

Pollinators and the Global Crisis:
Understanding the Importance, Impacts and Threats to Pollination Systems

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ABSTRACT

Pollinators are essential to the global economy, the wellbeing of humans, and are indispensable when it comes to maintaining food security for all humans. The ongoing decline of pollinators has led to a crisis that is being driven by anthropogenic threats. This portfolio examines pollinators and threats to pollinating systems through two bodies of work; a literature review and a research study. The literature review of previously published pollinator decline research displays a trend of study on agricultural systems and managed honey bees (*Apis mellifera*). Most research examining pollinator decline has focused on pesticides, agriculture and managed honey bees; in addition, most research was also focused in the global North. The research study portion of this portfolio examines the impacts of managed honey bees on wild bees in the city of Toronto. Honey bees were shown to impact the abundance of wild bees in urban landscapes. Increased abundance of honey bees in the city was also shown to impact the body size of certain groups of bees, *Xylocopa*, which proves that these managed bees compete over floral resources with native wild bees.

FOREWORD

This Portfolio is the culmination of the two years spent working towards the Master of Environmental Studies (MES) degree at York University. It is composed of two main sections a research study and a literature review. These two works reflect my area of concentration *Wildlife Conservation and Management*, through my focus on pollinators and pollinating systems and by integrating concepts of my three learning components ‘Ecological Threats and Processes,’ ‘Species Identification and Taxonomy,’ and ‘Current Practices in Wildlife Conservation and Management.’

The work submitted as part of this portfolio focuses greatly on the first two components, while addressing the third component to a somewhat lesser extent. The literature review examines trends in pollinator decline research. It sets a foundation to this portfolio and elaborates on the importance of pollinators and the ecosystem service they provide humans with. This review speaks greatly towards the first learning component, ‘Ecological Threats and Processes,’ while discussing the last component to a smaller extent through the examination of geography and funding of pollinator studies.

The research study focused on understanding impacts of the managed European honey bees on urban pollinators in Canada was a large undertaking. However, it has allowed me to further understand and tackle the first two learning components with a heavy emphasis on ‘Species Identification and Taxonomy.’ The field work associated with this research required a great knowledge of already existing pollinating species and plants in the city of Toronto. In addition, processing collected samples allowed me to meet this learning objective.

The importance of pollinators, the services they provide and threats to these systems have been well researched. My portfolio focuses on key components of pollination while addressing impacts of widely used managed pollinators on urban ecosystems in the research study as well as current gaps in pollinator decline research through the literature review. I hope with the work submitted in this portfolio a better understanding of pollinator systems can be achieved, which will result in the creation of more informed conservation strategies.

ACKNOWLEDGEMENTS

I would like to thank my advisor and supervisor, Dr. Sheila Colla, for her guidance and support during these past two years. I started out in pursuit of this degree not really sure what to expect and not knowing what I hoped to achieve. She has offered me tremendous support and helped me navigate through graduate school. Thank you for all your advice and detailed feedback on this portfolio.

The first chapter of this portfolio, the Pollinator Decline Review, would not have been possible without the work of Heather Kerriso, Lynn Miller, Melina Damian and Patrick Secord who started working on compiling the data for it two years ago.

The second chapter of this portfolio the honey bee competition paper, would not have been possible without the help and work of many people. I would like to thank Sarah MacKell, MSc student, who designed the research project and has allowed me to collaborate with her on it. This research project would not have been possible without all her hard work. Many thanks to Dr. Scott MacIvor who offered us feedback on and helped with choosing sampling sites. I would also like to thank the City of Toronto and the City of Mississauga personnel, park supervisors and Paul Zammit from the Toronto Botanical Gardens, who have all helped with choosing sampling sites across the GTA. I thank Camilla Gillis-Adelman and Rebecca Gasman, our two field assistants who were of immense support during the field season. I would like to thank Dr. Laurence Packer, Dr. Sheila Colla, Katherine Odanaka and Evan Keelman from the Rehan Lab, Amanda Liczner, Genevieve Rowe, Sheila Dumesh and Thomas Onuferko for their expertise and help with identifying all of the bee specimen. I would also like to thank Junaid Khan, Kennedy Shea, Briann Dorian from the Colla Lab and all of our volunteers; Andrew Gavloski, Arvind Heer, Beatrice Romeiro, Deborah Chute, Gurpartap Sohal, Laila Fayed, Melissa Ventura, Natalie Grande, Navroop Kaur, Nilanjana Ganguli, Noor Mazari, Sebastian David, Shai Li, Ruha Imran and Victor Carvalho with all their help processing and measuring all of the bee samples.

I want to thank Vanessa Campoli who has proof read and edited all my work and has been of tremendous support during my pursuit of this degree. Finally, to my friends, my siblings and most importantly my parents I thank you for always pushing me to strive for more and for putting up with my crazy work schedule. I could not have done this without your constant and unwavering support.

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Chapter 1: Introduction

Ecosystem services have been defined as services provided by ecosystems and the species that comprise them that benefit humanity (Daily, 1997). The products of these services have been dubbed, ecosystem goods (Daily, 1997). Climate regulation, nutrient cycling and soil formation are just some of the existing ecosystem services that are not given enough recognition for the impact they have on human life (Costanza *et al.*, 1997). Pollination and food production are more obvious ecosystem services. These are all different services that are relied upon greatly by humans in our everyday life. In 2011, the global annual value of all ecosystem services provided to humans was estimated to be \$145 trillion (Costanza *et al.*, 2014).

When it comes to food production, pollinators play a pivotal role. They pollinate both wild plants and crop foods (Klein *et al.*, 2007). While a large majority of plants can self-pollinate, this is only feasible in the short term. In the long term, pollinators are needed to pollinate plants so as to maintain genetic diversity (Winfree *et al.*, 2011). A vast diversity of pollinators exists including both invertebrates and vertebrates. Main pollinators include bats, birds, spiders and insects. Pollinators are declining due to various threats. The most predominate threats are of an anthropogenic nature land use change, use of pesticides, spread of pathogens, spread of alien (non-native) species, and climate change (Winfree *et al.*, 2011; Vanbergen and the Insect Pollinators Initiative, 2013). New research is being constantly published addressing different threats to different pollinating species and trying to formulate a conservation plan.

Bees constitute the largest group of pollinators with over 20,000 species worldwide. The city of Toronto alone is home to approximately 360 species of bees (City of Toronto, 2016). The image of the honey bee has been linked synonymously with the pollinator crisis (Smith & Saunders, 2016). This species is used in agriculture due to its more generalist approach when it comes to pollination, which is of benefit for mono-crops (Klein *et al.*, 2007; vanEnglesdorp & Meixner, 2010). They are easier to manage than wild native bees, but wild bees provide an increase in crop production that cannot be easily replaced by managed bees (Klein *et al.*, 2007; Lautenbach *et al.*, 2012; Rader *et al.*, 2013). Yet, the image of the honey bee is being used to inform the public of the pollinator plight and to sway public opinion towards saving the bees. The use of the honey bee as the 'spokesperson' of bee/pollinator decline is counterproductive. Introduced honey bees compete over floral resources with wild bees and negatively impacts their fecundity and abundance

(Paini, 2004). However, urban beekeeping is on the rise and much of the pollinator conservation force is directed at managed honey bees (Colla & MacIvor, 2017).

The second chapter of this portfolio is a literature review addressing current trends in pollinator decline research. This review tackles all research published on this topic from 2007-2018. The aim of the review is to understand existing and emerging trends in this field and identify gaps in the literature where knowledge is slightly lacking. Emerging trends studied were focused on which groups of pollinators were studied, the scope of the research (which threats were given the most attention), geographic locations of studies and finally funding sources (what type of research received most funding).

The third and final chapter of this portfolio is a research study that focuses on the impacts non-native managed honey bees have on wild bees in Toronto. The purpose of this study is to highlight the extent of competition over floral resources between honey bees and wild bees in the city. In this study, abundance, species diversity, and the functional diversity of wild bees were all examined in comparison to the abundance of honey bees. The purpose of this particular research study is to gain a clearer image of honey bee impacts in urban ecosystems especially in light of the increasing inclination to urban beekeeping and the growing number of hives in the city.

This portfolio explores the topic of pollinators and the ecosystem service they provide us with extensively across both chapter two and three. It addresses how pollinator decline research is shaped, the driving forces behind it and focuses on understanding one of these threats to a greater extent. The conundrum of the honey bee is tackled in the final chapter. It is an important aspect of agriculture and is important to the pollination of monocrops; however, it has negative impacts on wild bees that are more effective and efficient pollinators. The work presented in this portfolio addresses many of the arising questions when it comes to pollinator research and more specifically wild bee research. The aim of this portfolio is to create a comprehensive study of pollinating systems that can inform and influence future conservation plans.

The culmination of work presented here is based on multiple collaborative endeavors. Chapter two is a continuation of the work a group of students had commenced a few years back; Heather Kerriso, Lynn Miller, Melina Damian and Patrick Secord. Chapter three is a large collaborative study with Sarah MacKell, MSc student. We have worked in tandem over the past year and a half on this study, sampling and analyzing collected data. The work submitted as part of this portfolio would not have been possible without them.

Chapter 2: Examining Biases and Commonalities Among Pollinator Decline Studies Over the Last Decade

2.1 INTRODUCTION

In the age of the Anthropocene, it has become increasingly apparent of the drastic effects humanity has on wildlife (Kovács-Hostánski *et al.*, 2017; Svenning *et al.*, 2016). This is an era led by human appropriation of the Earth and the ecosystem services readily available in it (Kovács-Hostánski *et al.*, 2017). It has been attributed with the defaunation phenomenon, where large numbers of species are going extinct and populations of wild flora and fauna are declining at a fast rate (Dirzo *et al.*, 2014). Regardless of what trophic level a species inhabits, loss of species of this magnitude and at this rate changes the course of ecosystem functioning and its impacts will eventually trickle down to humans (Dirzo *et al.*, 2014; Marshman *et al.*, 2019; Wagner, 2020). The decline of larger fauna, primarily mammals, have been studied greatly; however, it is the decline of smaller fauna that are not given the same attention that carry the greatest impacts (Dirzo *et al.*, 2014; Sánchez-Bayo, 2019; Wagner, 2020).

The majority of small fauna that are being impacted the most by human-driven environmental stressors are all pollinators. Pollinators provide us with an important irreplaceable ecosystem service (Ollerton *et al.*, 2017). The services provided by pollinators to humans is essential in the maintenance of global food security (Bommarco *et al.*, 2013; González-Varo *et al.*, 2013; Bailes *et al.*, 2015). Pollinators are necessary in agriculture because of their role in the production of food crops (Garratt *et al.*, 2014; Burkle *et al.*, 2017). The decline of pollinators does not only hinder the ecosystem services that benefits humanity, but also disrupts the flow of the environment and will lead to the decline of food crops, wild flora and other non-pollinating animal species (Fantinato *et al.*, 2019). The value of pollinators to both human survival and global biodiversity are reasons why the pollinator crisis is of crucial importance (Vanbergen & the Insect Pollinators Initiative, 2013; Ollerton *et al.*, 2014).

With the increasing amount of research being done on this topic, it is hard to pinpoint where the gaps in knowledge lay with a never ending list of threats and pollinators to study. The aim of this systematic review is to analyze previous research done on the topic of pollinator decline, discuss rising trends in this field with regards to key species being studied, scope of research and funding as well as pin point knowledge gaps and address biases.

2.2 METHODS

Web of Science was used as our search engine because of its standing as a global multidisciplinary database. A basic search of the terms ‘pollinator’ AND ‘decline’ as a topic was used for the year range 2007-2018. The search terms used were left as simple as possible to encompass all possible publications referring to pollinators and pollination. The results of our database search were then thoroughly analyzed and classified as valid or invalid studies based on numerous criteria. The first criterion each publication was assessed on was whether or not it was a primary research article. For the basis of this review, only primary research articles were analyzed. The second criterion used for assessment was the focus of the publication. All search results were focused on pollinators in some form or mentioned the words pollination/pollinators in the body of the text. Only those that focused on the decline of pollinators and examined the causes of decline were labelled as valid. Invalid studies were all other articles that focused on general effects of pollination or conservation of pollinators without discussing the reasons for their decline. The final criterion used to establish validity for our review was language of publication. If no English version of a publication was found or if we were unable to find a translated version, then the article was categorized as invalid.

Following the division of results into valid and invalid, all the necessary information was extracted from the valid publications and compiled into a database for this literature review. The geographic region of each study as well as if it was conducted in a lab setting, including modeling, or field setting was identified. The threats to pollinators examined in each paper were also identified. The threats that all studies were analyzed on are based off major threats to pollinator decline which are: agriculture, climate change, competition, disease, flowering disparity, fragmentation, grazing, land conversion, loss of native vegetation, nutrition, pesticides, predation, pollution and urbanization (Vanbergen & the Insect Pollinators Initiative, 2013). The species of pollinator(s) studied for each publication was classified. This required reviewing data from the supplementary documents included for most articles. Finally, a list of all funding sources for each of the articles was included in the database. Funding information was easily found in the ‘Acknowledgments’ section for most of these articles.

