NEONICOTINOID USE, BEE TOXICITY, AND ACTIONS FOR CALIFORNIA LANDSCAPES

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This Master’s Project

NEONICOTINOID USE, BEE TOXICITY, AND ACTIONS FOR CALIFORNIA LANDSCAPES

by

Kendra Mann

is submitted in partial fulfillment of the requirements for the degree of:

Master of Science
in
Environmental Management

at the

University of San Francisco

Submitted: ............................................
Kendra Mann  Date

Received: ............................................
Allison Luengen, Ph.D.  Date
Table of Contents

List of Tables .................................................................................................................................................. i
List of Figures .................................................................................................................................................. ii
List of Acronyms ............................................................................................................................................ iii
Abstract ............................................................................................................................................................ iv

1. Introduction .................................................................................................................................................. 1
   1.1 Objective and Research Questions ......................................................................................................... 4

2. Methods ....................................................................................................................................................... 5

3. Managed and Wild Bees ............................................................................................................................... 6
   3.1. Honey bees (Apis mellifera) .................................................................................................................. 9
   3.2. Bumble bees (Bombus spp.) ................................................................................................................. 10
   3.3. Solitary bees (Osmia spp.) .................................................................................................................... 12

4. Neonicotinoid Use ....................................................................................................................................... 14
   4.1. Application Methods and Exposure Routes ............................................................................................ 14
   4.2. Agricultural vs. Urban Landscapes .......................................................................................................... 18
       4.2.a. Agriculture ......................................................................................................................................... 18
       4.2.b. Urban ............................................................................................................................................... 23
   4.3. Reporting ............................................................................................................................................... 26

5. Neonicotinoid toxicity to bee species ........................................................................................................ 30
   5.1. Lethal (Acute/Chronic) Toxicity ............................................................................................................ 30
   5.2. Sublethal Toxicity ................................................................................................................................... 34
   5.3. Risk Assessments ................................................................................................................................... 39

6. Alternative Actions to Neonicotinoid Use .................................................................................................. 41
   6.1. Post-restriction Actions .......................................................................................................................... 42
   6.2. Integrated Pest Management ................................................................................................................ 43
   6.3. IPM case studies in Italian agriculture and Canadian forests ............................................................... 45

7. Pesticide Policies ......................................................................................................................................... 46
   7.1. Federal ...................................................................................................................................................... 47
   7.2. California ............................................................................................................................................... 50
   7.3. Local ....................................................................................................................................................... 52
   7.4. Stakeholders and knowledge gaps ......................................................................................................... 54

8. Management Recommendations ................................................................................................................ 55
   8.1 Agriculture Recommendations .............................................................................................................. 56
List of Tables

Table 1. Comparison of life history traits and pesticide risk between managed and wild bee species................................................................. 7

Table 2. Synthesis of literature directly assessing neonicotinoid concentrations between agriculture and urban landscapes................................................................. 25

Table 3. U.S. EPA recommended language for acute and residual toxicity to bees.................... 27

Table 4. Lethal toxicity range (LD_{50} and LC_{50} values) for managed and wild worker bee species 32

Table 5. Sublethal effects on managed and wild worker bee species.................................................. 37
List of Figures

Figure 1. Photos taken on April 18, 2021 at Home Depot and Summer Winds Nursery in Campbell, CA. ............................................................... 3

Figure 2. Apis mellifera (western honey bee). ........................................................... 10

Figure 3. Bombus terrestris (buff-tailed bumble bee). ........................................... 12

Figure 4. Male and female Osmia bicornis (mason bee). ....................................... 13

Figure 5. Image of coated corn seeds in neonicotinoid pesticide. ......................... 15

Figure 6. Conceptual model of neonicotinoid application and exposure to bees in an agricultural environment. .................................................. 17

Figure 7. Mass of neonicotinoids (in million kilograms) used on different crop types throughout the United States. .......................................................... 19

Figure 8. Relationship between wild bee richness and neonicotinoid concentrations in field margins ........................................................................... 22

Figure 9. Examples of how the product label can differ from the U.S. EPA recommended language ........................................................................ 28

Figure 10. Integrated Pest and Pollinator Management framework .......................... 44

Figure 11. Bee advisory box to label bee-toxic pesticides and provide further application guidance and restrictions ................................................. 49
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDPR</td>
<td>California Department of Pesticide Regulations</td>
</tr>
<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
</tr>
<tr>
<td>ESA</td>
<td>Endangered Species Act</td>
</tr>
<tr>
<td>FIFRA</td>
<td>Federal Insecticide, Fungicide, and Rodenticide Act</td>
</tr>
<tr>
<td>IPM</td>
<td>Integrated Pest Management</td>
</tr>
<tr>
<td>LC$_{50}$</td>
<td>Median lethal concentration</td>
</tr>
<tr>
<td>LD$_{50}$</td>
<td>Median lethal dose</td>
</tr>
<tr>
<td>NOEC</td>
<td>No observed effect concentration</td>
</tr>
<tr>
<td>NOEL</td>
<td>No observed effect level</td>
</tr>
<tr>
<td>PUR</td>
<td>Pesticide Use Reporting database</td>
</tr>
<tr>
<td>U.S. EPA</td>
<td>United States Environmental Protection Agency</td>
</tr>
</tbody>
</table>
Abstract

Neonicotinoid insecticides are toxic to bees and enhance biodiversity loss due to decreased pollination. Despite the toxicity of neonicotinoids to bees, they are being applied in increasing amounts across California landscapes. To determine what measures can mitigate neonicotinoid effects on bees, I conducted a comparative analysis of toxicity for honey bees (Apis mellifera) vs. wild bees (e.g., Bombus spp. and Osmia spp.) in agriculture and urban landscapes. Then I analyzed alternative actions and current pesticide policies. While more studies are conducted in agricultural landscapes, neonicotinoids are also found at high levels (10 ng/g per bee; 11.2 ng/g in pollen) in urban environments. Neonicotinoids can persist in soil and vegetation for over 5 years and spread to untreated areas. There may be 77% more neonicotinoids in California agriculture landscapes than what is currently reported. Managed honey bees are the current surrogate species to determine pesticide risk for pollinators. However, due to life history traits wild bees are equally or more sensitive (clothianidin: LD50 20 ng/g [Bombus spp.]; 22-40 ng/g [Apis mellifera]) to neonicotinoids as honey bees. Physical and biocontrol actions are the most substitutable non-chemical alternatives, but 98% of farmers favored chemical alternatives. Policy limitations include pollinator conservation, regulation of sublethal exposure, use of seed coating, and implementing integrated pest management practices in agriculture. In California, only three local governments have policies that specifically address neonicotinoids, indicating that the local level is an area where more could be done. Recommend further restricting local neonicotinoid use and prohibit neonicotinoid-coated seeds from agriculture.
1. Introduction

Without bees, the world would look drastically different. Bees provide an important ecosystem service through pollination of wild and agricultural plants. Honey bees have been reported to provide 35% of pollination services to agricultural crops, which provides an economic value of approximately $170 billion annually worldwide (Gallai et al. 2009; Klein et al. 2007). This valuation does not include the pollination services provided by wild bees, who may be even better pollinators for some agricultural plants. Since bees play such an important role in the environment, it is concerning to see that both managed and wild bee species are in decline (Cameron et al. 2011; Potts et al. 2010). Bee population decline stems from numerous threats including habitat loss, competition, pathogens, and pesticide use.

Pesticide use is one of the main threats believed to contribute to the decline in bee species (Potts et al. 2010; Stokstad 2013). In recent decades, one pesticide in particular has become more prevalent: neonicotinoid insecticides. These insecticides have replaced other more toxic pesticides (e.g., organophosphates), since it is less harmful to humans and other mammals (Bonmatin et al. 2015; Hladik et al. 2018). Neonicotinoids are a neurotoxin insecticide that inhibits receptors in insects, which disrupts their nervous system and makes them lose control of their movement and function (Blacquière et al. 2012; Bonmatin et al. 2015; Stokstad 2013). Specifically, the receptors affected are the nicotinic acetylcholine receptors (nAChRs) (Sponsler et al. 2019). These receptors are within the postsynaptic cells, which allow the transfer of ions (i.e., Ca^{2+}, K^+ and Na^+) (Wu 2009). When this ion channel is altered it can cause many different symptoms, including loss of nervous system control.

Additionally, it is a systemic pesticide, which means it transports easily between the environment (e.g., from soil to plant tissue). Due to its ease of transport, both target and non-target species can be exposed through a variety of routes and potentially in areas where they are not applied. Target species are pests that humans wish to control in both agricultural and urban settings, while the non-target species are by-products affected by the applied chemical. Bees are one such non-target species that may be exposed to neonicotinoid insecticides by multiple routes. However, this exposure risk extends to other pollinators and species as well, such as birds and aquatic insects (Hladik et al. 2018). Unlike other pesticides, exposure can
happen not only from spray application, but also through residues found in soil and the plants themselves (i.e., nectar and pollen).

Neonicotinoids can be applied in a variety of ways: foliar spray, soil injection, soil drenching, bark injection, granules, and seed coating. They are also used in a variety of settings due to their effectiveness against soil and plant pests. They are found in rural, agricultural, and urban settings and can be purchased as a commercial or residential product. There are several active ingredient neonicotinoid insecticides: acetamiprid, clothianidin, dinotefuran, imidaclorpid, thiamethoxam, and thiacloprid (Heard et al. 2017; Hladik et al. 2018; Sanchez-Bayo and Goka 2014; Uhl et al. 2019). The top three most often found in commercial and consumer products, and are highly toxic to pollinators are clothianidin, imidacloprid, and thiamethoxam (Hladik et al. 2018).

