number of years participating in Bumble Bee Watch, or by area they live (urban/suburban/rural). Significance levels were adjusted to control False Discovery Rates (FDRs) using the Benjamini-Hochberg procedure.

Grouping Variable	Motivation	Kruskal-Wallis H Statistic	df	p-value	FDR-adjusted p-value
Respondent Age	To contribute to scientific data collection	6.01	7	0.539	0.774
Respondent Age	I want to learn what species are on my property	9.471	7	0.221	0.553
Respondent Age	I want to learn how to identify the biodiversity in my region	2.456	7	0.93	0.999
Respondent Age	Participation in special events (e.g. Great Canadian Bumble Bee Count or a Bioblitz)	0.653	7	0.999	0.999
Respondent Age	I have a personal interest in bumble bees	11.155	7	0.132	0.493
Respondent Age	I'm worried about bees and want to help save them	10.793	7	0.148	0.493
Respondent Age	To share the uncommon or rare species I find	13.058	7	0.071	0.493
Respondent Age	The preservation of ecological diversity	3.75	7	0.808	0.999
Respondent Age	Recreational learning/Family activity	6.572	7	0.475	0.774
Years Participated	To contribute to scientific data collection	9.414	4	0.052	0.173
Years Participated	I want to learn what species are on my property	1.501	4	0.826	0.899
Years Participated	I want to learn how to identify the biodiversity in my region	1.07	4	0.899	0.899
Years Participated	Participation in special events (e.g. Great Canadian Bumble Bee Count or a Bioblitz)	3.417	4	0.491	0.739
Years Participated	I have a personal interest in bumble bees	6.755	4	0.149	0.373

Grouping Variable	Motivation	Kruskal-Wallis H Statistic	df	p-value	FDR-adjusted p-value
Years Participated	I'm worried about bees and want to help save them	4.831	4	0.305	0.610
Years Participated	To share the uncommon or rare species I find	10.846	4	0.028	0.140
Years Participated	The preservation of ecological diversity	3.222	4	0.521	0.739
Years Participated	Recreational learning/Family activity	2.804	4	0.591	0.739
Area Live In	To contribute to scientific data collection	0.041	2	0.98	0.980
Area Live In	I want to learn what species are on my property	9.036	2	0.011	0.090
Area Live In	I want to learn how to identify the biodiversity in my region	1.966	2	0.374	0.637
Area Live In	Participation in special events (e.g. Great Canadian Bumble Bee Count or a Bioblitz)	8.029	2	0.018	0.090
Area Live In	I have a personal interest in bumble bees	2.921	2	0.232	0.580
Area Live In	I'm worried about bees and want to help save them	0.758	2	0.685	0.761
Area Live In	To share the uncommon or rare species I find	6.894	2	0.032	0.107
Area Live In	The preservation of ecological diversity	1.923	2	0.382	0.637
Area Live In	Recreational learning/Family activity	1.36	2	0.507	0.724

Table D.S2. Categories where user survey respondents (n=210) suggested improvements could be made to the Bumble Bee Watch program. Note that respondents could make multiple suggestions so the total of all categories do not add up to 100%. Free-form responses were initially coded into one of 29 categories by three individuals, and then further collapsed into these six categories.

Suggested Improvement Areas	Number of Respondents	Percent of Respondents
Happy - nothing to improve, can't think of anything	33	15.7
Feedback to users - faster identifications, more details on their submissions/identifications	58	27.6
IT related - improvement of app and website functionality, submission process (including showing real photos in addition to the diagrams)	88	41.9
Tools and resources - program usage tips, identification guides, local species lists, tutorials/workshops, etc. (for bees and plants)	40	19.0
Increased communication - results, reports, general feedback, etc.	24	11.4
Other ideas, comments	20	9.5

Table D.S3: A comparison of the relative percentage of user survey respondents, database records, and combined population per United States state or territory and Canadian province or territory (“jurisdiction”). There were 342 survey respondents and 23,017 records in the Bumble Bee Watch database as of February 28, 2018, covering both the United States and Canada. The United States population during the 2015-2017 period was 321,004,407 (excluding Puerto Rico)(United States Census Bureau 2017a), and the Canadian population in 2016 was 35,151,728 (Statistics Canada 2017b), for a combined population of 356,156,135.