Once all of this information was added to the database, funding sources for the research and the species of pollinators studies were categorized in order to analyze any emerging trends

clearly. Funding plays an important role in academia; it allows for the advancement of research in different areas. Understanding where the funding behind each of these published studies is coming from, can shed light on why certain threats to pollinators are given precedence over others when it comes to research. Funding sources were categorized to one of five groups: government, independent, industry, NGO, university or unknown (Table 2.1) (Stephan, 2010). An in-depth perspective of which species are being primarily studied allows for a broader take on which species or groups of pollinators are being overlooked. Studied species were categorized to one of eight groups: managed honey bees, managed bumble bees, wild bees, insects, spiders, birds, mammals or unspecified pollinators (Table 2.2).

Table 2.1 Descriptions of funding categories.

Type of Funding Source	Description
Government	Any type of funding or bursary received through a government entity.
Independent/ Private foundations	Research councils, societies, institutes, and trusts that are unassociated with governments or universities.
Industry	Large corporations
NGO University	Funding received from non-governmental/not for profit organizations. Any type of funding received from a university, including grants and scholarships.
Unknown	Funding was not disclosed

Table 2.2 Description of pollinator categories.

Type of Studied Pollinator	Description
Bumble bees	Wild bumble bees species (including non-commercially reared <i>Bombus impatiens</i> & <i>Bombus terrestris</i>)
Managed honey bees	<i>Apis mellifera</i>
Managed bumble bees	Two species (<i>Bombus impatiens</i> & <i>Bombus terrestris</i>). Only individuals that have been commercially reared for green houses or purchased for lab/field experiments not wild caught.
Wild bees	Any non- <i>Bombus</i> wild bee species.
Insects	All other insects besides bees.
Spiders	Species belonging to the Aranaea order.
Birds	Species belonging to class Aves.
Mammals	Species belonging to class Mammalia
Unspecified Pollinators	For studies that did not disclose the species of pollinators being studied.

2.3 TRENDS IN POLLINATOR DECLINE STUDIES

Our search in Web of Science for the terms ‘pollinator’ AND ‘decline’ resulted in a total 1447 research articles for the 2007-2018 time period. Of these 1447 articles, 481 were primary research articles focused on pollinator decline and its contributing threats. The remaining 966 articles were categorized as invalid (83% topic unrelated to pollinator decline, 14.8% not primary research articles, 2.1% no access and 0.1% not available in English). Studies that were invalid due to unrelated topics focused on foraging behavior, pollinator efficacy, pollination value, bee diversity, plant interactions, crop production among other similar topics.

2.3.1 Threats to Pollinators

With the increasing awareness of the pollinator crisis, a steady stream of research has been focused on this topic. There is an upwards trend of research published focused on threats to pollinator communities and possible mitigation tactics (Fig. 2.1). Our dataset shows 15 threats that are widely studied (Fig. 2.2). An analysis of the dataset indicates that there are different emerging trends when it comes to threats to and causes of pollinator decline being studied (Fig. 2.3)

Land Use Change and Correlated Threats

Land use change is a leading threat to pollinators (Sala *et al.* 2000, Winfree *et al.* 2009). Land use change threatens the availability of floral resources and nutrition for pollinators (Kearns & Inouye, 1997). In addition, land use changes impact the availability of habitats to pollinators (Kearns & Inouye, 1997; Winfree, 2010; Cameron & Sadd, 2019). Multiple threats can be grouped together underneath the umbrella of land use change. This umbrella would mainly encompass agriculture, fragmentation, land conversion and urbanization. For the purpose of this review, we have included loss of native vegetation and grazing as additional threats (Kearns & Inouye, 1997). The combination of these threats account for 44.48% of our reviewed research articles. Land use changes are the largest studied threats when it comes to pollinator decline due to the high impact this anthropogenic threat has on a wide variety of pollinator species and the implications on habitat availability.

Agricultural intensification makes up the largest proportion of land use change threats studied. While agriculture and crop food production is necessary, it has become apparent that our agricultural practices are not compatible with maintaining pollinator diversity (Kremen *et al.*, 2002; Burkle *et al.*, 2017). A large number of emerging studies examine how some forms of land use changes are causing certain pollinators to thrive. Namely, urbanization has been shown to support some species of wild bees and has shown an increase in abundance of these species (Cane *et al.*, 2006; Winfree *et al.*, 2007). The increasing number of green spaces as well as the planting of more native wild plants is attracting some pollinators to urban and suburban areas. While land

use change accounts for most of pollinator decline, a proportion of pollinating species are thriving in urban areas (Winfree *et al.*, 2007).

Pesticides

Pesticides play a large role in agriculture and hence are linked to food security (Stokstad, 2013). Pesticides (primarily insecticides) as threats to pollinators account for 27% of our reviewed papers. A focus on this topic is to be expected with the role pollinators play when it comes to food crop production. Studies focused on pesticides as a threat mainly examined effects of neonicotinoids and organophosphates. Neonicotinoids are the largest class of pesticides used in agriculture (Jeschke, 2010; Blacquière *et al.*, 2012). Pesticides have been of growing concern due to their wide use in agriculture and in retrospect their highly negative impacts on pollinators. Effects of pesticides have been extensively researched on arthropod pollinators. At the individual level, pesticides have been known to impact the behavior, development and physiology of arthropods (Thompson, 2003; Desneux *et al.*, 2006; Cameron & Sadd, 2019). Behavioral changes resulting from exposure to pesticides include changes in foraging activity (Thompson, 2003; Desneux *et al.*, 2006; Blacquière *et al.*, 2012). At the community level, sublethal effects of neonicotinoids are known to affect reproduction of both managed and wild bees while lethal dosages have resulted in the death of bees (Desneux *et al.*, 2006; Blacquière *et al.*, 2012; van der Suijls *et al.*, 2013; Cameron & Sadd, 2019).

Parasites and Pathogens

Parasites and Pathogens were the third most examined threat at 12.47% of examined studies. The most studied parasites and pathogens were found to be *Crithidia bombi*, Deformed Wing Virus (DWV), *Nosema apis*, *Nosema bombi*, *Nosema ceranae*, and *Varroa destructor*. These specific parasites/pathogens are the most commonly studied, because they infect either bumble bees or honey bees which are the most studied groups of pollinators. Due to the surmounting cases of colony collapse disorder (CCD) in the late 2000s and the role parasites and pathogens played in

it, most of our reviewed studies have been focused on honey bee pathogens (vanEgelsdorp *et al.*, 2009). In addition, the focus on honey bee parasites/pathogens can be attributed to the role these managed pollinators play in agriculture and their subsequent economic value (Kearns & Inouye, 1997). Managed bees (both honey bees and bumble bees), have been known to be sources of pathogen spillover into wild bee populations (Mallinger *et al.*, 2017; Colla *et al.*, 2006; Cameron & Sadd, 2019; Pereira *et al.*, 2019).

Climate Change

Climate change is a growing global concern. The impacts of this threat can be felt across all levels of the biosphere (Sala *et al.*, 2000). Climate change has resulted in species range shifts and mismatches between flowering time and emergence of arthropod pollinators (Hegland *et al.*, 2009; Marshman *et al.*, 2019). Range shifts are driving specialized pollinators out of their habitat and they are getting replaced by more generalist pollinators, which will limit the ecosystem services provided by pollinators (Bartomeus *et al.*, 2014; Sánchez-Bayo & Wyckhuys, 2019). Only 6.03% of our reviewed research articles focused on climate change as the primary threat to pollinators. However, 9.77% of reviewed articles did mention climate change as a threat to pollinators but did not examine it as the primary threat. By extrapolating the climate change trendline (Fig. 2.3), it can be seen that this threat is slowly on the rise in terms of pollinator decline studies. While climate change is globally recognized as an anthropogenic threat to all biomes (Sala *et al.*, 2000); however, it has not been given the same degree of importance when it comes to pollinator decline studies. Our analysis does show though, that this topic is being increasingly studied as of 2017 (Fig. 2.3).

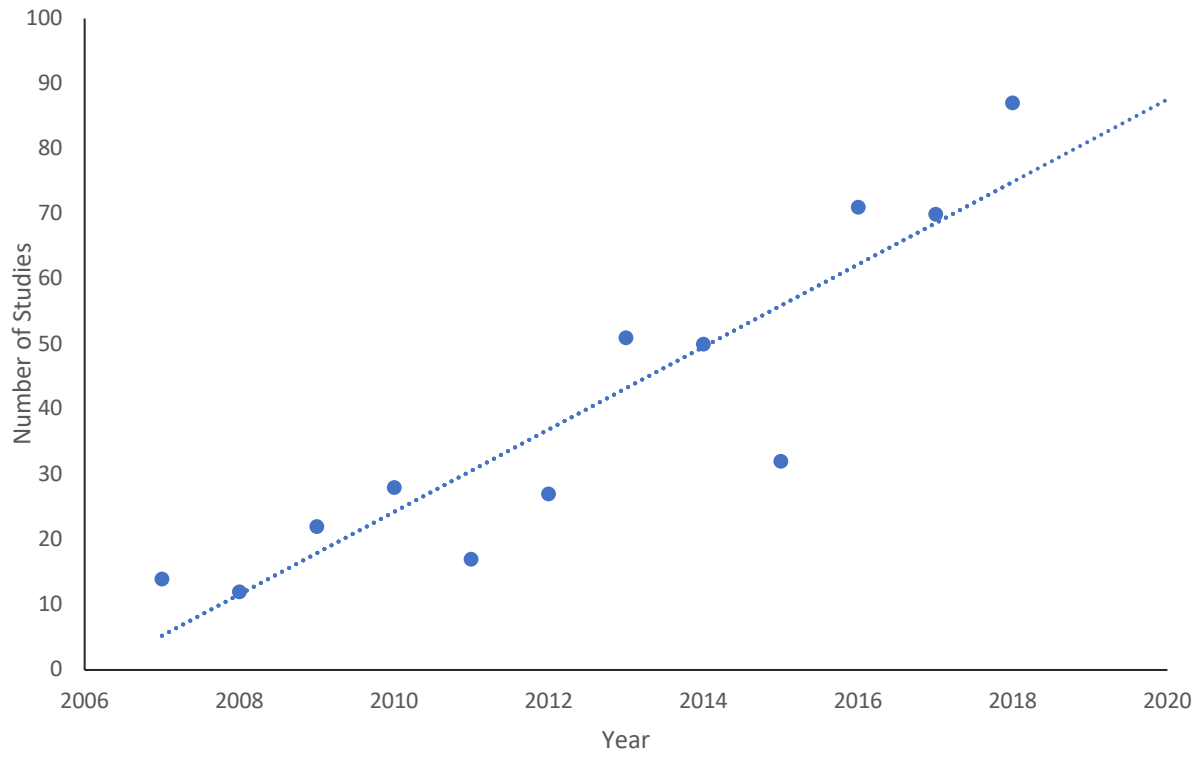


Figure 2.1 Number of pollinator decline studies used in this study per year from 2007-2018. Forecast trendline shows that number of studies published about pollinator decline will continue to increase. (N = 481)