Unknown to many, neonicotinoids are found in pesticide products in home and garden centers for residential use (e.g., Bayer Advanced: All-In-One Rose & Flower Care, 2-In-1 Insect Control Plus Fertilizer Plant Spikes, and Fruit, Citrus & Vegetable Insect Control) (Center for Food Safety 2016). Figure 1 shows a few that I found at my local Home Depot and Summer Winds nursery in Campbell, California. The most popular product found with neonicotinoid active ingredients (imidacloprid and clothianidin) was produced by Bayer BioAdvanced (Figure 1A-D), and only one other product by Monterey was found to contain imidacloprid (Figure 1E). Oftentimes these products do not have appropriate labeling of how deadly it is to pollinators to allow the consumer to make informed decisions (Bucy and Melathopoulos 2020). Even though pesticides toxic to bees are required to be labelled with precautionary statements under 40 CFR § 156.85(a) (U.S. EPA 2012).
Figure 1. Photos taken on April 18, 2021 at Home Depot and Summer Winds Nursery in Campbell, CA. Bayer BioAdvanced had products with neonicotinoid active ingredients for rose & flower, tree & shrub, fruit, citrus, & vegetable, and insect disease & mite control (A-D). Monterey product only had insect control specific for tree and shrub with neonicotinoid active ingredients (E).

As neonicotinoid use has increased, there are growing concerns of its toxic effects on bees and other non-target species (Bonmatin et al. 2015; Hladik et al. 2018). However, the approaches taken toward regulating these pesticides are not equal throughout the world. For instance, Europe has taken great steps to reduce the use of neonicotinoid insecticides by banning several found to be the most toxic to pollinators (Stokstad 2013). However, the United States has still not banned any of the neonicotinoid insecticides but continues to reevaluate the risk to pollinators by encouraging pesticide companies to submit more studies to be included in risk assessments (Durant 2020; Stokstad 2013; Tafarella et al. 2018). The difference in regulatory measures between the two regions may be the result of different sets of cultural values or how science is used to build policies between each (Suryanarayanan 2015).

Current pesticide policies in the United States focus on apiculture and pesticide use in agriculture settings, but neonicotinoids are applied across landscapes and have been found to seep into areas where it was not applied (Botías et al. 2016; Colla and Maclvor 2017; David et al. 2016; Hall and Steiner 2019). Risk assessments are conducted on honey bees to determine
the lethal and sublethal doses and the amount that can be applied where populations can continue to thrive successfully. These assessments are determined by the United States Environmental Protection Agency (U.S. EPA) guidance document for pesticide risk assessments (U.S. EPA 2014). Honey bees are currently used as a proxy species for all other bees during risk assessments. However, honey bees are a managed pollinator and may not always be the most sensitive species to neonicotinoids (Arena and Sgolastra 2014; Heard et al. 2017). The different life history traits of each bee species need to be considered when conducting risk assessments (Brittain and Potts 2011).

1.1 Objective and Research Questions

To better understand the significance of neonicotinoids on managed and wild bee species in California, this paper will assess the use and application of neonicotinoids, their toxicological effects on bees, other practices that can be implemented to help reduce or eliminate the toxic effects, and the policies that regulate them. Ultimately the objective is to determine what policies and practices may help reduce the toxicological effects of neonicotinoids to managed and wild bee species in agricultural and urban settings of California. The main goals are to determine where and how neonicotinoids are used, their toxicity to bee species, alternative practices available, and pesticide policies in place to protect pollinators from neonicotinoids. I developed several sub-questions to help answer the main research question and goals of this research.

To determine where and how neonicotinoid insecticides are applied I evaluated its persistence in the environment and its ability to spread. During my literature review, I analyzed studies that evaluated the fate and transport of neonicotinoids and its ability to spread to field margins untreated by neonicotinoids. Then based on several studies, I evaluated which landscapes (agricultural versus urban) neonicotinoids are more often used. This is important to understand and develop focused management recommendations for each affected landscape. Then to understand if honey bees are an appropriate surrogate for all bee species, I evaluated toxicity studies on bumble bee, honey bee, and solitary bee species and compared their sensitivities. Then I evaluated the current pesticide risk assessment process used by the United
States Environmental Protection Agency (U.S. EPA) to understand how toxicity risks are determined and if they are limited in any way.

After evaluating the toxicity and risk assessment process, I identified which alternative practices are available and most popular instead of using neonicotinoid insecticides. From the literature, Integrated Pest Management (IPM) is one program level alternative available for both agriculture and urban landscapes. I analyzed a case study assessing IPM practices in farm and forest systems instead of applying neonicotinoids to determine their success. Finally, I reviewed current pesticide policies in the United States and California to determine what is missing in these policies to protect pollinators from neonicotinoids. From this analysis, I determined the type of approaches that may improve current policies and stakeholder engagement to protect bee species from neonicotinoid toxicity.

2. Methods

This research was conducted through a comparative analysis of toxicological studies on managed and wild bees in urban and agricultural settings and alternative practices. Then I conducted a case study analysis of alternative practices to neonicotinoids in farms and forests for pest control. Finally, I reviewed current pesticide policies that relate to neonicotinoids and pollinator conservation. The primary method used for this research paper was through a literature search through the University of San Francisco’s Library database (scopus) and comparative analysis of peer-reviewed literature and professional reports. Using scopus, I searched the following keywords: neonicotinoid, acute, toxicity, bee, California, pesticide, policy, honey bee, bumble bee, and solitary bee. To further narrow my search, I only selected articles from journals with a Scimago score in quartile one or two.

For ease of comparison in the toxicity section of the paper, I converted the original units of lethal and sublethal toxicity from several literature sources of the main active ingredients reviewed for this research (clothianidin, imidacloprid, and thiamethoxam). Lethal toxicity is most often measured in micrograms or nanograms per bee (μg or ng/bee) or in parts per million/billion (ppm/b) or milligrams per liter (mg/L) in sucrose. For this paper, units were converted from μg to ng and mg/L to ppm. Additionally, the units for sublethal toxicity were also converted. These are often measure in No Observed Effect Level or Concentration
(NOEL/NOEC) in micrograms or nanograms per bee (μg/kg or ng/g) or parts per million/billion (ppm/b) or microgram or milligram per liter (μg/L or mg/L). For this paper, units were converted from μg to ng and μg/L or mg/L to ppm.

Through my research, I identified a case study that assessed alternative actions to neonicotinoids in Italian corn fields and Canadian forests to control common pests. This study provides an in-depth overview of integrated pest management (IPM) practices to utilize instead of neonicotinoid insecticides on agricultural crops and woody plants. This source allowed for a better discussion of alternative practices and recommendations for agricultural and urban landscapes. Other case studies evaluating alternative practices in such depth were limited.

In the policy section, I searched through federal (i.e., United States Environmental Protection Agency) and state (i.e., California Department of Pesticide Regulations and California Department of Food and Agriculture) regulatory agency webpages to identify current pesticide regulations related to neonicotinoids and pollinator protection. To search for current and past neonicotinoid legislation in the State of California (i.e., assembly bills and laws) I used the California Legislative Information website (California Legislative Information 2021). I also searched for local municipal ordinances related to neonicotinoids in California. Additionally, to assess stakeholders and potential policy approaches, I reviewed several peer-reviewed articles evaluating the lack of knowledge on pesticides and pollinator conservation policies.

3. Managed and Wild Bees

There are over 4,000 species of bees in the United States and 1,600 species in California (Frankie et al. 2009). However, when people think of bees, they normally think of the Apis mellifera (western honey bee) (Figure 2). This species is a managed species in the United States under apiculture (beekeeping). They are managed for their honey and wax production and pollination services for agricultural land. However, wild bee species also provide pollination services for managed and wild flora. Two of these wild bee species have also become a managed species for pollination services on farms: Bombus spp. (bumble bee) (Figure 2) and Osmia spp. (solitary bee) (Figure 4). However, they are mostly still found in the wild. Both managed and wild bee populations are in decline throughout the world (Cameron et al. 2011; Potts et al. 2010).
Currently, the honey bee is used as a surrogate for pesticide risk assessment for all bee species due to their sensitivity to pesticides (U.S. EPA 2014). However, the life histories of each species play an important role in determining the exposure and risk of toxicity from neonicotinoid pesticides applied across landscapes (Brittain and Potts 2011). For instance, wild bee species have a slightly different life history than the commonly managed honey bee species, which may increase their exposure risk. To create best management practices and policies to protect managed and wild pollinators we need to understand the life histories and the toxicity risk each bee may be exposed to in lab and field settings. This section focuses on the life history comparison of managed and wild bees (i.e., honey bee, bumble bee, and solitary bee) and their potential exposure risks.

The main life history traits evaluated for each bee include their nesting and floral preferences, body size, queen lifespan, and sociality. Each has evolved based on their floral resources and habitats, which is important to consider when developing policies and practices to conserve these species. Due to their different life history traits, each bee species may have a different exposure risk to neonicotinoids in the field. Since honey bees are currently used as a proxy for all bee species in pesticide risk assessments, it is important to understand the ecological differences and gaps that may create more exposure risk to each species. Some research has been conducted to compare the life history traits between these three species to understand if honey bees are a good surrogate for all bees (Brittain and Potts 2011). However, more research needs to be conducted if honey bees continue to be used as a proxy species in the pesticide risk assessment process. A summary of each species life history traits is described below, along with a comparison of traits and risk to pesticides synthesized in Table 1.