Federal Jurisdiction	Percent of User Survey Respondents	Percent of Records in Database	Percent of Combined National Populations
Alabama	0.88	0.47	1.36
Alaska	0.00	0.25	0.21
Alberta	3.80	4.99	1.14
Arizona	0.58	0.16	1.91
Arkansas	0.29	0.11	0.84
British Columbia	4.97	5.21	1.31
California	2.92	2.87	10.95
Colorado	4.39	1.72	1.53
Connecticut	0.58	0.10	1.01
Delaware	0.00	0.17	0.26
District of Columbia	0.29	0.03	0.19
Florida	1.75	0.51	5.69
Georgia	0.29	0.36	2.86
Hawaii	0.00	0.00	0.40
Idaho	1.75	1.48	0.47
Illinois	1.46	1.26	3.61
Indiana	0.88	0.68	1.86
Iowa	0.88	0.49	0.88
Kansas	0.29	0.17	0.82
Kentucky	0.00	0.22	1.24
Louisiana	0.00	0.05	1.31
Maine	1.46	2.36	0.37
Manitoba	1.17	1.89	0.36
Maryland	2.05	0.73	1.68
Massachusetts	1.17	0.85	1.91
Michigan	2.63	2.35	2.79

Federal Jurisdiction	Percent of User Survey Respondents	Percent of Records in Database	Percent of Combined National Populations
Minnesota	7.60	6.05	1.54
Mississippi	0.00	0.06	0.84
Missouri	1.75	0.58	1.71
Montana	0.29	1.24	0.29
Nebraska	0.29	0.49	0.53
Nevada	0.00	0.25	0.81
New Brunswick	0.29	0.66	0.21
New Hampshire	0.29	0.53	0.37
New Jersey	0.58	0.40	2.52
New Mexico	0.58	0.16	0.59
New York	2.63	1.49	5.56
Newfoundland and Labrador	0.00	0.31	0.15
North Carolina	0.58	0.87	2.82
North Dakota	0.00	0.15	0.21
Northwest Territories	0.29	0.13	0.01
Nova Scotia	1.75	1.63	0.26
Nunavut	0.00	0.03	0.01
Ohio	3.22	1.99	3.26
Oklahoma	0.00	0.33	1.09
Ontario	18.13	26.50	3.78
Oregon	5.85	5.73	1.13
Pennsylvania	1.46	1.33	3.59
Prince Edward Island	0.29	0.19	0.04
Quebec	1.46	1.04	2.29
Rhode Island	0.00	0.06	0.30
Saskatchewan	3.22	1.92	0.31
South Carolina	0.00	0.33	1.37
South Dakota	0.29	0.21	0.24
Tennessee	1.46	0.40	1.85
Texas	1.17	1.58	7.70
Utah	0.88	0.40	0.84
Vermont	1.17	0.85	0.18
Virginia	1.75	1.02	2.35
Washington	4.39	7.07	2.01
West Virginia	0.00	0.08	0.52
Wisconsin	3.51	3.95	1.62
Wyoming	0.29	0.49	0.16
Yukon	0.00	0.05	0.01

Table D.S4. Statistical output for a series of Dunn's post-hoc tests comparing the total number of years the user survey respondents have participated in Bumble Bee Watch to their reported number (class) of submissions. Significance levels were adjusted to control False Discovery Rates (FDRs) using the Benjamini-Hochberg procedure.

Years of Participation Comparisons	Test Statistic	<i>p</i>-value	FDR-adjusted <i>p</i>-value
year 0 & 1	9.04	0.49	0.49
year 0 & 2	-20.01	0.09	0.10
year 0 & 3	-63.96	<0.001	<0.001
year 0 & 4	-104.86	<0.001	<0.001
year 1 & 2	-29.05	0.02	0.02
year 1 & 3	-73.01	<0.001	<0.001
year 1 & 4	-113.90	<0.001	<0.001
year 2 & 3	-43.96	<0.001	0.001
year 2 & 4	-84.85	<0.001	<0.001
year 3 & 4	-40.90	0.04	0.054

Appendix E. Statement on Candidate's Contributions to Written Works

Statement of Victoria J. MacPhail's contribution to co-authored works included in this dissertation titled "Assessing the benefits, challenges, and scientific value of community science programs: A case study using Bumble Bee Watch" (note: previously referred to as "The power of an observation: how community scientists with Bumble Bee Watch can fill knowledge gaps and inform pollinator conservation efforts while increasing their own knowledge and skills").

Chapter 1:

The overview introduction chapter was written by VM

Chapter 2:

MacPhail, V.J and Colla, S.R. 2020. Power of the People: A Review of Citizen Science Programs for Conservation. *Biological Conservation*. 249: 108739.
<https://doi.org/10.1016/j.biocon.2020.108739>

VJM designed the literature review, identified, read, and extracted information from relevant papers, and wrote the manuscript. SRC provided input into the study design, and critically revised the manuscript.

Chapter 3:

Victoria J. MacPhail, Richard Hatfield, Sheila R Colla. A Community Science program worth buzzing about: Bumble Bee Watch increases ecological understanding and range coverage of an important pollinator group across the continent. To be submitted.

VJM designed the study, obtained and cleaned the data, conducted the data analysis, and wrote the manuscript. RH provided input into the study design, contributed to the data set from Bumble Bee Watch, and provided feedback on the manuscript. SRC provided input into the study design and critically revised the manuscript.