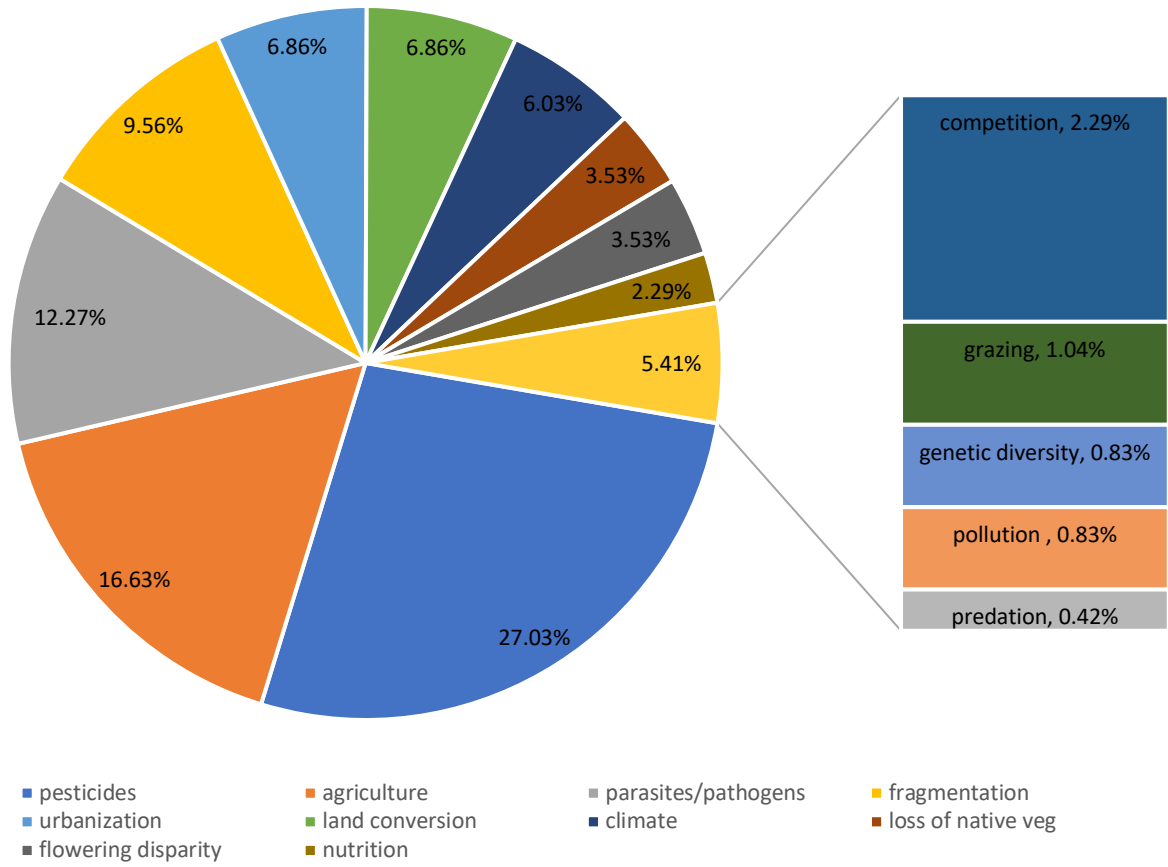


Figure 2.2 Pie chart depicting main threats to pollinators studied. (N = 481)

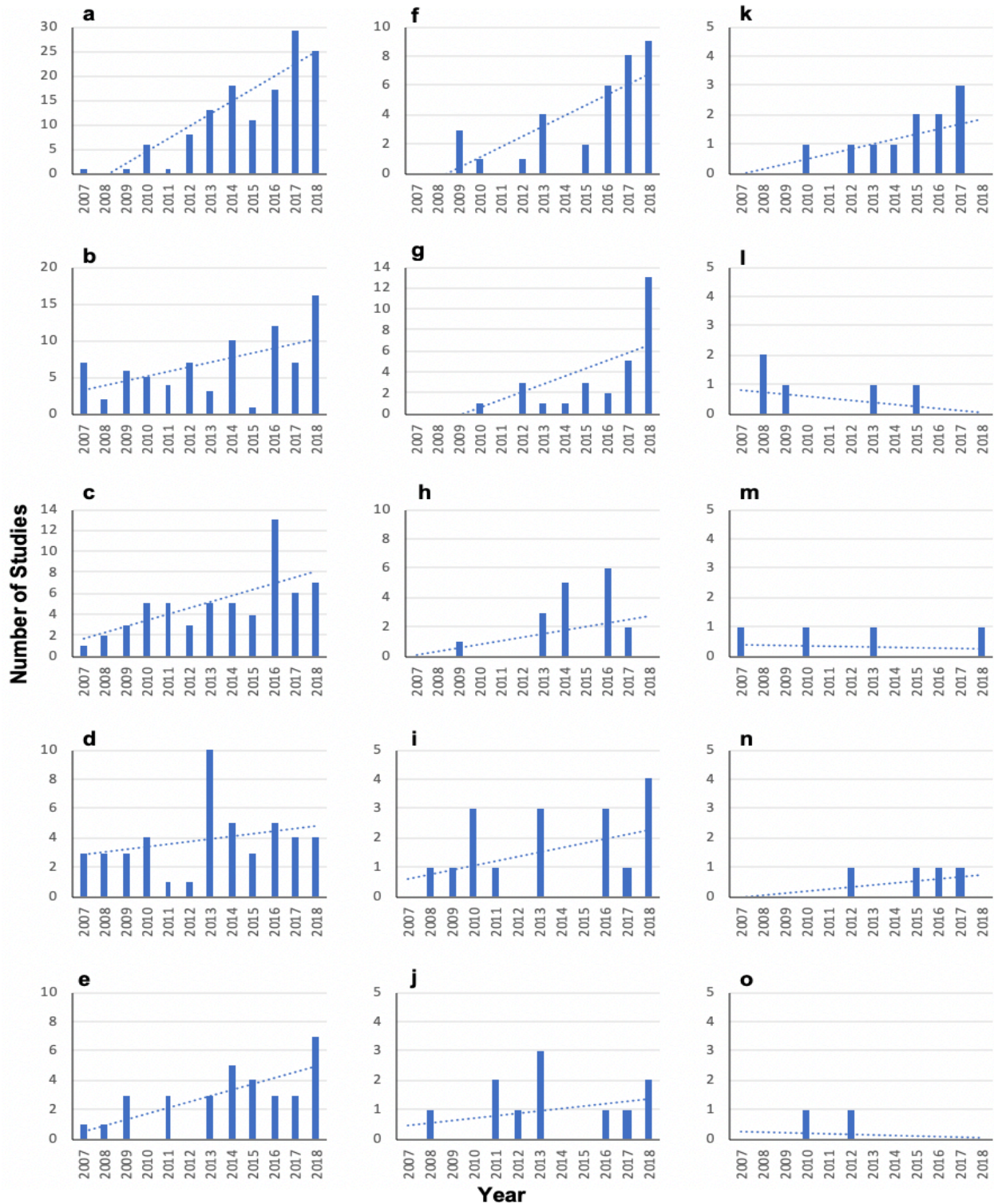


Figure 2.3 Breakdown of number of studies published per year for individual threats. a) pesticides (N = 130) b) agriculture (N = 80) c) parasites and pathogens (N = 59) d) fragmentation (N = 46) e) urbanization (N = 33) f) land conversion (N = 33) g) climate change (N = 29) h) loss of native vegetation (N = 17) i) flowering disparity (N = 17) j) nutrition (N = 11) k) competition (N = 11) l) grazing (N = 5) m) genetic diversity (N = 4) n) pollution (N = 2) o) predation (N = 2). Linear trendline depicts changes in trends for each of the studied threats over time.

2.3.2 Geography and Pollinator Decline Studies

A map of geographic locations for all studies analyzed for this review shows that most research is clustered in North America and Europe (Fig. 2.4). A geographic bias such as this implies that pollinator decline research so far is not comprehensive and cannot speak to all pollination systems (Archer *et al.*, 2014). Most research on the decline of pollinators is focused in temperate regions, even though the tropics are more pollinator diverse (Viana *et al.*, 2012). Data regarding pollinator decline and threats are often generalized when it comes to conservation plans (Archer *et al.*, 2014; De Palma *et al.*, 2016). Conservation plans for pollinator communities benefiting the global North will not necessarily have the same outcome in the global South. Community composition of pollinators depends on geographic location. The functional traits possessed by the community determines how they will respond to environmental stressors (Williams *et al.*, 2010; Archer *et al.*, 2014; De Palma *et al.*, 2016). The effects of the pollinator crisis will be disproportionately felt across the world, especially in the global south. The global South is also the region most dependent on animal pollination for food security (Aizen *et al.*, 2009; Gallai *et al.*, 2009). The South, mainly tropical regions, are 50% more dependent on animal pollination for food production than the North and they are losing these native pollinators at a faster rate (Ricketts *et al.*, 2008; Aizen *et al.*, 2009). The loss of native pollinators puts the South's agriculture and food security at risk (Aizen *et al.*, 2009).

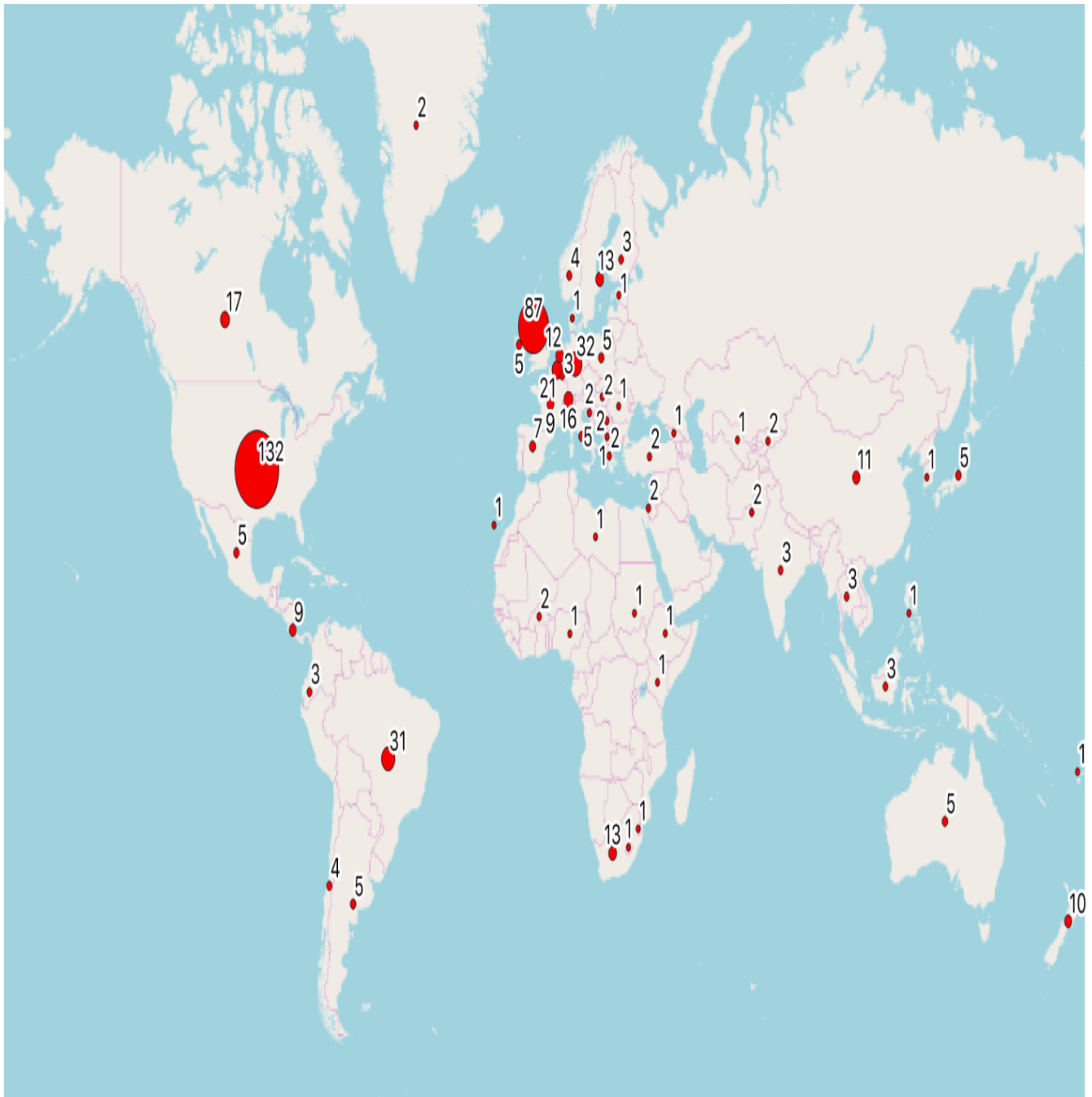


Figure 2.4 Map of origination of studies. Size of red markers reflects relative amount of studies published and numbers denote the number of studies published per country.

2.3.3 Funding, Pollinators and Research Scopes

Funding plays an important role in regard to the type of research being performed. It influences research in terms of where the research is occurring, what is being studied, and the questions that are being asked (Stephan, 2010; De Palma *et al.*, 2016). Most of the studies evaluated for this review received funding from multiple types of funders; only 9% of the research papers did not disclose anything with regards to funding (Fig. 2.5). Government entities are the largest funders of research, our review indicates that 64% of all studies are either fully or partially funded by government sources (Fig. 2.5) (Stephan, 2010).

Managed honey bees are the pollinating group receiving the greatest amount funding across most funding types, followed closely by wild bees and bumble bees (Fig. 2.6). Funding disbursements reflect pollinator demographics, where bees make up the largest proportion of pollinators (Winfree, 2010). A look at how pollinating groups studied has changed over time, shows that either bumble bees or wild bees have predominantly been the most studied groups until 2013 (Fig. 2.7). Starting 2013, a trend towards more managed honey bee focused studies emerges. This trend ends in 2018, when the number of studies published on the decline of wild bees surpasses that of managed honey bees. Not many studies have focused on the decline of pollinating birds and mammals (compromised of mainly bat species). A look at the 15 most studied pollinator species shows that *Apis mellifera*, the managed honey bee, is the most commonly studied species followed by various bumble bee species (*Bombus*) and two sweat bee species (*Lasioglossum* and *Halictus*) (Fig 2.8).