**Table 1. Comparison of life history traits and pesticide risk between managed and wild bee species.**

<table>
<thead>
<tr>
<th>Trait</th>
<th><em>Apis mellifera</em></th>
<th><em>Bombus spp.</em></th>
<th><em>Osmia spp.</em></th>
<th>Trait with high risk to pesticide exposure</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>body length (mm)</td>
<td>10 to 15</td>
<td>10 to 23</td>
<td>5 to 20</td>
<td>small body</td>
<td>Brittain and Potts 2011; LeBuhn 2013; Page Jr. and Peng 2001; Sgolastra et al. 2019</td>
</tr>
<tr>
<td>Trait</td>
<td><em>Apis mellifera</em></td>
<td><em>Bombus spp.</em></td>
<td><em>Osmia spp.</em></td>
<td>Trait with high risk to pesticide exposure</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>--------------</td>
<td>--------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>body weight (mg)</td>
<td>100 to 225</td>
<td>200 to 250</td>
<td>2 to 400</td>
<td>small body</td>
<td>Arena and Sgolastra 2014; Brittain and Potts 2011; LeBuhn 2013; Sgolastra et al. 2019</td>
</tr>
<tr>
<td>color/body hair</td>
<td>yellow, brown, black/very fuzzy</td>
<td>yellow, brown, black/very fuzzy</td>
<td>green, metallic sheen/small hairs</td>
<td>no data</td>
<td>Goulson 2010; LeBuhn 2013; Sgolastra et al. 2019</td>
</tr>
<tr>
<td>sociality (social vs. solitary)</td>
<td>eusocial</td>
<td>eusocial</td>
<td>solitary</td>
<td>solitary</td>
<td>Brittain and Potts 2011; LeBuhn 2013; Page Jr. and Peng 2001; Sgolastra et al. 2019; Thorp et al. 1983</td>
</tr>
<tr>
<td>fecundity (eggs/day)</td>
<td>1,500</td>
<td>8 to 16</td>
<td>2</td>
<td>low fecundity</td>
<td>Brittain and Potts 2011; Goulson 2010; Sgolastra et al. 2019; Ruddle et al. 2018</td>
</tr>
<tr>
<td>hive size (# of bees)</td>
<td>20,000 to 40,000</td>
<td>50 to 1,000</td>
<td>2 to 40</td>
<td>small hive</td>
<td>LeBuhn 2013; Page Jr. and Peng 2001; Sgolastra et al. 2019; Thorp et al. 1983</td>
</tr>
<tr>
<td>queen life span (year)</td>
<td>1 to 3</td>
<td>1</td>
<td>1</td>
<td>short life span</td>
<td>LeBuhn 2013; Page Jr. and Peng 2001; Pyke et al. 2016; Sgolastra et al. 2019; Thorp et al. 1983</td>
</tr>
<tr>
<td>forage distance (km)</td>
<td>1.5</td>
<td>2</td>
<td>2</td>
<td>short forage distance</td>
<td>Dramstad et al. 2003; Goulson 2010; Hatfield and LeBuhn 2007; Jha and Kremen 2013; LeBuhn 2013; Osbourne et al. 1999; Sgolastra et al. 2019; Wojcik and McBride 2012</td>
</tr>
<tr>
<td>pollen transport method</td>
<td>corbiculum</td>
<td>corbiculum</td>
<td>corbiculum and abdomen</td>
<td>both</td>
<td>Goulson 2010; LeBuhn 2013; Sgolastra et al. 2019</td>
</tr>
<tr>
<td>food source/product</td>
<td>nectar and pollen (honey, bee bread, royal jelly)</td>
<td>nectar and pollen (honey, pollen ball)</td>
<td>nectar and pollen (pollen ball)</td>
<td>all</td>
<td>Brittain and Potts 2011; Goulson 2010; LeBuhn 2013; Sgolastra et al. 2019</td>
</tr>
<tr>
<td>Trait</td>
<td><em>Apis mellifera</em></td>
<td><em>Bombus spp.</em></td>
<td><em>Osmia spp.</em></td>
<td>Trait with high risk to pesticide exposure</td>
<td>Source</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------</td>
<td>----------------</td>
<td>--------------</td>
<td>------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>nesting preference</td>
<td>cavity (use wax/resin, above ground)</td>
<td>cavity (use wax, below/above ground)</td>
<td>cavity (use mud, below/above ground)</td>
<td>below ground</td>
<td>Brittain and Potts 2011; LeBuhn 2013; McFrederick and LeBuhn 2006; Sgolastra et al. 2019; Wojcik and McBride 2012</td>
</tr>
<tr>
<td>hibernate (yes/no)</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no data</td>
<td>Goulson 2010; LeBuhn 2013; Sgolastra et al. 2019</td>
</tr>
</tbody>
</table>

3.1. Honey bees (*Apis mellifera*)

Honey bees (Figure 2) are a part of the *Apidae* family, they have a body size of 10 to 15 mm long, weighing 100 to 225 mg, and fuzzy bodies with yellow, brown or black stripes (Page Jr. and Peng 2001; Sgolastra et al. 2019). They are a eusocial species with a caste system, which means that each bee is assigned a role within the hive. Each hive contains between 20,000 to 40,000 individual bees with one queen (Page Jr. and Peng 2001). Hives are perennial and can persist for several years, since queens are able to live between 1 to 3 years and each generation of worker bee live over a year (Page Jr. and Peng 2001). When a new queen emerges, she leaves the hive and mates with several drones (approximately 1 to 13 males) in a single mating flight (Page Jr. and Peng 2001). After her only mating flight, the queen finds a nest and begins to lay her eggs (approximately 1,500 eggs/day) to develop her first generation of worker bees (Sgolastra et al. 2019).

Honey bees are cavity nesters and create their nests from wax and propolis (resin). They are generalist (polylectic) species, which means they do not have one floral preference to rely on for nectar or pollen (Sgolastra et al. 2019). They can travel great distances, on average 1.5 km, to forage for nectar and pollen (Sgolastra et al. 2019). The pollen is collected using the corbiculum on their hind legs to bring back to the nest (LeBuhn 2013). Nectar is their main source of food, with small consumption of pollen, but pollen is mostly used to create honey,
royal jelly, and bee bread back at the hive (LeBuhn 2013; Sgolastra et al. 2019). The honey bees ability to filter pollen and store food sources through royal jelly and bee bread is important to understand how nurse bees and larvae may be exposed long-term to neonicotinoids. However, due to their large colony size they may be less susceptible to neonicotinoids through a buffer system.

3.2. Bumble bees (Bombus spp.)

Bumble bees (Figure 3) are also from the Apidae family but are larger and fuzzier than honey bees, weighing 200 to 250 mg and measuring 10 to 23 mm long (Arena and Sgolastra 2014; Goulson 2010; LeBuhn 2013; Thorp et al. 1983). Like honey bees, they are a eusocial species with a caste system, but they have much smaller hives containing between 50 to 1,000 individual bees annually (LeBuhn 2013; Thorp et al. 1983). Unlike the honey bee, they have an annual life cycle, which means the queen and colony die off each year in the fall and early-winter. A new queen is born before the die off, who mates with a male and then hibernates in nests (hibernaculum) during the winter (Goulson 2010; Thorp et al. 1983). Then later emerges in the spring to develop a new colony (Goulson 2010; LeBuhn 2013; Pyke et al. 2016; Thorp et
A queen will typically lay between 8 to 16 eggs in her first brood and creates a wax pot of nectar for each larva to feed on while developing (Goulson 2010; Thorp et al. 1983).

Similar to honey bees they are also cavity nesters. However, unlike the honey bee they are also found nesting below ground in ready-made holes (e.g., old rodent dens) (LeBuhm 2013; McFrederick and LeBuhm 2006; Wojcik and McBride 2012). Due to their large body size, fuzzy exterior, and endothermic abilities the new queens are able to live through the winter in their hibernaculum nests (Goulson 2010; Thorp et al. 1983). Unlike the honey bee, the bumble bee does not store honey as long due to their annual life cycle, so they need a landscape with abundant and diverse floral resources (Hatfield and LeBuhm 2007; Jha and Kremen 2013; Thomson 2016; Wojcik and McBride 2012). Luckily, they are a polylectic species and do not rely on one floral species for sustenance.

A bumble bee’s large body size also allows them to travel great distances from their hives (between 100m to 2km) to forage for nectar and pollen (Dramstad et al. 2003; Goulson 2010; Hatfield and LeBuhm 2007; Jha and Kremen 2013; Osborne et al. 1999; Wojcik and McBride 2012). While traveling great distances, the bumble bees will drink nectar for energy and use the corbiculum on their hind legs to carry pollen back to their hives. The differences and similarities of life history traits between the bumble bee and honey bee is important to understand. Bumble bees may have a greater exposure risk due to their smaller nest sizes and feeding preferences but may also fair well due to their larger body sizes (Brittain and Potts 2011).
There are a variety of solitary bee species, but the *Osmia* spp. or mason bee (Figure 4) is most commonly studied and has been proposed as a proxy for future risk assessments for solitary bee species (Sgolastra et al. 2019; Uhl et al. 2019). This is because they are easy to rear in laboratory and semi-field studies to determine pesticide exposure risk and effects (Sgolastra et al. 2019; Uhl et al. 2019). Based on this proposal and more available literature, the mason bee will be used for solitary bees in this paper.

Mason bees are part of the *Megachilidae* family and do not rely on a caste system (i.e., worker bees) to develop nests and produce broods (LeBuhn 2013; Sgolastra et al. 2019). This life history trait differs from the honey and bumble bees. Instead, this solitary species develops single brood cells with a pollen store for each larva to feed on during development (Ruddle et al. 2018). This species only has one annual generation (univoltine) and produces 2 eggs per day or approximately 10 to 40 eggs during their life span (Sgolastra et al. 2019). These solitary bees are generally the same size or smaller than honey and bumble bees with a length of 5 to 20 mm and body weight of 2-400 mg (LeBuhn 2013; Sgolastra et al. 2019). Solitary bees have a slightly
different appearance than what one may think of for a bee. For example, mason bees have a
green or blue metallic sheen with small hairs over their body (LeBuhn 2013; Sgolastra et al.
2019).