Chapter 4:

MacPhail, V.J., Richardson, L.L., Colla, S.R.. 2019. Incorporating citizen science, museum specimens, and field work into the assessment of extinction risk of the American Bumble bee (*Bombus pensylvanicus* De Geer 1773). *Journal of Insect Conservation*. 23(3):597–611.
<https://doi.org/10.1007/s10841-019-00152-y> (note: acknowledgements were missed in the publication process of this paper, but printed as a correction in the journal with the same authors, year, at <https://doi.org/10.1007/s10841-019-00159-5>)

VJM designed the study, obtained and cleaned the data, conducted the data analysis, and wrote the manuscript. LLR provided input into the study design, contributed the Bumble Bees of North America dataset, and provided feedback on the manuscript. SRC provided input into the study design and critically revised the manuscript.

Chapter 5:

MacPhail, V.J., Gibson, S.D., Hatfield, R., Colla, S.R.. 2020. Accuracy of Initial Identification of Bumble Bees (*Bombus* spp.) to the Species-level by Citizen Scientists on Bumble Bee Watch. PeerJ, PeerJ 8:e9412 DOI 10.7717/peerj.9412

VJM designed the study, obtained and cleaned the data, conducted the data analysis, and wrote the manuscript. SDG provided input into the study design, assisted with data collection and cleaning, assisted with data analyses, and provided feedback on the manuscript. RH provided input into the study design, contributed to the data set from Bumble Bee Watch, and provided feedback on the manuscript. SRC provided input into the study design and critically revised the manuscript.

Chapter 6:

MacPhail, V.J, Gibson, S.D. and Colla, S.R. 2020. Community science participants gain environmental awareness and contribute high quality data but improvements are needed: insights from Bumble Bee Watch. PeerJ 8:e9141. <http://doi.org/10.7717/peerj.9141>.

VJM designed the study, including the survey to both experts and participants, obtained and cleaned the data, conducted the data analysis, and wrote the manuscript. SDG provided input into the study and survey design, assisted with data collection and cleaning, assisted with data analyses, and provided feedback on the manuscript. SRC provided input into the study design and critically revised the manuscript.

Chapter 7:

The final conclusion chapter was written by VJM.

Sincerely,
Victoria J. MacPhail
Faculty of Environment and Urban Change, York University
July 24, 2021

Approved by,
Sheila R. Colla, PhD
Associate Professor
Faculty of Environment and Urban Change, York University
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MacPhail, V.J., Richardson, L.L. & Colla, S.R. Correction to: Incorporating citizen science, museum specimens, and field work into the assessment of extinction risk of the American Bumble bee (*Bombus pensylvanicus* De Geer 1773) in Canada. *J Insect Conserv* **23**, 785 (2019). <https://doi.org/10.1007/s10841-019-00159-5>

MacPhail VJ, Gibson SD, Hatfield R, Colla SR. 2020. Using Bumble Bee Watch to investigate the accuracy and perception of bumble bee (*Bombus* spp.) identification by community scientists. *PeerJ* 8:e9412 <https://doi.org/10.7717/peerj.9412>

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Sincerely,

Sheila R. Colla

--

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 York Research Chair in Interdisciplinary Conservation Science
 Faculty of Environmental & Urban Change, York University
 Websites:
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Sincerely,

Richard Hatfield

Rich Hatfield
 Senior Conservation Biologist, Endangered Species Program
 Red List Authority, IUCN Bumble Bee Specialist Group
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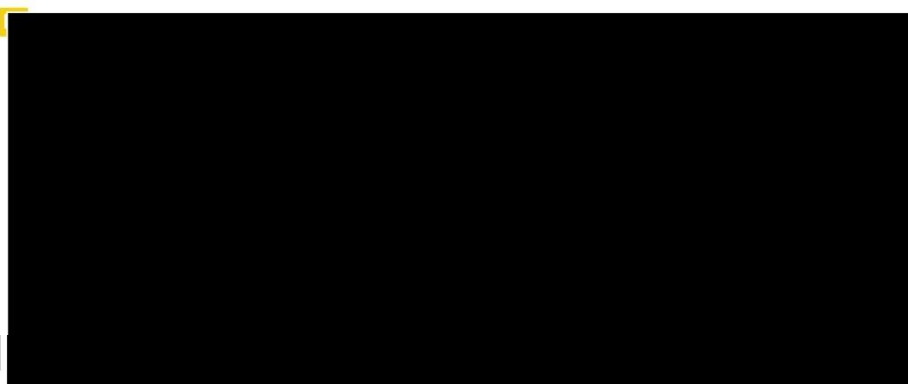
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Signed,
Leif Richardson



--

Leif Richardson
Ecologist
Montpelier, Vermont
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Sincerely,

Shelby D. Gibson

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