The breakdown of funding sources and threats to pollinators studied (Fig. 2.9) shows the research receiving most funding pertains to pesticides, agriculture and parasites/pathogens across all five funding groups. Currently, it is hard to pinpoint whether funding has impacted the research direction or if the large interest in these topics resulted in more funding. All three of these threats can be traced back to the agricultural sector and managed honey bees. Managed honey bees, even though non-native to various parts of the world, have been introduced globally as managed pollinators to aid in crop production. The production of food crops is the driving force of agriculture and important to the food security of all communities across the globe (Bommarco *et al.*, 2013; Potts *et al.*, 2016; Marshman *et al.*, 2019). Pesticides are widely used throughout

agriculture to maintain crops through weed and pest management in addition to protection against crop diseases (Aktar *et al.*, 2009).

It is apparent that studies focused on managed honey bees and agriculture, parasites/pathogens and pesticides are most favored when it comes to funding opportunities. However, that does not imply that other pollinators and threats to pollinators are of less importance. This simply shows that current pollinator decline studies are merely focused in one direction that benefits the agricultural sector and in turn managed honey bees; however, they should be diversifying more and examining all anthropogenic threats to all species of pollinators more in depth.

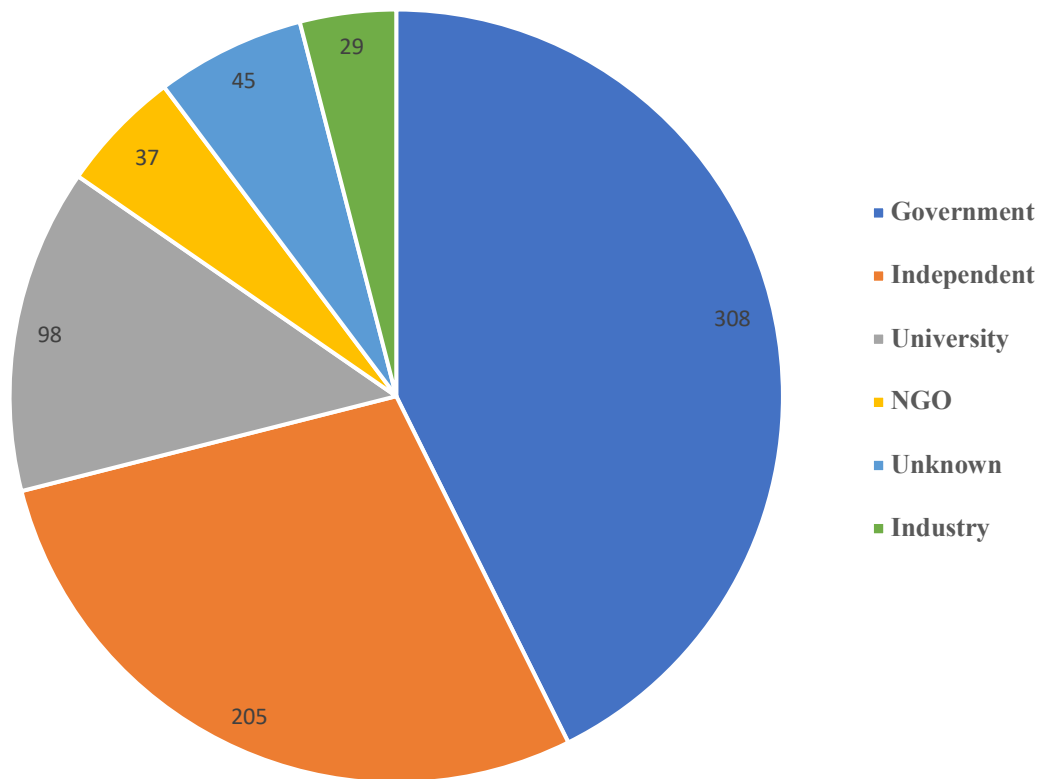


Figure 2.5 Pie chart depicting number of studies funded by each funding group. (N=481)

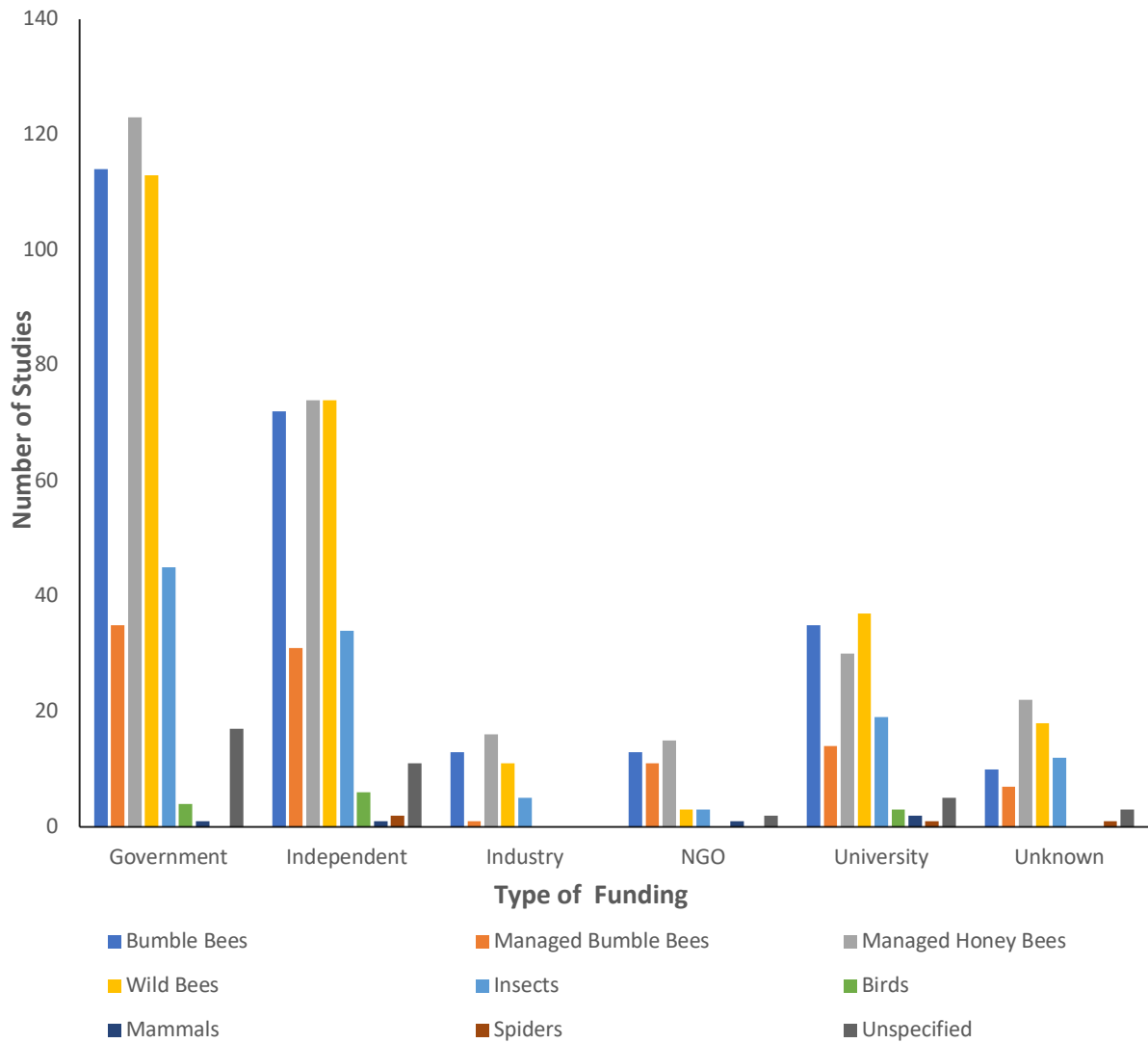


Figure 2.6 Number of studies funded by each group for the eight pollinating categories. (N=481)

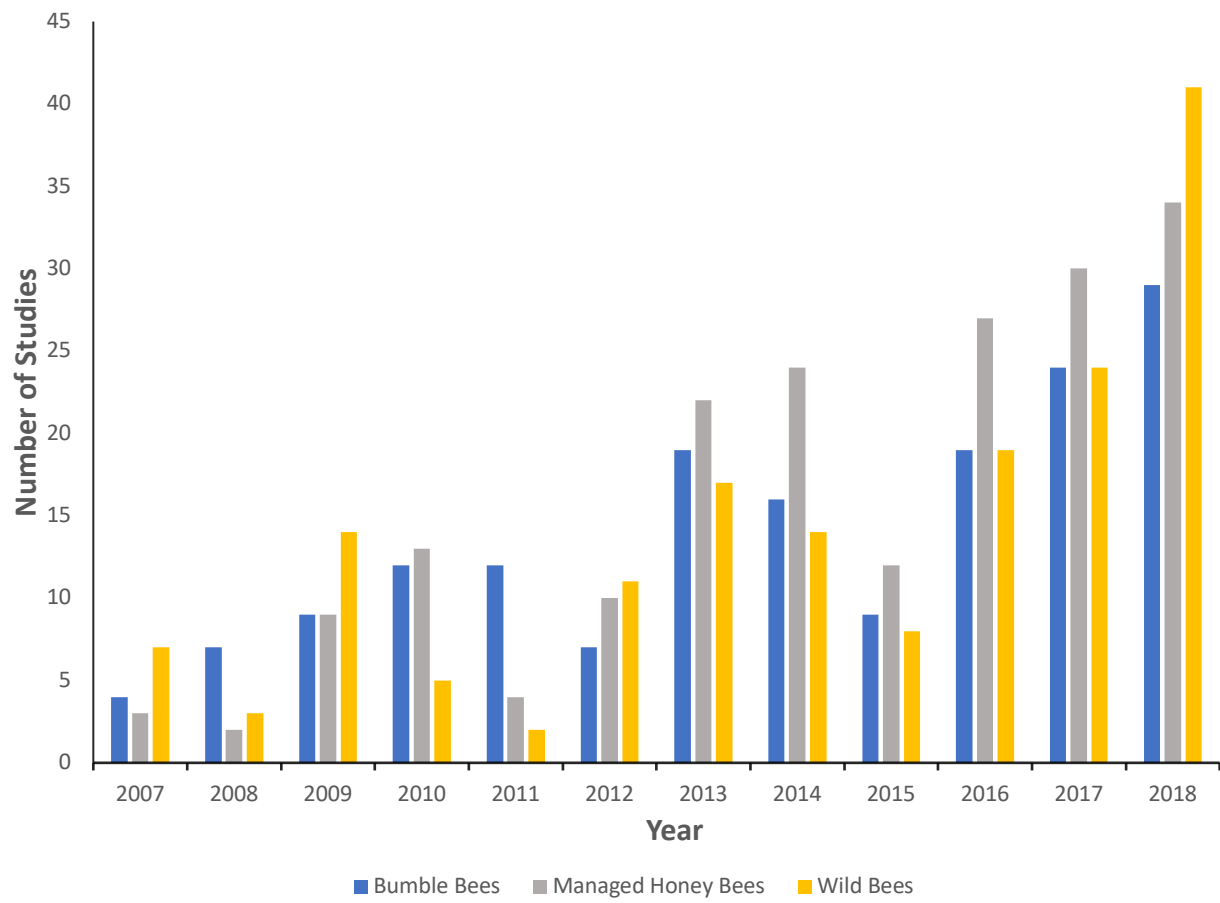


Figure 2.7 Number of studies per year focused on the top three pollinating groups that received the most funding. (N = 373)