However, like honey and bumble bees, mason bees are also cavity nesters but will use
mud to create partitions in their single cell nests for each of their larvae (Sgolastra et al. 2019).
Some other solitary bee species will burrow underground, which is a risk exposure to soils that
are contaminated with neonicotinoids (Brittain and Potts 2011; Sgolastra et al. 2019). Solitary
bees are able to forage between 100 m to 2 km from their nests, and are mostly polylectic (e.g.,
Osmia spp.) but others are oligolectic (specialist) (LeBuhn 2013; Sgolastra et al. 2019). Similar to
the honey and bumble bees, the mason bee also consumes nectar and collects pollen by using
its hind legs and abdomen. However, unlike the honey bees solitary bee species provide a raw
pollen ball to their brood instead of filtering it to create “bee bread” (Sgolastra et al. 2019). This
lack of pollen filtration before the larvae consumes the pollen may increase the exposure risk to
the young of this species (Brittain and Potts 2011).

![Figure 4. Male and female Osmia bicornis (mason bee). Photo by By André Karwath aka Aka - Own work, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=130945](image-url)
4. Neonicotinoid Use

Understanding the current use and application of neonicotinoids across landscapes is important to determine how they affect target and non-target species. Unfortunately, the appropriate application may not matter if the use and fate of neonicotinoids persists in the environment, increasing the longevity of negative effects on non-target species (i.e., terrestrial and aquatic). Neonicotinoid use has increased throughout the world and in the United States, and accounts for approximately 25% of pesticide sales in the world (Hladik et al. 2018).

In California, the use of four active ingredient neonicotinoids (imidacloprid, thiamethoxam, clothianidin, and dinotefuran) has increased by 70% between 2007 and 2016 (Tafarella et al. 2018). By comparison, organophosphates decreased by 42% during the same timeframe (Tafarella et al. 2018). This increase is very concerning for non-target beneficial species, such as bees. One of the main reasons their use has increased is due to the ease of application and possessing fewer toxic effects on mammals and humans (Bonmatin et al. 2015; Hladik et al. 2018). However, non-target species (e.g., pollinators) are still greatly affected by them (Blacquière et al. 2012; Hladik et al. 2018).

To understand where and how non-target species are affected, it is important to know how neonicotinoids are applied in each landscape and their persistence. Since neonicotinoids are a systemic pesticide, there are multiple potential exposure routes that can occur after application. As a systemic insecticide, it has the ability to transport through different environmental compartments which increases the exposure potential for target and non-target species. This may also increase the ability of these pesticides to spread where it was not applied. This section discusses the application methods, potential exposure routes, comparison of application on agricultural and urban landscapes, and the reporting requirements for applicators and managed beekeepers.

4.1. Application Methods and Exposure Routes

Neonicotinoids are applied through spray, injection, and seed coating based on the pest of concern (Bonmatin et al. 2015). These insecticides are especially favored due to their less volatile application method through seed coating or injected into the soil or trunks. While foliar spray is an option, it was not noted to be used less often in agricultural settings (Bonmatin et al. 2015).
The preferred method of application on farmland is through seed coating and soil application (Figure 5). Seed coating is the number one application method for neonicotinoid pesticides, while soil application (e.g., injection) is a close follow up (Bonmatin et al. 2015; Douglas and Tooker 2015). Soil application can include injection, drenching, or applying granules of the pesticide. These two methods are most often used due to its ease of application and limited exposure risk to humans. In urban settings, depending on the pest, all applications are available (foliar spray, seed coating, plant injection, and soil application). However, the most discussed application for urban settings is soil application and plant injection (Larson et al. 2013; Mach et al. 2018). By understanding the application methods, the exposure routes will be easier to identify.

Figure 5. Image of coated corn seeds in neonicotinoid pesticide. Photo: USDA-NRCS / Lance Cheung. https://xerces.org/blog/xerces-urges-california-to-step-up-for-pollinators

In seed coating and soil application methods, the greatest exposure route comes from soil contamination and plant uptake of the insecticide. These application methods reduce the exposure risk from pesticide drift, which is a common concern with other pesticides. However, it has been noted there is potential for dust exposure from treated seeds as well. When treated seeds are sown into the ground the coating can become abraded and release dust particles into the air (Bonmatin et al. 2015). Some mechanical processes have been created to try and reduce
dust exposure to protect the applicator, but this does not protect non-target species during application.

After application, the plant takes up the neonicotinoid insecticide through the xylem, but some of the chemical remains in the soil (Bonmatin et al. 2015). This is a concern for ground dwelling species, particularly ground nesting bees (i.e., some solitary and bumble bees), which have an increased exposure potential. For the remainder of the insecticide that is drawn into the plant, bees can then be exposed to residues of the active ingredients from the leaves, pollen, or nectar. Another exposure risk is from water contamination after irrigation or rain events. Neonicotinoids are a highly soluble contaminant and transports easily in aqueous environments (Bonmatin et al. 2015). Bees may also drink water droplets from the plant leaves or from contaminated puddles from runoff.

Additionally, due to their high solubility, neonicotinoids may become an increasing pollutant of concern to water quality and aquatic invertebrates (Bonmatin et al. 2015). Neonicotinoids not only affect pollinators, but other non-target species. Specifically, aquatic invertebrates could be greatly affected from runoff where neonicotinoids are applied. For instance, neonicotinoids have been found globally in surface and ground water bodies (Hladik et al. 2018). This class of pesticide is quickly becoming a pollutant of concern to waterways and should be monitored and regulated alongside toxicity to pollinators. Although discussing aquatic contamination is beyond the scope of this paper, future studies should continue to assess the toxicity of neonicotinoids to aquatic invertebrates and water quality.

When applying neonicotinoids to landscapes it is important to keep in mind the soil type (i.e., organic matter), season (i.e., rainfall), temperature, landscape type (i.e., hardscapes), and longevity of the product (Bonmatin et al. 2015). When organic matter is high neonicotinoids have a lower mobility, but their persistence increases when rainfall and temperatures are low. Since they are a systemic insecticide, they easily transfer between environmental compartments (Figure 6). Neonicotinoids are also found to persist for a long time in the environment (Bonmatin et al. 2015; Nicholls et al. 2018; Wintermantel et al. 2020). These pesticides have been noted to take more than 1,000 days to be removed from soil and over a year to be removed from woody plants (Bonmatin et al. 2015). However, depending on the
environmental conditions they can persist even longer than intended. For instance, they have been found to persist longest in cold climates, soil with high organic matter, and dry conditions (Bonmatin et al. 2015). With climate change, some areas may become more prone to increased neonicotinoid persistence. Due to these insecticides’ persistence, pollinators are still at serious risk of exposure. Evidence of their persistence and potential to spread to untreated landscapes is further discussed below.

Figure 6. Conceptual model of neonicotinoid application and exposure to bees in an agricultural environment. Illustration by Xerces Society / Justin Wheeler: https://xerces.org/pesticides/understanding-neonicotinoids
4.2. Agricultural vs. Urban Landscapes

During the literature review, I found several field studies conducted at agriculture and urban sites, and a few directly comparing neonicotinoid exposure between agricultural and urban environments (Botías et al. 2017; David et al. 2016; Lawrence et al. 2016; Nicholls et al. 2018). Two of the studies also compared exposure in agricultural landscapes pre- and post-contamination of neonicotinoids after restrictions became effective in the European Union in 2013 (Nicholls et al. 2018; Wintermantel et al. 2020). The majority of these studies take place in Europe, which has taken a more robust approach to prohibiting neonicotinoids, specifically from agricultural crops. However, the two studies that focus on urban settings take place in the United States (Larson et al. 2013; Mach et al. 2018). One report submitted by the Natural Resources Defense Council in a rule-making petition to regulate crop seed treatment specifically assesses neonicotinoid use within California (Mineau 2020). The subsections below discuss the main findings in agriculture and urban landscapes, evidence of persistence and spread to nontreated areas, the type of plants receiving insecticide treatment, and the reporting requirements for each landscape.

4.2.a. Agriculture

Since the mid-2000s neonicotinoids have become a popular pesticide of choice (Douglas and Tooker 2015). Neonicotinoids have multiple application methods, are easy to apply, and pose extremely less risk to humans during application and harvesting. Most often, neonicotinoids are applied to crop lands through seed coating and soil application methods (Bonmatin et al. 2015; Douglas and Tooker 2015; Stokstad 2013). Neonicotinoids are most often used in maize, oilseed rape (canola oil), and sunflower farms to combat soil and flying pests associated with these crops (personal comm. Cruz 2021). However, they are also often found in cotton, vegetables and fruit, orchards, wheat, rice, and other crops throughout the United States and California (Douglas and Tooker 2015; Tafarella et al. 2018). Douglas and Tooker (2015) found that 93% of neonicotinoid sales in Minnesota were primarily for field crops and the remainder 7% was for urban/suburban land use (e.g., ornamental, lawns, gardens, and structural pest control) (Figure 7). While a study specifically on neonicotinoid sales in California was not found, California has robust pesticide reporting requirements.
Figure 7. Mass of neonicotinoids (in million kilograms) used on different crop types throughout the United States. Overall use has significantly increased between 1992 and 2011, with the most used on agricultural crops (Douglas and Tooker 2015).

California requires all pesticides applied by certified applicators on agricultural lands to be reported to each County Agricultural Commissioner and submitted into the California Department of Pesticide Regulation’s (CDPR) Pesticide Use Reporting (PUR) database (California Department of Pesticide Regulation 2021a). This comprehensive database allows for pesticides to be reviewed for human health and non-target species. The United States Geological Survey regularly compiles and analyzes data from the PUR (Mineau 2020). The most recent compilation in 2016 identified approximately 410,000 pounds of the three main active ingredients (clothianidin, imidacloprid, and thiamethoxam) have been applied in the agricultural regions (Mineau 2020). However, the PUR does not include neonicotinoid seed coatings. Due to this, the PUR is not accurately accounting for neonicotinoid application in California agricultural lands.

Douglas and Tooker (2015) noted in their study that most neonicotinoid applications for agricultural crops were from seed coatings, which was encouraged by seed companies as an insurance policy for the crop. However, some scientists are not convinced that crop yields produce more with neonicotinoid coated seeds than without (Stokstad 2013). Despite the lack of data that seed coatings provide a greater crop yield, the use of seed treatments has exponentially grown in the last few decades (Douglas and Tooker 2015). There are a few reasons that this increase has occurred: 1) increase promotion by seed companies as an
insurance policy, 2) preemptive treatment by farmers, 3) lack of enforcement by regulatory agencies. Currently, seed treatments are not registered or regulated as pesticides by the CDPR or the U.S. EPA (California Department of Pesticide Regulation 2018; U.S. EPA 2000).

Without appropriate regulation and enforcement, it is difficult to understand the actual use of neonicotinoids across landscapes and their potential harm to organisms. A recent rule-making petition to the CDPR, by the Natural Resources Defense Council, to regulate neonicotinoid treated seeds included a report to assess neonicotinoid use in California (California Department of Pesticide Regulation 2021; Mineau 2020). One section of the report estimated the potential amount of neonicotinoid treated seeds used throughout California agricultural regions. This was conducted by calculating the PUR data in 2016, the field crops planted in 2016, the registered seed treatment rates for each field crop, and the application rate per acre alongside the crops planted in California (Mineau 2020). The estimated neonicotinoid treated seed use was 512,000 pounds of the active ingredients: clothianidin, imidacloprid, and thiamethoxam (Mineau 2020). If combined with the PUR report (410,000 pounds), there is approximately 922,000 pounds of neonicotinoids potentially applied on agricultural landscapes in 2016. This is 77% greater than what was found in the PUR for California. The discrepancy and lack of reporting from all applications does not provide confidence to assess the contamination from neonicotinoids across landscapes or the potential harm to humans and non-target organisms in California.

Unfortunately, the potential for exposure is not limited to conventional farmlands. Concerningly, neonicotinoids have been detected in both organic and conventional crop fields (Humann-Guilleminot et al. 2019). To evaluate the detection of neonicotinoids on cultivated land, samples were taken from pollen, soil, and plant tissues (Cutler and Scott-Dupree 2014; Humann-Guilleminot et al. 2019). When compared, detection of neonicotinoids was found to be highest in conventional agricultural lands. However, Humann-Guilleminot et al. (2019) found that 93% of the organic cultivated fields in Switzerland were contaminated with at least one neonicotinoid above the concentration limit (> 0.05 ppb). Additionally, commercial organic seeds were analyzed and found to be contaminated with neonicotinoids. This contamination may have occurred during commercial production if organic seeds had been prepared alongside
treated seeds. Overall, it is very concerning to see quantifiable concentrations still present in both conventional and organic fields, especially considering this study was taken after the neonicotinoid ban in the European Union.

However, other studies conducted several years after the ban found that neonicotinoid concentrations both decreased or stayed the same. In one study conducted in the United Kingdom, Nicholls et al. (2018) found that neonicotinoid concentrations in pollen collected by bumble bees decreased by approximately 99% (5.1 ng/g to 0.06 ng/g) in agricultural areas only two years post the 2013 ban. Pollen and nectar samples from honey and bumble bee colonies were taken from both agricultural (oil seed rape) and semi-urban locations throughout the United Kingdom. However, another study comparing neonicotinoid concentrations five years post-ban found there was no decrease in neonicotinoid exposure in agricultural settings (Wintermantel et al. 2020). This study evaluated nectar residue contaminated from imidacloprid on oilseed rape fields in France. In most cases imidacloprid samples were found to be below 1 ng/mL in nectar samples, but there was one extreme case where 70 ng/mL was found. Overall, both studies noted and agreed that honey and bumble bees are still at serious risk of exposure despite the moratorium due to the persistence of this synthetic insecticide.

Additionally, neonicotinoid use has shown to affect plants and non-target species outside of the treated landscape. Recent studies have found that non-target field margins, wild plants, and pollinators have been impacted by farms that apply neonicotinoids through seed treatments (David et al. 2016; Main et al. 2020). Main et al. (2020) evaluated both native bee richness and plant and soil concentrations in field margins surrounding crop fields treated with clothianidin, imidacloprid, and thiamethoxam. They found that 50 to 90% of the field margins near treated sites were contaminated with neonicotinoids, but concentrations in soil (0 to 41.7 μg/kg) was higher than in wild plants (0 to 9.8 μg/kg) in the field margins (Main et al. 2020). Another concerning finding was the neonicotinoid concentration in the soil of untreated fields (0 to 9.33 μg/kg) (Main et al. 2020). This may likely be due to the coated seeds leaching into the ground and plants not holding onto the chemical, allowing it to travel to untreated lands. Additionally, as the concentrations of neonicotinoids increased, the species richness of native bees (i.e., bumble and solitary bees) decreased (Figure 8). This field study evaluated the soil and
plant tissue contaminated with fungicide and neonicotinoids on treated and untreated field margins (Main et al. 2020). This confirms that population levels decrease in areas where neonicotinoids are present.

![Figure 8](image)

**Figure 8. Relationship between wild bee richness and neonicotinoid concentrations in field margins.** There is a significant relationship ($P < 0.001$) between wild bee richness, neonicotinoid concentration (ug/kg) in soil, and fungicide concentration (ug/kg) in plants of field margins. As neonicotinoid concentration increased bee species richness decreased. A potential synergistic effect between fungicides and neonicotinoids is indicated by the high bee richness when neonicotinoid concentration was low and fungicide concentrations was high (Main et al. 2020).

David et al. (2016) also found wildflowers to be contaminated by nearby agricultural fields. However, the method of this field study was conducted differently. They evaluated the pollen contamination between the crop (oil seed rape), wildflowers, and bumble bees instead of evaluating the soil and plant tissue contamination as in the study by Main et al. (2020). While the methods were different, the contamination between agricultural land and field margins was synonymous. Although contamination was seen less in non-treated versus treated sites, it is concerning to see the potential for the neonicotinoids to move through the environment. This greatly increases the potential exposure rate for non-target species. With this movement,
neonicotinoids will be found in all types of land use areas, including those not targeted for pest control in agricultural environments.

4.2.b. Urban

Neonicotinoids are applied in urban areas to control pests on mostly woody shrubs, urban trees, and lawn landscapes (Larson et al. 2013; Mach et al. 2018). For woody plants, it is most often applied as a soil or trunk injection to help control common beetle pests (e.g., emerald ash borer, *Agrilus planipennis Fairmare*) (Furlan and Kreutzweiser 2015; Mach et al. 2018). While in turf landscapes the pest of concern are grubs, which feed on roots (Larson et al. 2013). Out of the three highly toxic neonicotinoids previously discussed, all three (clothianidin, imidacloprid, and thiamethoxam) were found in urban landscapes (Botías et al. 2017; David et al. 2016; Larson et al. 2013; Lawrence et al. 2016; Mach et al. 2018; Nicholls et al. 2018).

Neonicotinoid residues are most often found in the bark and leaves of the plant, as well as in the soil where it was injected or seeped into the ground. Exposure routes include soil contamination, when leaves excrete water, and pollen or nectar from flowers or woody plants. A concerning note by Mach et al. (2018), stated that there is currently no regulatory measure for neonicotinoid residues on ornamental woody plant. Current regulations are further discussed in Section 7: Pesticide Policies.

Overall, most exposure risks are found to be greatest in agricultural landscapes, but there is evidence of high exposure risk in urban areas as well (Botías et al. 2017; David et al. 2016; Larson et al. 2013; Lawrence et al. 2016; Mach et al. 2018). In some cases, exposure was found to be as high in urban environments as in their agricultural counterparts. Additionally, Nicholls et al. (2018) found that after the neonicotinoid ban in Europe, neonicotinoid exposure remained the same in urban areas for several active ingredients (clothianidin, imidacloprid, and thiamethoxam). The neonicotinoids may have not decreased due to a couple reasons. The ban specifically focuses on neonicotinoid application to agricultural crops, which is not broad enough to control the use of neonicotinoids in urban and suburban areas. Additionally, despite the bans for agricultural use, there is a knowledge gap and lack of education on the use of neonicotinoids in urban and residential settings. Neonicotinoid active ingredients are still available in urban use products, and many people do not know how to look out for this type of
pesticide or how it is harmful to bees. The lack of knowledge and patrolling of how often neonicotinoids are purchased and applied by consumer residents makes it difficult to build evidence on the actual use of neonicotinoid insecticides on urban landscapes, including in California. Lack of knowledge and understanding by residents on the potency of products and how to best use them can be detrimental to non-target insects that reside in urban areas.

As urban areas increase, so will the abundance of ornamental plants. Ornamental plants are beneficial for some insect species, like the bumble bee (McFrederick and LeBuhn 2006). However, without proper outreach and education to applicators and the community, the use of neonicotinoids will further exacerbate the declining bee population. For instance, Larson et al. (2013) noted after their study that applicators should continue to follow and educated on the U.S. EPA guidelines to not apply to flowering plants (e.g., dandelions or clovers). If the flowers are thought to be contaminated with these insecticides, they advise to mow the lawn immediately to eliminate the exposure risk to bees. As natural habitats (e.g., fields and pastures) become less viable and abundant we need to ensure the number of floral resources in homes and urban greenspaces is not contaminated with these pesticides, or if no other option is available, used correctly.

When possible, it is important to compare landscapes side-by-side. Fortunately, a few studies compared neonicotinoid concentration in pollen and nectar from beehives, pollen, and nectar from individual bumble bees in urban and agriculture landscapes side-by-side. The studies offer a unique comparison of landscapes and neonicotinoid exposure to bee species. However, these studies only analyzed honey bee and bumble bees. None were found for solitary bee species and all but one study took place in Europe (primarily the United Kingdom). Table 2 compares the main outcomes from each study. Between the four studies, there was an equal detection between agricultural and urban landscapes (Botías et al. 2017; David et al. 2016; Lawrence et al. 2016; Nicholls et al. 2018).
Table 2. Synthesis of literature directly assessing neonicotinoid concentrations between agriculture and urban landscapes. Concentrations were found in pollen and nectar from honey and bumble bee hives and in bumble bee individuals.