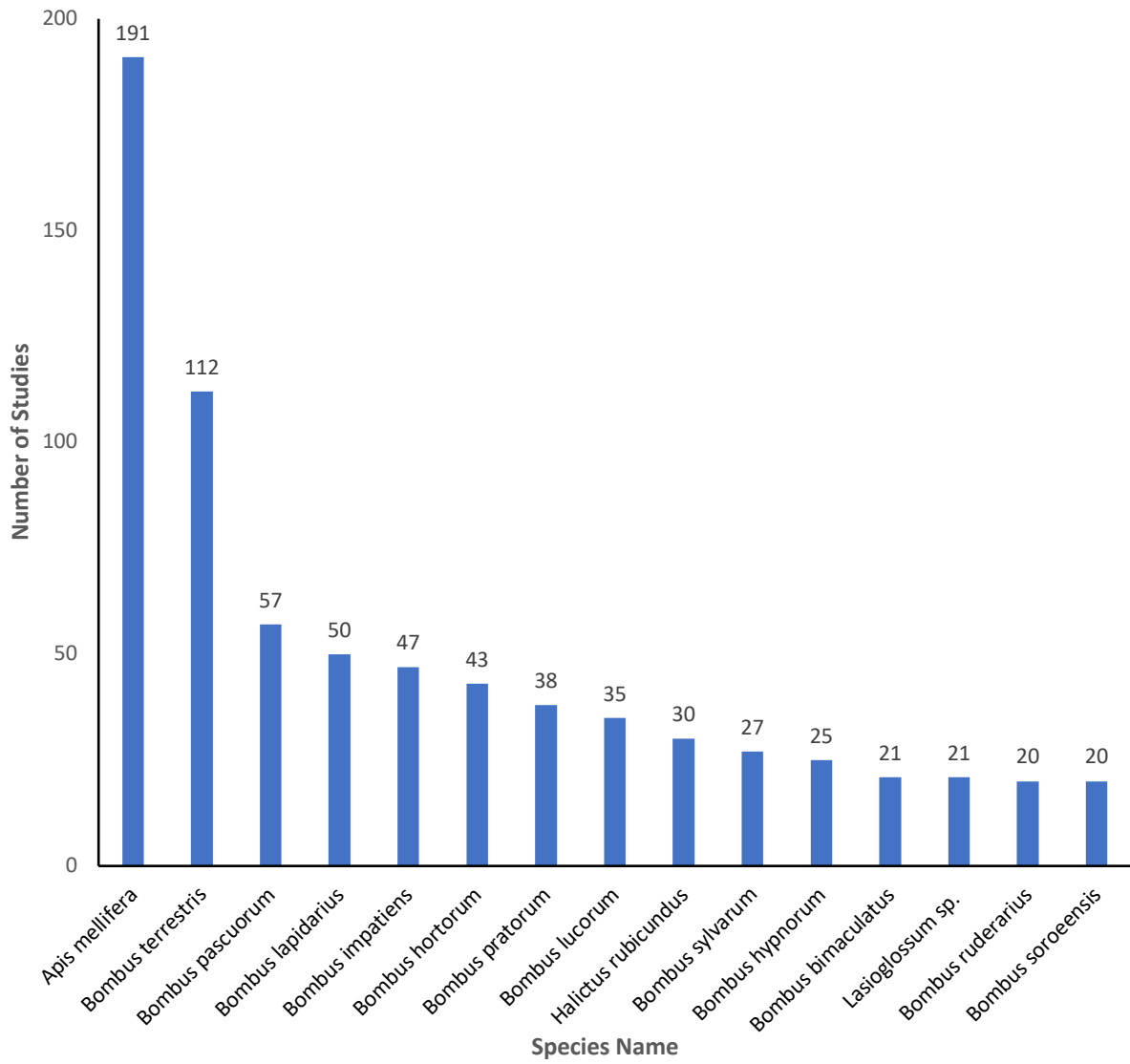


Figure 2.8 Top 15 pollinating species studied.

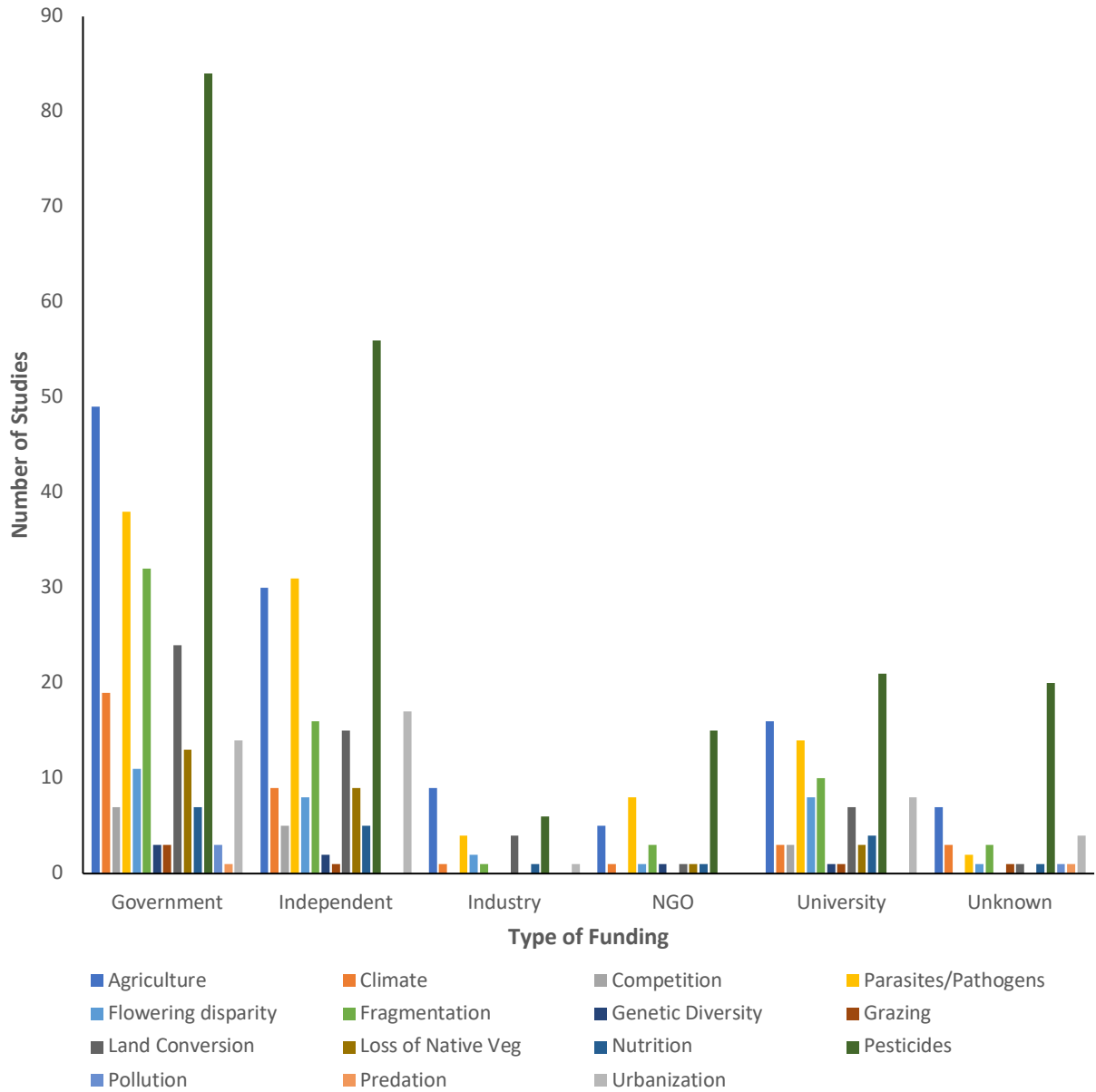


Figure 2.9 Number of studies funded by each group for all 15 threats to pollinator decline. (N=481)

Table 2.3 Summary of gaps in pollinator decline research.

Area of Research	Current State	Research Gap
Threats to pollinators	Research is largely focused on threats related to land use change, more specifically threats pertaining to the agricultural sector.	Numerous threats to pollinators exist including climate change and competition. A focus on a selected group of threats only does not paint a clear picture of pollinator decline and how pollinators are responding to these different anthropogenic threats..
Geography	Research is concentrated in North America and Europe.	Not much research is conducted in the Global South, especially the tropics. Tropical regions contain the largest diversity of pollinators and will feel the effects of pollinator decline disproportionately from temperate regions due to their increased reliance on animal pollination for food security.
Studied Species	Most research is focused on managed honey bees (<i>Apis mellifera</i>) and bumble bee species (<i>Bombus</i>).	While insects are the largest group of pollinating animals, only a few bee species are given the bulk of research focus. Not many bird, mammal or other arthropod species are studied.

2.4 CONCLUSIONS

Our review of pollinator decline research has revealed various gaps in knowledge (Table 2.3). While there are numerous threats to pollinators, it is apparent that threats given the most attention are those related to agriculture. Agriculture plays an important role in food crop production and maintaining food security (Bailes *et al.*, 2015; Potts *et al.*, 2016). However, this large disproportionality in funding disbursements reflects the inclination towards more economically gainful studies when it comes to pollinator conservation (Gallai *et al.*, 2009). Furthermore, clustering of studies in the global North versus the global South reveals a geographic bias in terms of pollinator decline studies. There exist apparent biases in pollinator decline research when it comes to funding opportunities, research focus and pollinating species. A shift away from managed honey bees and the agricultural sector towards other pollinating species and anthropogenic threats is needed to understand the complexity of the pollinator crisis. These biases must be accounted for and corrected in future research, so as to preserve the biodiversity of pollinators and the ecosystem services they provide.

The data sheets for this review can be accessed here:

https://docs.google.com/spreadsheets/d/1OtNT_cDRUw62aY3j1FwUF3BCzpL9e08FAKtupWErMVE/edit?usp=sharing

Chapter 3: The Effect of Honey Bee (*Apis mellifera*) Abundance on the Functional Diversity of Wild Bees in Urban Ecosystems

3.1 INTRODUCTION

Ecosystem services play a large role in the well-being of the human population both directly and indirectly (Costanza *et al.*, 1997). Pollination is an ecosystem service that is relied upon directly for food production, global economic growth and hence entwined with human survival (Costanza *et al.*, 1997; Costanza *et al.*, 2014; Lautenbach *et al.*, 2012). Animal pollinators are necessary for the production of many wild plants as well as crop plants (Klein *et al.*, 2007; Ollerton *et al.*, 2011; Lautenbach *et al.*, 2012). Approximately 85% of all flowering plants and 75% of all food crops are animal pollinated (Klein *et al.*, 2007; Ollerton *et al.*, 2011; Bartomeus *et al.*, 2014). This percentage of food crops accounts for roughly \$361 billion of the world economy (Lautenbach *et al.*, 2012). The ongoing pollinator crisis impacts have many potential rippling negative effects on the human population through threats to global food security and the economy (Ghazoul, 2005).

Insects make up the largest group of animal pollinators. However, pollinators are rapidly declining (Potts *et al.*, 2010). While urbanization and loss of habitat are drivers of pollinator decline, it has recently become apparent that cities are harbors for diverse pollinator communities (Hall *et al.*, 2016). The increased prevalence of green spaces in urban landscapes has acted as a refuge for insect pollinators, especially bees (Hall *et al.*, 2016; Wenzel *et al.*, 2020). The pollination crisis has led to the decline of several species from their native range (Ollerton *et al.*, 2014). This crisis is driven by several factors with climate change (which impacts flowering time), pesticides, and land use intensification being at the forefront (Kremen *et al.*, 2002; Potts *et al.*, 2010). The combination of these factors makes it highly unpredictable to forecast how much crops the agricultural sector will be able to produce yearly. For this reason, the managed honey bee (*Apis mellifera*) has become the face of crop pollination because it has been introduced worldwide to support and supplement services in farming (Potts *et al.*, 2010; Breeze *et al.*, 2011). Honey bees are non-native to North America; however, due to their generalist pollination behavior they have been introduced for intensive crop pollination service and for the production of honey (Goulson, 2003; vanEnglesdorp & Meixner, 2010).

The introduction of non-native species into an ecosystem increases pressure on the native inhabitants of the ecosystem. The introduction of honey bees to North America has brought about the spread of diseases to wild bee populations and has increased competition over resources (Goulson, 2003; Thomson, 2006; Potts *et al.*, 2010; Mallinger *et al.*, 2017). The spread of diseases caused by introduced honey bees in wild bee populations has been studied in depth. Non-native honey bees have been negatively associated with wild bee diversity (Badano & Vergara, 2011; Mallinger *et al.*, 2017); however, this may be subjective to the abundance of honey bees in the area, availability of resources as well as other landscape factors. Lack of floral resources or limited availability of floral resources has been shown to impact species diversity in a given community (Mallinger *et al.*, 2017; Cameron & Sadd, 2019). They are also known to skew sex ratios in bees. The quantity and quality of pollen provided to developing eggs determines production of males and females. Female eggs require a larger quantity of more nutritional pollen compared to the males (Kapheim *et al.*, 2011). In cases of low resource availability, it is easier for bees to produce males (Kapheim *et al.*, 2011; Fitch *et al.*, 2019). Male bees are known for long distance foraging while females tend to forage in close proximity to nest sites while spending more time per flower increasing their pollinator efficiency (Ne'eman *et al.*, 2006; Fitch *et al.*, 2019). Populations with skewed sex ratios towards more males may result in negative impacts on pollination services in the long term.