<table>
<thead>
<tr>
<th>Literature source</th>
<th>Sample Analyzed</th>
<th>Landscape with highest neonicotinoid detection</th>
<th>Active ingredient most detected¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Botías et al. 2017</td>
<td>Bumble bee individuals (ng/g)</td>
<td>Urban</td>
<td>Imidacloprid (10 ng/g in bee)</td>
</tr>
<tr>
<td>David et al. 2016</td>
<td>Pollen from bumble bee hives and individuals (ng/g)</td>
<td>Agriculture</td>
<td>Thiamethoxam (1.7-35 ng/g in pollen; 0.3-0.9 ng/g in bee)</td>
</tr>
<tr>
<td>Lawrence et al. 2016</td>
<td>Bee bread from honey bee hives (ng/g)</td>
<td>Agriculture</td>
<td>Thiamethoxam (0.47-2.41 ng/g in bee bread)</td>
</tr>
<tr>
<td>Nicholls et al. 2018</td>
<td>Pollen and nectar from bumble bee hives (ng/g)²</td>
<td>Urban³</td>
<td>Imidacloprid (11.16 ng/g in pollen; ≤ 0.14 ng/g in nectar)</td>
</tr>
</tbody>
</table>

¹Each study analyzed for the three main neonicotinoid insecticides: clothianidin, imidacloprid, and thiamethoxam.
²Study surveyed samples from 2013 to 2015. Only 2015 samples were synthesized for this table for the most recent data between urban and rural landscapes.
³Nicholls et al. 2018 surveyed, peri-urban landscapes which is defined as domestic gardens on the outskirts of urban areas. For the purposes of this research, it is reclassified as urban.

However, to better synthesize the results only the most recent data from 2015 in Nicholls et al. (2018) was used. In the first year of the study (2013) pre-ban, agricultural areas had a greater detection of neonicotinoids present than in urban areas. It is interesting to note that each landscape with the highest neonicotinoid detection had the same active ingredient. In agricultural landscapes, the active ingredient thiamethoxam was detected the most out of the neonicotinoids tested. While in urban landscapes, the active ingredient imidacloprid was the most detected. Starting in the 1990s, imidacloprid was the main neonicotinoid insecticide used on agricultural landscapes, but in the early 2000s it was overtaken when thiamethoxam was created (Douglas and Tooker 2015). This suggests that imidacloprid became less used (potentially due to effectiveness) in agricultural landscapes but is still often used in urban landscapes.

Aside from the difference in methods, it is important to note the potential for confounding factors in these field studies. For instance, Botías et al. (2017) found one species of
bumble bee that had a very high neonicotinoid detection from an urban area. This may be due to recent spraying that was not documented before sampling. In urban landscapes, it is difficult to account for use near residential areas since some products may be applied near the study site without researcher’s knowledge. While these studies help provide a clearer comparison between these two landscapes, there is still a need for more field and sub-field studies comparing urban and agricultural areas side-by-side along with neonicotinoid use and exposure to bees. Additional studies on the effects of neonicotinoids post-ban will also help guide how long it takes for these insecticides to be effectively removed from both landscapes.

The amount of time for landscapes to recover from neonicotinoids is not well documented. They have been found to persist in agricultural landscapes for over two years, even after application has ceased, depending on environmental conditions. Their persistence is even more concerning, considering their ease of transport between environments. They have been detected in soil and plants where neonicotinoids were not applied, including along field margins where the land was treated and where lands were not treated by neonicotinoids. The high solubility and low sorption rate of neonicotinoids (when organic matter is low) may play a key role in their ability to leach into nearby untreated landscapes. Overall, there are more studies that assess the use of neonicotinoids in agricultural areas versus urban areas. However, when comparing landscapes side-by-side, the detection of neonicotinoids was evenly split between agricultural and urban landscapes. This could be due to lack of reporting, neonicotinoids ban in Europe, and lack of studies focusing on urban landscapes. California currently has no bans on neonicotinoid insecticides in agriculture or urban landscapes.

4.3. Reporting

Data drives decisions and reporting is a great tool to help make informed decisions to improve actions that alter natural resources. Currently, farmers and local municipalities are required to report their pesticide use. California farmers report their pesticide use to the County Agricultural Commissioner, while municipalities report to their county and to their Regional Water Quality Control Board as part of the Municipal Regional Stormwater National Pollutant Discharge Elimination System Permit (California State Water Resources Control Board 2021; Durant 2020). Municipalities are required under Provision C.9 – Pesticide Toxicity
Controls to report the amount of pesticide of concern used on city property. The data reported to the county is then entered into CDPR’s PUR database. Honey bee apiaries are also required under 13 Food and Agriculture Code 7 § 29101 to report their hive locations to be adequately notified of potential spray drift (Durant 2020). However, this does not take into account seed coating or injections, which have been found to lead to sublethal effects in bees (Blacquièire et al. 2012; Bonmatin et al. 2015; Woodcock et al. 2017).

Pesticide applicators most often include farmers, but there are also contractors that professionally apply the pesticide as well as residential applicators. Commercial and professional applicators are taught how to read U.S. EPA recommended labels. Pesticide applicators can also be residents, but this is not as well documented due to lack of reporting (Bucy and Melathopoulos 2020). If the U.S. EPA recommended language is not used, the difference in labeling can be confusing to understand and the potential acute and residual toxicity of pesticides may be misrepresented. Applicators also need to be taught how to read product labels not using the U.S. EPA language to better assess ones that may be toxic to bees (Bucy and Melathopoulos 2020). Table 3 displays the recommended language for pesticide labels that have acute and residual toxicity to bees. There are several ways that the labelling can differ from the recommended language (Figure 9). Bucy and Melathopoulos (2020) found most often the label differs by mislabeling the acute toxicity of the active ingredient in the product and not using recommended language for residual and acute toxicity. There is no reporting required for residential applications, which is problematic for bees in urban environments (Botías et al. 2017). However, municipalities are required to report on their pesticide use in annual reports to the Regional Water Board and to the County Agricultural Commissioner.

Table 3. U.S. EPA recommended language for acute and residual toxicity to bees (Bucy and Melathopoulos 2020).

<table>
<thead>
<tr>
<th>Toxicity</th>
<th>Category (I to III)</th>
<th>Recommended Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute Toxicity (LD₅₀)¹</td>
<td>I (LD₅₀ &lt;2 μg/bee)</td>
<td>This product is highly toxic to bees</td>
</tr>
<tr>
<td></td>
<td>II (LD₅₀ &gt;2 μg/bee and &lt;11 μg/bee)</td>
<td>This product is moderately toxic to bees OR This product is toxic to bees</td>
</tr>
<tr>
<td></td>
<td>III (LD₅₀ ≥11 μg/bee)</td>
<td>No statement required on label</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Category (I to III)</td>
<td>Recommended Statement</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------------------</td>
<td>----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Residual Toxicity (RT&lt;sub&gt;25&lt;/sub&gt;)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>RT&lt;sub&gt;25&lt;/sub&gt; &lt;8 hrs</td>
<td>Do not apply…while bees…are actively foraging the treatment area OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Do not apply…while bees…are actively visiting the treatment area</td>
</tr>
<tr>
<td></td>
<td>RT&lt;sub&gt;25&lt;/sub&gt; &gt;8 hrs</td>
<td>Do not apply…if bees…are foraging the treatment area OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Do not apply…if bees…are visiting the treatment area</td>
</tr>
</tbody>
</table>

<sup>1</sup>Lethal dose to 50% mortality  
<sup>2</sup>Residual time to 25% mortality

### Figure 9.
Examples of how the product label can differ from the U.S. EPA recommended language (Bucy and Melathopoulos 2020).
One study evaluated the gaps in reporting knowledge concerning honey bee apiaries and pesticide exposure (Durant 2020). Durant (2020) identified the knowledge gaps and ignorance loops currently in place between apiaries, regulatory agencies, and farms. This is often due to the fact that apiaries must follow the guide of the farms and not the other way around. She found a lack of education and outreach, poor reporting by honey bee farmers (for both bee kills and where hives are placed), and described the “label is law” thought process that often hinders investigations. The “label is the law” means that only pesticides that are already labelled as toxic will be investigated if a bee kill occurs. Investigators will not conduct investigations if a bee kill occurred by a pesticide that is not currently on the list of toxic pesticides to bees (Durant 2020). This is problematic, as it can hinder early evaluation of new pesticides used and their effects on pollinators. Additionally, this is important to make sure that neonicotinoids are labelled properly for risk assessments to encourage appropriate reporting.

Although urban and agricultural municipalities are required to report their pesticide use, there is a short fall or gap in knowledge in urban reporting on the residential use of neonicotinoids. There are numerous pesticides that contain neonicotinoids that are readily available in garden or home improvement centers (Bucy and Melathopoulos 2020). Bucy and Melathopoulos (2020) found that 63% of the products assessed in their study for were specifically for urban settings (e.g., garden use). However, the average resident is not well versed on pesticide toxicity, aside for determining if the product will take care of the pest at hand. Additionally, most of these products do not accurately display their toxicity to bees, which makes it difficult for homeowners to make educated decisions on what products to use. The non-profit organization, Center for Food Safety (2016), has provided a fact sheet of commonly available products in home and garden centers that contain neonicotinoids. However, it does not include all products that contain a neonicotinoid active ingredient. While this information is extremely helpful, homeowners are not required to report pesticide use and many are unaware of the effects their use may ultimately have on non-target species. This gap in knowledge of the amount of neonicotinoids applied by residential consumers has made it difficult to account for the potential synergistic effects of neonicotinoid insecticides in urban environments.
5. Neonicotinoid toxicity to bee species

Since its first use in 1990, neonicotinoid insecticides have exponentially grown throughout the world and are now a primary chemical pest control in agriculture and urban settings (Douglas and Tooker 2015; Hladik et al. 2018; Tafarella et al. 2018). It is found to be less toxic to mammalians (i.e., humans) compared to other toxic insecticides like organophosphates, which may be a reason for its increase (Hladik et al. 2018). Despite the reduced risk to mammalian species, neonicotinoids have lethal and sublethal toxic effects to pollinators. Neonicotinoid insecticides are a neurotoxin that disrupts the mobility of insect species, which can lead to death at certain doses (Blacquière et al. 2012; Stokstad 2013). These insecticides can be applied through spray, injection into soil or woody plants, or coated on seeds (Bonmatin et al. 2015). Additionally, they are a systemic insecticide, which means it is taken up by plants and remains in plant matter, including in the pollen and nectar of flowering plants, which is the main food source for bees (Bonmatin et al. 2015). The multiple application options and systemic properties creates several potential exposure routes for non-target insects, like bees. Understanding the toxicity of neonicotinoids after application is important to determine when bees may be at risk of lethal or sublethal effects. The subsections below describe the lethal and sublethal toxicities of the main active ingredients frequently found in literature and discusses current risk assessments conducted for managed and wild bee species.

5.1. Lethal (Acute/Chronic) Toxicity

There are two measurements of lethal toxicity: acute and chronic. Acute toxicity is when a species perishes from a toxin at a certain threshold from oral or topical exposure. It is most often measured using the median lethal dose (LD_{50}), where 50% of the population dies after a single dosage of a toxin between 24 and 48 hours. This measurement is currently used to determine the acute toxicity of pesticides to pollinators (Blacquière et al. 2012; U.S. EPA 2014). Chronic toxicity is normally measured through lethal concentration (LC_{50}) where 50% of the population perishes after a concentration of an active ingredient (usually via sucrose solution or applied directly to species) is tested over a 10-day period (Blacquière et al. 2012; U.S. EPA 2014). Both LD_{50} and LC_{50} values are often compared alongside each other in meta-analyses (Arena and Sgolastra 2014; Cresswell 2011; Sanchez-Bayo and Goka 2014). The majority of the
lethal values are determined in a laboratory setting rather than a field setting, since conducting field studies is often more complex and expensive to complete (U.S. EPA 2014). The LD$_{50}$ is most often measured by dose in micrograms or nanograms per bee (μg or ng/bee), and LC$_{50}$ is measured in parts per million/billion (ppm/b) or milligrams per liter (mg/L). For this paper, units were converted from μg to ng and mg/L to ppm for ease of comparison (Table 4).

The most common method to evaluate LD$_{50}$ and LC$_{50}$ values is through oral exposure studies by feeding pesticide contaminated sucrose solutions to bees (Cresswell 2011; Heard et al. 2017; Hladik et al. 2018; Mommaerts et al. 2010; Sanchez-Bayo and Goka 2014). However, some studies also evaluate contact exposure (LD$_{50}$) by applying the pesticide directly to the bee (Iwasa et al. 2004; Uhl et al. 2019). Contact exposure can be measured by the amount of pesticide residue in pollen, nectar, or within the bee itself (Botías et al. 2017; David et al. 2016). To measure the concentration in a bee, the specimen is ground up, mixed with a solution, and evaporated to measure the weight of the pesticide.

There are ranges of lethal toxicity levels since each neonicotinoid active ingredient needs to be evaluated for each individual bee species. Each active ingredient has been found to have a slightly different lethality than the other (Blacquière et al. 2012; Heard et al. 2017; Sanchez-Bayo and Goka 2014; Uhl et al. 2019). There are six different active ingredient neonicotinoid insecticides that are currently applied and analyzed in bee toxicity studies: 1) acetamiprid 2) clothianidin, 3) dinotefuran, 4) imidacloprid, 5) thiamethoxam, and 6) thiacloprid (Heard et al. 2017; Hladik et al. 2018; Sanchez-Bayo and Goka 2014; Uhl et al. 2019). The top three most often found and highly toxic active ingredients to pollinators are clothianidin, imidacloroprid, and thiamethoxam (Hladik et al. 2018). For these three neonicotinoids, Hladik et al. (2018) found the oral acute toxicity (LD$_{50}$) is 1 to 5 ng/bee.

Several other studies identified LD$_{50}$ and LC$_{50}$ values based on the bee species assessed and type of exposure (oral vs. contact), but they are not consistent between each species (Table 4). The honey bee has been analyzed individually for all three most toxic neonicotinoids with LD$_{50}$ of 4.5 to 13 ng/bee (oral), 18 to 245 ng/bee (contact), and LC$_{50}$ of 0.104 ppm (oral) (Blacquière et al. 2012; Hladik et al. 2018; Sanchez-Bayo and Goka 2014; Uhl et al. 2019). There are not as many acute toxicity studies available for the three most toxic neonicotinoids on wild
bee species compared to managed bees. However, there are a few studies that found LD$_{50}$/LC$_{50}$ values for the three neonicotinoids for bumble bees (Table 4). The LD$_{50}$ values were identified in laboratory and semi-field studies and ranged from 20 (contact) to 30 (oral) ng/bee (clothianidin and imidacloprid), and oral LC$_{50}$ between 0.02 and 0.12 ppm (clothianidin, imidacloprid, and thiamethoxam) depending on if the bumble bee was foraging (Heard et al. 2017; Mommaerts et al. 2010; Sanchez-Bayo and Goka 2014). While solitary bees were noted to have a contact exposure LD$_{50}$ of 30 ng/bee (imidacloprid) and oral exposure LC$_{50}$ of 0.042 ppm (clothianidin) (Heard et al. 2017; Uhl et al. 2019). While toxicity can begin to be pieced together, there is still a dearth of toxicity information for both oral and topical exposure for wild bees.

Additionally, it is difficult to compare the neonicotinoid sensitivity between the species due to the type of methods used within each study and lack of field studies to assess field concentrations. However, Table 4 allows for some comparison between oral and topical exposures for LD$_{50}$ and LC$_{50}$ values. The majority of lethal toxicity tests conducted used oral exposure, which also had lower LD$_{50}$s compared to topical exposures. This suggests that oral exposure is more toxic to bees than topical exposure. When evaluating each individual active ingredient, some comparisons between species for clothianidin and imidacloprid can be made.

Table 4. Lethal toxicity range (LD$_{50}$ and LC$_{50}$ values) for managed and wild worker bee species. Bee species were tested with oral and contact exposure from three highly toxic neonicotinoid active ingredients (clothianidin, imidacloprid, and thiamethoxam).

<table>
<thead>
<tr>
<th>Exposure$^1$</th>
<th>Clothianidin</th>
<th>Imidacloprid</th>
<th>Thiamethoxam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LD$_{50}$ (ng/g)</td>
<td>LC$_{50}$ (ppm)</td>
<td>LD$_{50}$ (ng/g)</td>
</tr>
<tr>
<td><strong>Bee</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apis mellifera</td>
<td>4</td>
<td>22 to 40</td>
<td>0.104</td>
</tr>
<tr>
<td>Bombus spp.</td>
<td></td>
<td>20</td>
<td>0.037</td>
</tr>
<tr>
<td>Osmia spp.</td>
<td></td>
<td></td>
<td>0.042</td>
</tr>
</tbody>
</table>

$^1$Exposure route specimen was subjected to during study is categorized between oral (O) and topical (T).
First, there were not enough studies reviewed that assessed lethality of thiamethoxam. For clothianidin, the bumble bee (Bombus spp.) was the most sensitive for LC$_{50}$ out of the three species, and was more sensitive to the topical exposure (LD$_{50}$) compared to the honey bee (Apis mellifera). For imidacloprid the honey bee is noted to be more sensitive from oral and contact exposure than the bumble bee. However, the topical exposure values had a greater range difference. The honey bee often had a range of LD$_{50}$ values, which may be due to the higher number of studies conducted on them. These comparisons show that honey bees may be an adequate surrogate for wild bee species, depending on the active ingredient or if an order of magnitude is applied. However, these studies were only conducted via laboratory and semi-field studies. Field studies must be conducted to account for each species life histories and determine real-field exposure rates that may impact each bee.

As previously mentioned, the most common method used to assess toxicity is through oral exposure. This is important to consider based on how the neonicotinoid is applied in the field and how long the toxin remains lethal in the plants and soil. However, none of the lethal studies analyzed were conducted fully in the field. To find the lethal value the majority of studies were conducted in laboratory settings. While laboratory methods provide valuable information, it does not take into account potential real-field doses. Laboratory studies may overlook the potential synergistic or additive effects that may occur in the environment, since multiple neonicotinoid insecticides are used across landscapes (along with other pesticides). For instance, it has been noted that the application of fungicides may cause an additive effect to neonicotinoids when applied concurrently (Figure 8) (Main et al. 2020).

Because of the broad application of pesticides, bees may come across a variety of neonicotinoids that may harm them faster than the lethal dose of a single neonicotinoid exposure (Blacquière et al. 2012; Hladik et al. 2018; Sanchez-Bayo and Goka 2014; Woodcock et al. 2017). For instance, Woodcock et al. (2017) found three neonicotinoid active ingredients mixed together (clothianidin, thiamethoxam, and imidacloprid) in farm landscapes that impacted honey bee, bumble bee, and solitary bee species. These interactions were found to cause lethal and sublethal effects to the three bee species. While it is important to know the
lethal dose of neonicotinoid insecticides on pollinators, it is just as important to understand the sublethal toxicity of each neonicotinoid active ingredient.