When cataloguing the diversity of an ecosystem, species diversity has been considered the standard method with which to do so (Forrest *et al.* 2015). Recently, it has become apparent that species richness is not the best way to define the ecological standing of an ecosystem because it is a poor predictor of ecosystem functionality (Schleuter *et al.* 2010; Forrest *et al.* 2015; Gagic *et al.*, 2015). Assessing the diversity and abundance of functional traits rather than species is viewed as a better indicator of overall ecosystem health and productivity (Schleuter *et al.* 2010). Functional diversity focuses on what different organisms contribute to their ecosystem while accounting for complementary traits and overlapping species' ranges (Schleuter *et al.* 2010). A study of functional diversity in a shrubland ecosystem shows that increased presence of honey bees resulted in the presence of less generalist wild bees (Valido *et al.*, 2019).

With increased urbanization and a global movement towards city structures, it has become apparent that bees and other pollinators must adapt to making urban landscapes their homes (Hall *et al.*, 2016). The Greater Toronto Area (GTA) is an example of a large urban area that is home to

both the managed non-native honey bee as well as many wild bee species. In this study, I will be examining how the abundance of honey bees in the GTA is impacting the functional diversity of wild bee populations. In addition, I will be looking at how the abundance of honey bees, floral diversity and floral density are impacting species diversity and if these factors are skewing the sex ratios of wild bees. The functional diversity of wild bees within a designated area evaluates all unique traits within the community (Scheiner *et al.*, 2017; Sydenham *et al.*, 2015). Evaluating the functional diversity of wild bee communities within the GTA will result in a clearer understanding of honey bee effect on wild bee diversity. Although honey bees are used widely for their pollination potential, in the long term increased use of these managed bees will potentially decrease overall pollination due to their impacts on wild bees (Mallinger *et al.*, 2017).

3.2 METHODS

3.2.1 Site Selection

To adequately assess the impacts of honey bee abundance on wild bee populations, five high honey bee abundance sites and five corresponding low abundance sites were chosen throughout the GTA (Table 3.1). High abundance sites were characterized as sites containing 5 or more hives within a 2 km radius. Since it is hard to select sites that have no honey bees present in the city due to the vast introduction of honey bees, low abundance sites were chosen based off of distance away from honey bee hives (Valido *et al.*, 2019). Low abundance paired sites were 2-5 km away from high abundance sites (Fig. 3.1) and characterized as having no known hives.

Table 3.1 High honey bee abundance sites and their paired low abundance sites. Number of honey bee hives noted for each site are the number of reported (registered) hives.

Low Abundance Sites			High Abundance Sites		
Site Name	Abbreviation	Number of Hives	Site Name	Abbreviation	Number of Hives
Centennial Park	CP	0	Etobicoke Creek Trail (near Pearson Int'l Airport)	ECT	≥ 25
Northwood Park	NP	0	Downsview Park	DP	≥ 20
Wanita Park	WP	0	University of Toronto Scarborough	UTSC	10
Serena Gundy Park	SGP	0	Toronto Botanical Gardens	TBG	5
G Ross Lord Park	GRL	0	Maloca Gardens, York University	MG	5

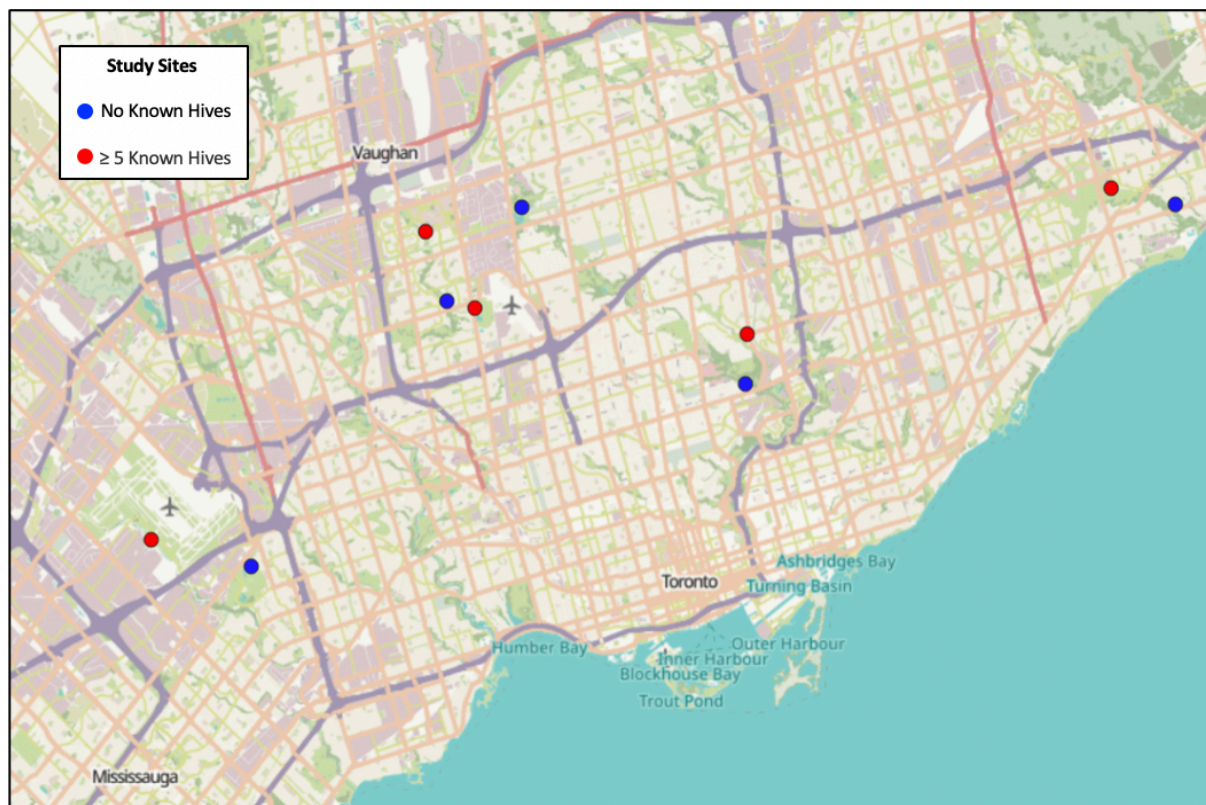


Figure 3.1 Map of paired high and low abundance honey bee study sites throughout the GTA.

3.2.2 Bee Sampling

Sites were surveyed during peak pollinator season, early May to late August, to obtain a comprehensive sample of all available wild bees in the city (Valido *et al.*, 2019). Each site was sampled once a week for the duration of this period. A combination of both pan trapping and sweep netting was utilized to gain a clear picture of bee abundance and diversity (Prado *et al.*, 2017; Prendergast *et al.*, 2020). At each of the ten sites, pan traps were set out once a week for an 8 hour duration (8AM-4PM). A total of 30 small pan traps (96 mL) coated in fluorescent paint (blue, white and yellow) (New Horizons Support Services, Upper Marlboro, Maryland, USA) were filled two-thirds of the way with soapy water (Prendergast *et al.*, 2020). Pan traps were evenly spaced out at each site along a 30 m path with 1 m separating each pan trap. Ten pan traps of each of the three fluorescent colors were used at every site for equal representation of colors visible to pollinators (Prado *et al.*, 2017), colors were alternated to maintain consistency. Sweep netting

occurred for thirty minutes three times a day, when pan traps are first set out in the morning, midday and at the end of the day before pan traps are collected.

3.2.3 Specimen Processing and Trait Measurements

Bees caught in the field were frozen and returned to the lab for processing. Each collected bee was thawed and then rinsed to remove any residue left behind from the soapy water of the pan traps. Bees were then pinned, labelled and given a unique specimen number, which was then entered into the lab database. All bees were then sexed (male or female), identified to the species level and verified by experts in the field to ensure the validity of identification.

To get a clear picture of functional diversity in an urban ecosystem, data pertaining to nine functional traits relating to life-history have been compiled for each of the collected species (Table 2) (Forrest *et al.*, 2015; Normandin *et al.*, 2017; Sydenham *et al.*, 2016). Body size measurements for functional diversity are composed of head width and tegular distance (TD) for abdomen width using a digital Vernier caliper (Forrest *et al.*, 2015; Sydenham *et al.* 2017).

3.2.4 Floral Density and Diversity

Floral density and diversity were measured biweekly for the duration of the field season. This was done by quadrant sampling. A 0.58 m² quadrant was thrown randomly ten times along an 8 m transect across our pan trap line. The 8 m transect accounts for floral vegetation present at the edges of the pan trap line as well as for dense vegetation that could not be traversed. For each quadrant, the number of open flowers for each distinct species was counted. More commonly known plant species were identified in the field and plants that we were unable to identify in the field had pictures taken of them that were later submitted into iNaturalist for help with identification. The identifications given through iNaturalist will then be verified through field guides.

Table 3.2 Life history traits used for functional diversity analysis.

Trait	Trait Type	Categories	Data Source
Body Size	Continuous		Mean tegular distance and mean head width of collected specimen
Tongue Length	Categorical	Short, Medium, Long	Normandin <i>et al.</i> , 2017; Fortel et al. 2014
Lecty (diet)	Categorical	Oligolectic, Polylectic, Cleptoparasitic	Normandin <i>et al.</i> , 2017
Generations per year	Categorical	Univoltine, Bivoltine	Mitchell, 1960; Mitchell, 1964; Michener, 2000
Sociality	Categorical	Solitary, Eusocial, Cleptoparasitic	Packer <i>et al.</i> , 2007; Fortel et al. 2014; Normandin et al., 2017
Seasonality	Categorical	All season, Spring, Summer, Fall, Spring & Summer, Summer & Fall	Normandin <i>et al.</i> , 2017; Forrest <i>et al.</i> , 2015
Type of nesting site	Categorical	Above-ground, Below-ground, Cleptoparasitic	Packer <i>et al.</i> , 2007
Nest Building	Categorical	Excavate, Rent, Cleptoparasitic	Mitchell, 1960; Mitchell, 1964; Michener, 2000; Forrest et al., 2015
Pollen Strategy	Categorical	Corbiculae, Legs, Abdomen	Mitchell, 1960; Mitchell, 1964; Michener, 2000

3.2.5 Data Analysis

Data Analysis reflects both analysis that have been completed and analysis that will be completed in the near future and are further elaborated on in section 3.5 Next Steps.

Bee Abundance

A quasi-poisson generalized linear model (GLM) to account for overdispersion of data was run to analyze the relationship between number of native bees, floral diversity, floral density and relative abundance of honey bees (Osorio-Canadas *et al.*, 2018).

Genus Diversity

A principal component analysis (PCA) was run to account for any associations between relative abundance of honey bees and genus level diversity within communities.

Body Size

A multivariate regression was used to analyze how body size (thorax width and head width) of native bees was impacted by relative abundance of honey bees. Only species with over 50 specimens collected have been studied for impacts on body size, to ensure there is a large enough dataset and that any trend seen will be significant.

Species diversity

We will be using Shannon's diversity index (H) and Simpson's (D) to account for species diversity within populations at individual sites taking into account both abundance and evenness (Ramirez *et al.*, 2015). Fisher's α will be used as a measure of species richness within these communities (Forrest *et al.*, 2016).

Functional Diversity

The functional traits will be assessed on three different indices using the FD package in R: functional richness (FR), functional evenness (FE) and functional divergence (FD) to obtain a clearer picture of functional diversity within the ecosystem (Schleuter *et al.*, 2010). Each of these three indices is available as a one dimensional and multidimensional index (Schleuter *et al.*, 2010). For the purposes of this study the multivariate approach will be taken, as it will be able to indicate the overall difference in trait diversity across all ten sites (Schleuter *et al.*, 2010; Forrest *et al.*, 2015). Categorical life history traits will be assessed using functional dispersion to accurately measure functional diversity (McCravy *et al.*, 2019; Schleuter *et al.*, 2010).

Sex Ratios

Observed sex ratios will be calculated simply by dividing overall number of females at one site by the total number of bees collected there (Fitch *et al.*, 2019). To factor in how floral density, floral diversity and abundance of honey bees is affecting this ratio GLMs will be used (Fitch *et al.*, 2019).

3.3 PRELIMINARY RESULTS

3.3.1 Bee Abundance

Over the course of the four-month field season, a total of 9,389 bees were collected across the ten sites comprising 32 different genera (Fig. 3.2). Honey bees comprised the largest proportion of our samples at 19.43% of total collected specimens. Relative abundance of honey bees was calculated for each site by dividing total number of honey bees by total number of bees collected at that site. This shows that honey bees species are far more prevalent at our chosen sites than previously anticipated (Fig. 3.3).

The quasipoisson GLM resulted in a negative relationship between number of wild bees and relative abundance of honey bees ($p < 0.01$) (Fig. 3.4). The GLM showed no significant relationship between the number of wild bees and floral density ($p = 0.98$) or floral diversity ($p = 0.77$).

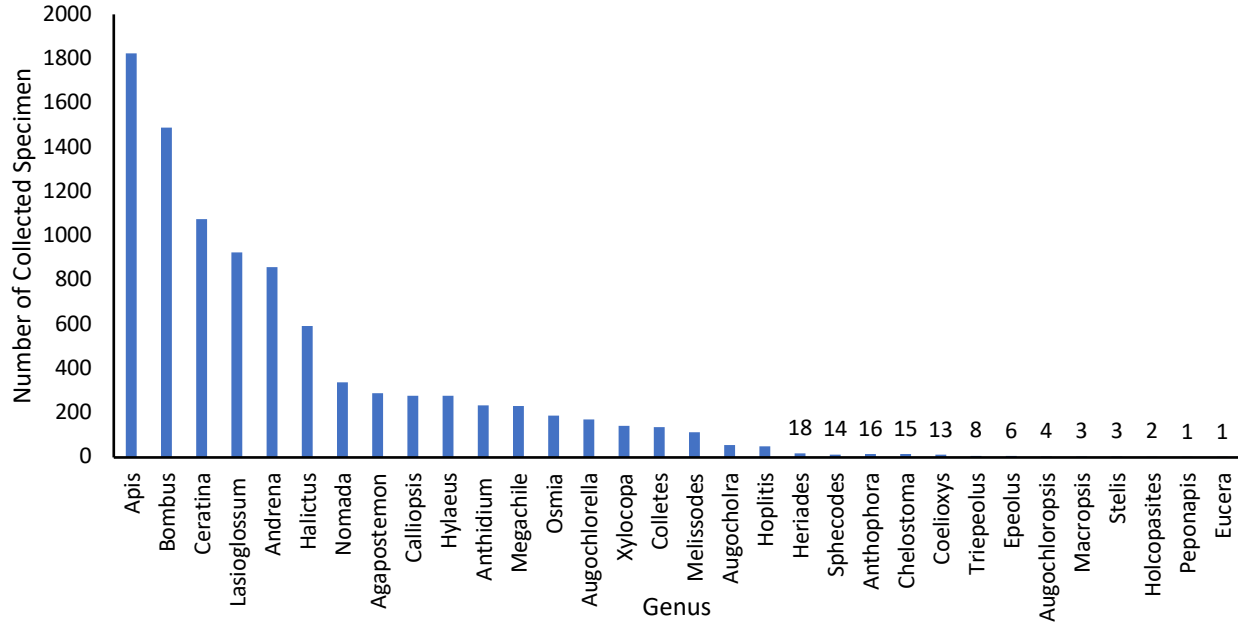


Figure 3.2 Breakdown of collected bee genera. (N = 9,389)

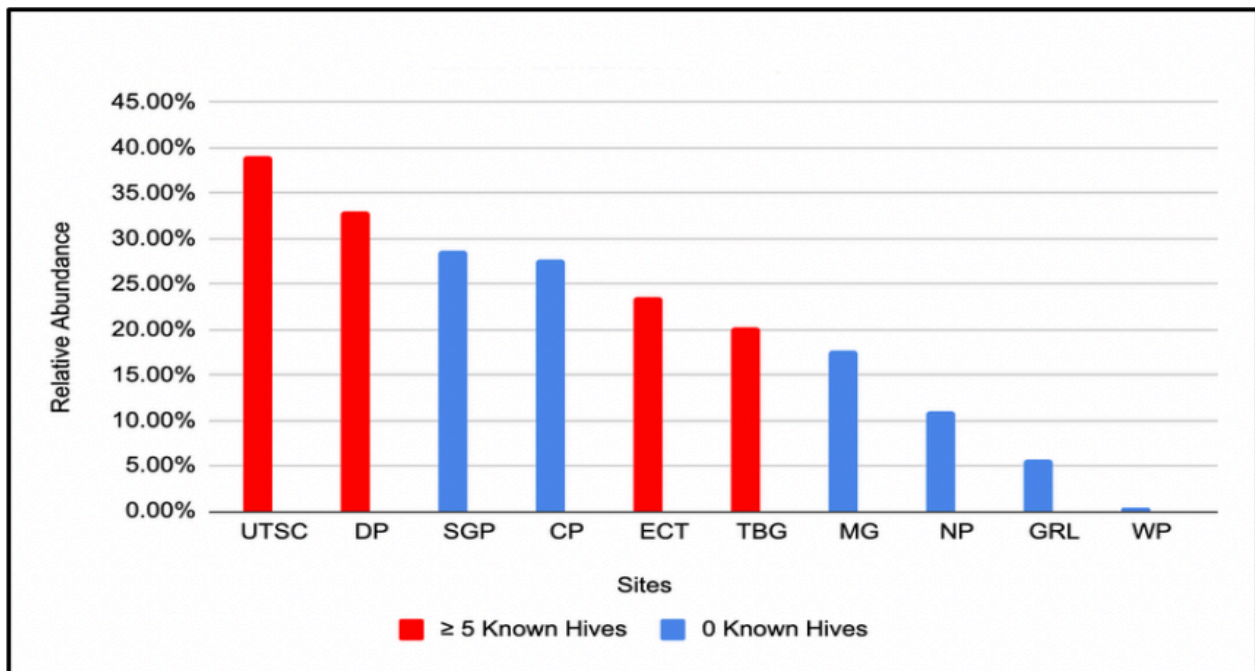


Figure 3.3 Relative abundance of honey bees across all ten sites. Red denotes sites with 5 or more registered honey bee hives (high abundance) at beginning of field season. Blue denotes sites with no registered honey bee hives (low abundance) at beginning of field season. (N = 1,824)

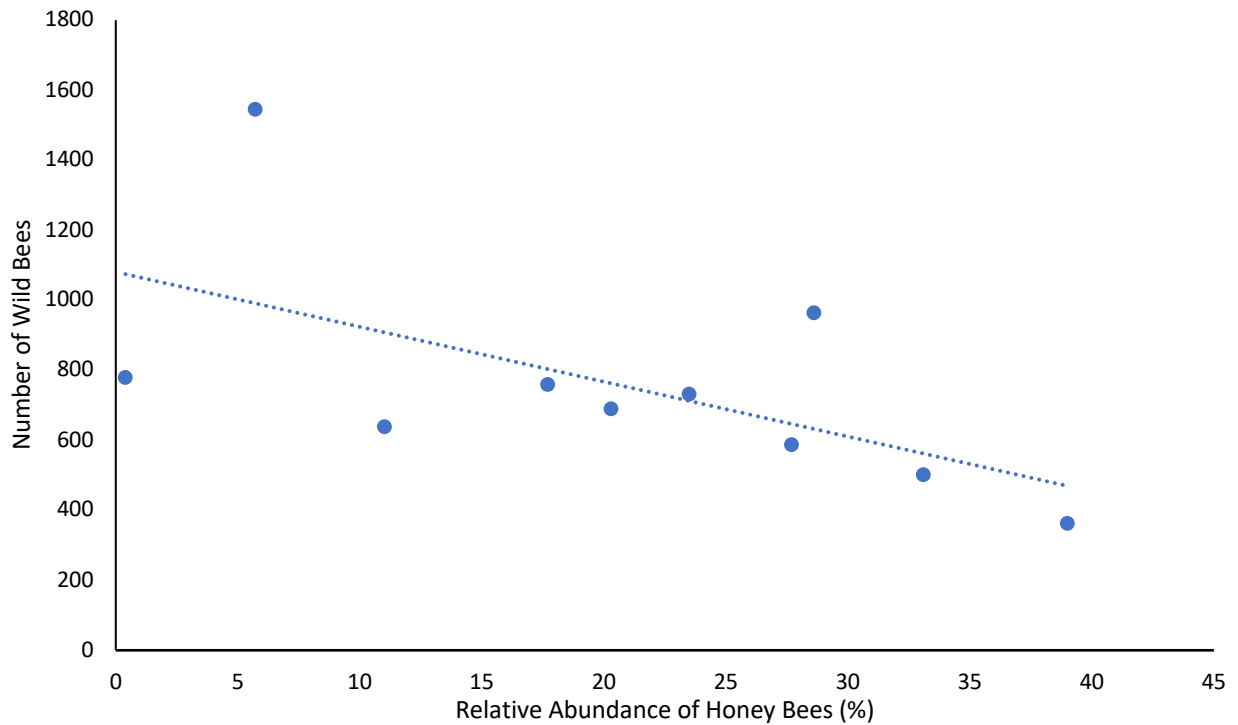


Figure 3.4 Number of wild bees decreases with increased relative abundance of honey bees. Each point represents one of the ten sampled sites. $R^2 = 0.3543$ ($N = 7,565$)

3.3.2 Genera Diversity

The PCA indicates possible negative relationship existing between relative abundance of honey bees and the following genera; *Halictus*, *Coelioxys*, *Sphecodes*, *Triepeolus* and *Nomada* (Fig. 3.5). A GLM quasipoisson performed on these genera indicates that only *Coelioxys* has a negative relationship to the relative abundance of honey bees ($p < 0.05$) (Fig. 3.6).

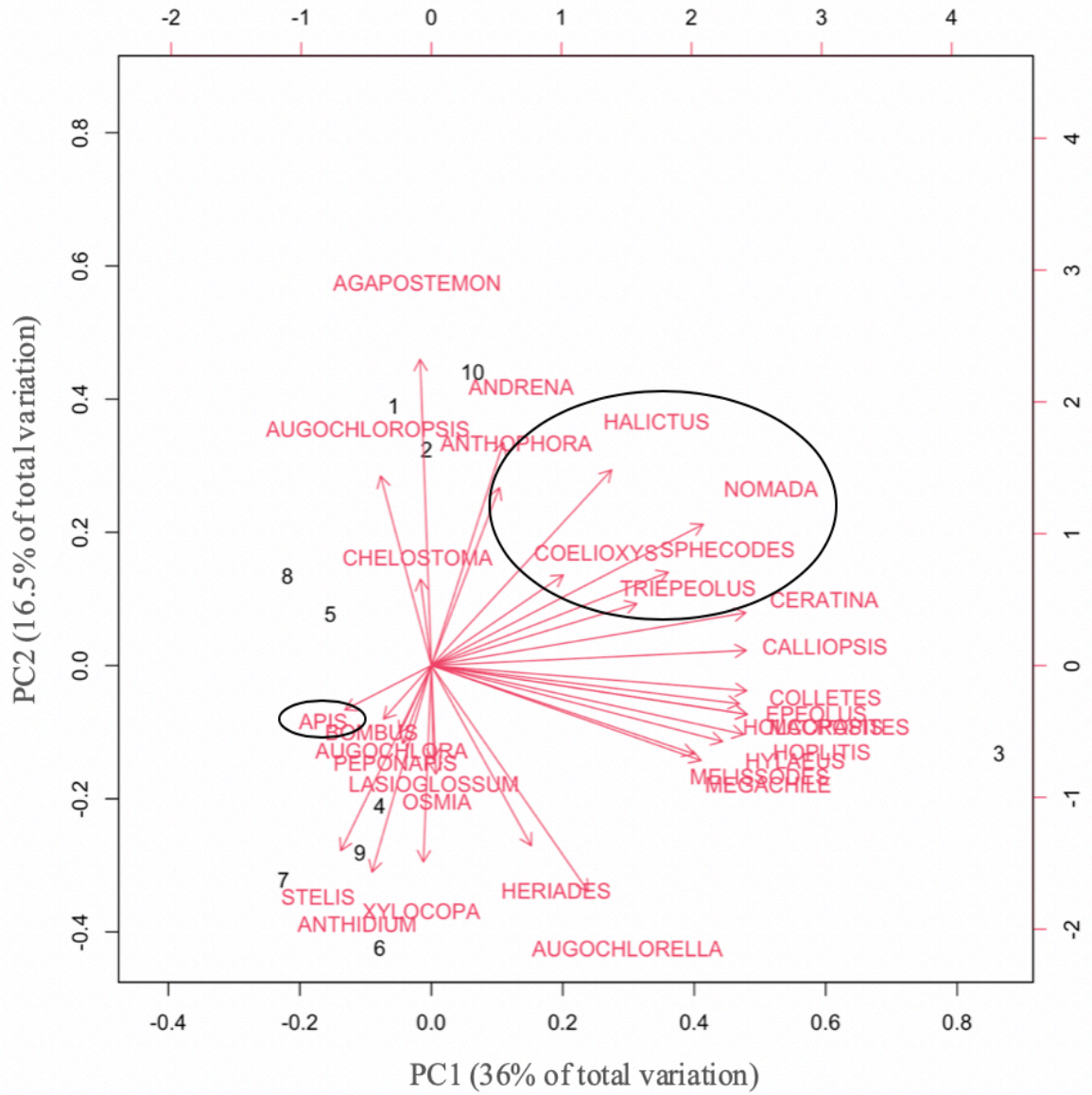


Figure 3.5 PCA of relative honey bee abundance and all bee genera sampled. Each of the numbers indicate one of the ten sites. Circled genera are those most impacted by honey bees (Apis).

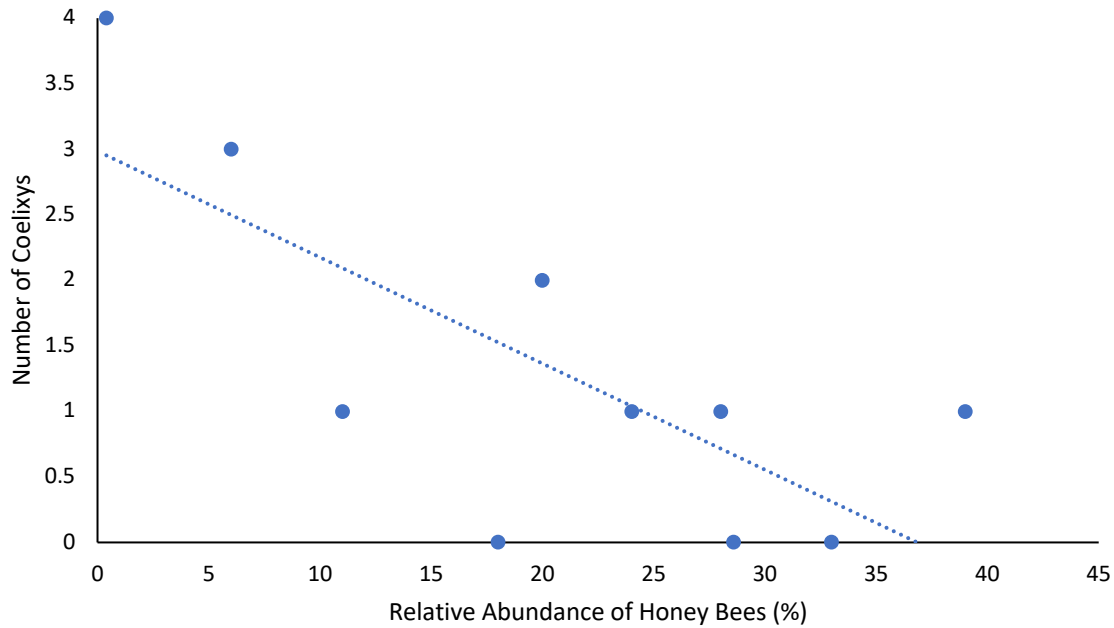


Figure 3.6 Number of Coelioxys decreases with increased relative abundance of honey bees. Each point represents one of the ten sampled sites. $R^2 = 0.5476$ ($N = 13$)

3.3.3 Impacts on Body Size

Currently, only the Eastern Carpenter bee (*Xylocopa virginica*) has shown impacts on body size. This species has been verified for identification and body measurements have been double checked for errors. There is a total of 144 *Xylocopa* specimens in our collection, 118 females and 26 males. Mean thorax width and mean head width for specimens collected at each site were used in this regression to understand how relative abundance of honey bees impacted overall size. Multivariate regression shows a significant negative relationship between female *Xylocopa* size and relative abundance of honey bees ($p < 0.05$) (Fig. 3.7), while no significant relationship is seen for males ($p = 0.23$) (Fig. 3.8).

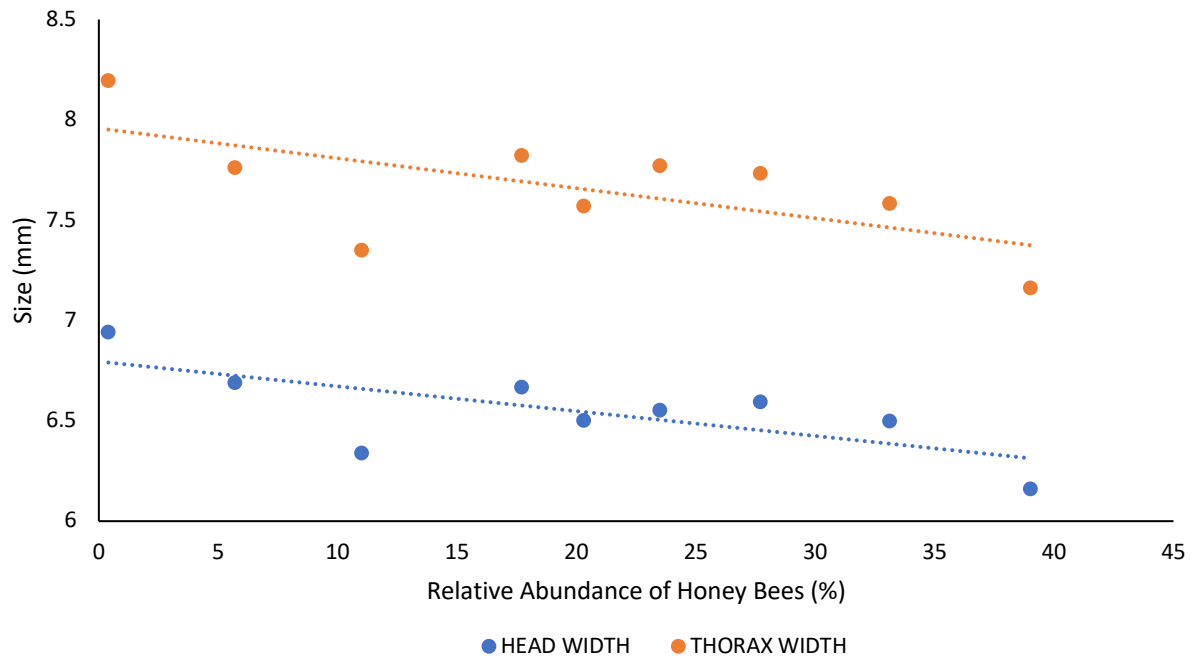


Figure 3.7 Female *Xylocopa virginica* decrease in size with increasing relative abundance of honey bees. Joint R² for thorax width and head width is 0.37. (N = 118)

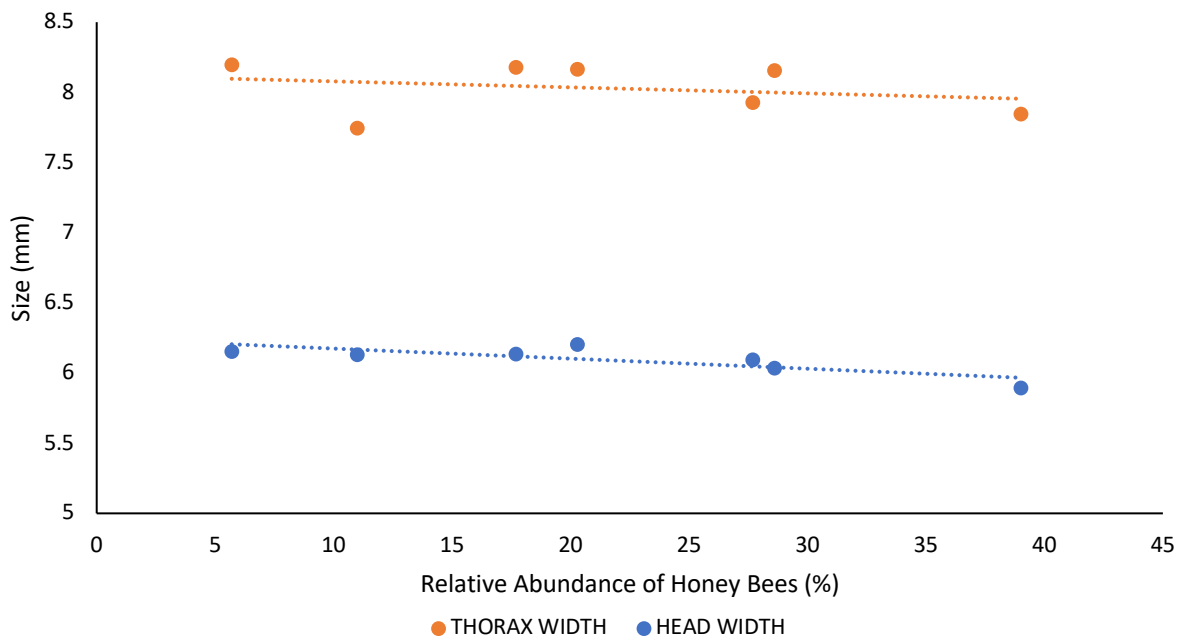


Figure 3.8 Male *Xylocopa virginica* show no body size trends with increasing relative abundance of honey bees. Joint R² for thorax width and head width is 0.13. (N = 26)

3.4 DISCUSSION OF PRELIMINARY RESULTS

Results of relative abundance of honey bees (Fig. 3.3) show that two sites, SGP and CP, which were thought to previously have no honey bee hives present actually exhibit high relative abundance. This reflects the rising number of urban beekeeping in the city as well as lack of knowledge of where these hives are located. It has become apparent that simply going off of reported honey bee hive numbers is not enough when studying honey bee abundance in urban landscapes (McCune *et al.*, 2020). These acquired hives are not registered with the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) and make it hard to account for actual abundance of these non-managed bees. The relative abundance of honey bees data will be used onwards in this study to accurately represent abundance of honey bees in the GTA.

Variation in body sizes is impacted by how much nutrients are provided to individual bees early on in the developmental stage (as eggs). Negative relationships between body size and honey bee abundance implies competition over floral resources exists. *Xylocopa virginica* are currently the only species from our dataset with over 50 specimens and with body size measurements rechecked for errors that have exhibited a trend. For this reason, they are the only species that a multivariate regression for effects of honey bee abundance on body size was included. Only females exhibit a negative relationship to increased relative abundance of honey bees. This variation in impacts between sexes could potentially be a result of foraging distances. Males are known to forage across a larger distance, while females tend to remain in close proximity to their nest (Greenleaf *et al.*, 2007; Fitch *et al.*, 2019). The increased abundance of honey bees increases the probability of there being interspecific competition over floral resources between wild bees and the managed honey bees (Mallinger *et al.*, 2017).

Our preliminary results thus far, indicate that honey bee abundance impacts both abundance and diversity of wild bees. In addition, they have been shown to impact body sizes of certain groups of wild bees. This suggests that competition between this introduced species and wild bees does exist in urban areas. With the steady inflow of honey bees into cities, due to increases in urban beekeeping, this will result in long-term negative impacts on wild bee communities. Further analysis remains to be completed in order to obtain a clear understanding of the magnitude of honey bee impacts on wild bees. However, with the current available data it

is apparent that limiting the number of hives within cities is a necessity and future pollinator conservation plans must address the issue of the ever increasing honey bee.

Due to the large scope of this research and an underestimation of how long each step of the study would take to complete, there are still various components that have not been completed and analyzed yet. These components are addressed in the following section ‘Next Steps’ and will be completed within the next couple of months.

3.5 NEXT STEPS

3.5.1 Verification of Species Identification

The amount of time required to identify all of the collected bees to species level for this project was underestimated. Most of the identified species require experts to verify that the species have been identified correctly (Packer *et al.*, 2018). There remain three main groups that are in the midst of verification and should be completed by the end of August/Early September 2020 (*Lasioglossum*, *Nomada* and *Osmia*).

3.5.2 Body Size

Most of the species with over 50 specimens have been measured but showed no impacts on body size. While most of the specimens have been previously measured for head and thorax width, some species measurements are being reassessed for potential human error or mechanical errors with the Vernier calipers. The remaining groups to be checked are *Ceratina*, *Colletes*, *Hylaeus*, *Melissodes* and *Nomada*. As mentioned in the discussion, floral abundance plays a secondary component in the impacts of honey bee abundance on the body sizes of wild bees. For this reason, the impacts on body sizes will be written as a separate paper from functional diversity. This will be done so as to delve further into all possible variables (mainly floral abundance and diversity) along with honey bees that factor into body size variations in wild bees.

3.5.3 Sex Ratios

Observed sex ratios have yet to be calculated. This analysis cannot be accurately run without accounting for time of emergence for each distinct species. Depending on the species, males and females tend to emerge at different times with males staggered towards either end of the season. The 2019 field season was characterized with an unseasonably cool April and a warm September. No bees were sampled during the month of September for this reason time of emergence must be accounted for. Our samples may have missed any late male bee emergence in September. This analysis will be run once all bee identifications have been verified and time of emergence data for each species compiled.

3.5.4 Functional Diversity

Analysis of functional diversity cannot be completed without a dataset of all natural history traits for each of the available species. This step will be completed after the verification of species identification is completed. Once a dataset is created, the statistical analysis of honey bee abundance on the functional diversity of wild bees can be commenced. This step will potentially take place by early September 2020.

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