5.2. Sublethal Toxicity

Sublethal toxicity is the long-term effects from a toxin (e.g., neonicotinoid insecticides) after exposure through ingestion or topical application. These sublethal effects are normally identified using no observed effect concentrations/levels (NOEC/L), no observed adverse effect concentrations/levels (NOEAC/L), or effect concentration for 50% (EC$_{50}$) (Blacquière et al. 2012; Mommaerts et al. 2010; U.S. EPA 2014). The most common method to evaluate NOEC/L values is through oral exposure studies by feeding pesticide contaminated sucrose solutions to bees (Table 5). However, the level of neonicotinoid residue (μg/kg or ng/g) in nectar, pollen or nests was also evaluated in several studies (Blacquière et al. 2012; Woodcock et al. 2017). The NOEL is most often measured by dose in micrograms or nanograms per bee (μg/kg or ng/g), and NOEC is measured in parts per million/billion (ppm/b) or microgram or milligram per liter (μg/L or mg/L). For this paper, units were converted to ng and or ppm for ease of comparison (Table 5).

Sublethal effects include inhibiting the behavior, reproduction, and overall fitness of bee species. Bee species are more likely to experience sublethal effects than lethal effects in the field, due to increased policies to limit acute exposure of pesticides in the field (California Department of Pesticide Regulation 2018). For example, farmers and pesticide applicators should not apply a pesticide while bees are in active flight (i.e., during the day). With the continued and escalated use of neonicotinoids, and its systemic and persistent abilities, understanding the sublethal toxicity is more important than ever to develop practices to reduce chemical treatments (Tafarella et al. 2018). The different sublethal effects are discussed below, but most often include decreased navigation, foraging, mobility, reduced queen viability, brood reproduction, reduced vitality (susceptibility to parasites), and overall population decline (Blacquière et al. 2012).

Even low levels of neonicotinoids over a long period of time can reduce bee fitness for honey bee, bumble bee, and solitary bee species (Blacquière et al. 2012; Woodcock et al. 2017). Several laboratory studies have found that this neurotoxin decreases the motor ability, sensory
functions, and cognitive ability of honey bee and bumble bee species (Blacquière et al. 2012; Cresswell et al. 2012; Siviter et al. 2018). Cresswell et al. (2012) found that as the active ingredient imidacloprid in the sucrose solution increased (> 0.00128 ppm), the bumble bees’ ability to move greatly decreased. While the honey bee saw less adverse effects in their movement and seemed to be able to metabolize the active ingredient more effectively. The lack of ability for the bumble bee to metabolize neonicotinoids may be due to their larger body sizes (Cresswell et al. 2012; Siviter et al. 2018). In addition to a decrease in mobility, both honey bee and bumble bee species were found to experience significant negative effects to their learning and memory abilities from neonicotinoids (Siviter et al. 2018). This effect may cause the hive to decrease if bees have difficulty remembering where to collect food resources or returning to their hives, which indicates the importance of foraging to sustain the hive.

Foraging, homing, pollen collection, nectar consumption, and brood reproduction was seen to decrease at sublethal levels for all three bee species (Laycock et al. 2012; Mommaerts et al. 2010; Stanley et al. 2016; Woodcock et al. 2017). The foraging behavior, nectar consumption, and pollen collection was noted to decrease when exposed to imidacloprid and thiamethoxam between 0.00127 and 0.02 ppm in sucrose solutions the bees consumed (Laycock et al. 2012; Mommaerts et al. 2010; Stanley et al. 2016). This behavior change causes adverse impacts to the hive by decreasing the overall health and population. For example, the lack of sustenance inevitably decreases brood reproduction. Brood reproduction for bumble bees was found to decrease at sublethal doses as low as 0.001 ppm of imidacloprid in sucrose solutions (Table 5) (Laycock et al. 2012).

However, other field studies found that neonicotinoids did not have an adverse effect on bee species. In a field study for solitary bees, the brood cell production and fecundity were not affected at the highest residue of thiamethoxam of 4 ng/g in pollen (Ruddle et al. 2018). Additionally, in a field study for honey bees near organic and conventional corn fields, foraging and colony growth was found to not be affected by pollen residue contaminated with clothianidin (0.8 ng/g) (Cutler and Scott-Dupree 2014). These conflicting results stress the importance of conducting behavior studies on a wide range of sublethal doses for each neonicotinoid active ingredient and bee species. This will help determine the dose of
neonicotinoids that may still be safely used, and which active ingredient poses the greatest risk to the overall health of each bee species based on their life history traits.

In the recent risk determination by the California Environmental Protection Agency and CDPR, NOEC values were determined for four neonicotinoid insecticides (imidacloprid, thiamethoxam, clothianidin, and dinotefuran) (Tafarella et al. 2018). Respectively the values range from 97.5-372 μg/kg for pollen and 19-71 μg/kg for nectar (Tafarella et al. 2018). These NOEC values were determined to be the lowest level of no observable effect to honey bee colonies taken from several colony level studies evaluating sucrose solutions and pollen balls. These are considered acceptable levels of neonicotinoid residues that honey bees may be exposed to on agricultural crops. However, a recent field study to assess long-term effects of thiamethoxam on honey bee colonies in agricultural fields does not support the NOEC value identified in the risk determination (Thompson et al. 2019). Thompson et al. (2019) found that no effects were observed for thiamethoxam at 38 ng/g in sucrose solution, but when reaching above 50 ng/g in sucrose the offspring, colony growth, and pollen/nectar consumption began to decrease. This finding is significantly lower than the values presented in the risk determination.

In another field study, the sublethal effects of thiamethoxam were observed in bumble bee and solitary bee species at even lower levels. Woodcock et al. (2017) identified clothianidin, thiamethoxam, and imidacloprid exposure to wild bees through a sum concentration of all three residues found in nests ranging from 0 to 9 ng/g. As these residue levels increased the queen production of bumble bees and brood cell size of solitary bees decreased. This is a much lower range of neonicotinoid exposure than noted in other studies, but it is worth noting that the neonicotinoid active ingredients were combined in this analysis. This finding indicates that a lower level of neonicotinoid residues can cause sublethal effects at lower ranges when combined creating an additive effect.

A summary of the studies discussed above are further compared in Table 5. Overall, there was an even split between laboratory and field studies conducted to determine sublethal effects. The majority of the studies also used sucrose solution as the exposure medium, which allows for a better control of exposure, and identifying the level when sublethal effects are observed. The sublethal effects most often analyzed was brood reproduction and foraging.
ability. These two endpoints are extremely important in the sustainability of bee populations. Without adequate foraging, there will be less food resources brought back to the hives, and with lower brood reproduction the species will quickly face population decline. When comparing the NOEL/C values, the bumble bee seems to be more sensitive to neonicotinoids than the honey bee. However, it is important to note the difference in study methods here. For instance, the majority of honey bee studies evaluated were colony level exposure (Cutler and Scott-Dupree 2014; Tafarella et al. 2018). Additionally, honey bees may be able to handle greater levels of neonicotinoids due to their colony buffer or higher rate of metabolism to process the chemicals (Cresswell et al. 2012). Solitary bee species may be more sensitive to neonicotinoids at sublethal toxicities as well, but there were only two studies that included solitary bees (Table 5), which had differing results. Woodcock et al. (2017) found that solitary bee brood cell reproduction decreased between 0 to 9 ng/g in pollen residues, while Ruddle et al. (2018) found no effect at 4 ng/g in pollen. Overall, there is a lack of sublethal studies for wild bee species, especially for solitary bees. More studies assessing the sublethal effects of solitary bees need to be conducted.

Table 5. Sublethal effects on managed and wild worker bee species from three highly toxic neonicotinoid active ingredients (clothianidin, imidaclorpid, and thiamethoxam).

<table>
<thead>
<tr>
<th>Literature</th>
<th>Bee Species</th>
<th>Exposure Medium</th>
<th>Study Type</th>
<th>Sublethal effect analyzed</th>
<th>Active Ingredient</th>
<th>NOEL (ng/g)</th>
<th>NOEC (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodcock et al. 2017</td>
<td>Bombus spp / Osmia spp</td>
<td>P/N Field</td>
<td>brood reproduction</td>
<td>CLT/ IMD/ THX2</td>
<td>0 to 9 (Bombus/ Osmia)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cresswell et al. 2012</td>
<td>Apis mellifera / Bombus spp</td>
<td>SS Lab</td>
<td>feeding rate, mobility, longevity</td>
<td>IMD</td>
<td>4.9 (Apis)</td>
<td>0.00128 (Bombus)</td>
<td></td>
</tr>
<tr>
<td>Laycock et al. 2012</td>
<td>Bombus spp</td>
<td>SS Lab</td>
<td>brood reproduction</td>
<td>IMD</td>
<td></td>
<td>0.00127</td>
<td></td>
</tr>
<tr>
<td>Mommaerts et al. 2010</td>
<td>Bombus spp</td>
<td>SS Lab</td>
<td>foraging</td>
<td>IMD; THX</td>
<td></td>
<td>0.01-0.02; 0.01</td>
<td></td>
</tr>
<tr>
<td>Thompson et al. 2019</td>
<td>Apis mellifera</td>
<td>SS Field</td>
<td>brood reproduction &amp; pollen</td>
<td>THX</td>
<td>37.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stanley et al. 2016</td>
<td>Bombus spp</td>
<td>SS Lab/Semi-field</td>
<td>foraging &amp; pollen/nectar collection</td>
<td>THX</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Literature</td>
<td>Bee Species</td>
<td>Exposure Medium¹</td>
<td>Study Type</td>
<td>Sublethal effect analyzed</td>
<td>Active Ingredient²</td>
<td>NOEL (ng/g)</td>
<td>NOEC (ppm)</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
<td>------------------</td>
<td>------------</td>
<td>--------------------------</td>
<td>---------------------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>Cutler and Scott-Dupree 2014</td>
<td>Bombus spp</td>
<td>P</td>
<td>Field</td>
<td>foraging &amp; colony growth</td>
<td>CLT; THX</td>
<td>0.1 to 0.8; &lt;0.1</td>
<td></td>
</tr>
<tr>
<td>Ruddle et al. 2018</td>
<td>Osmia spp.</td>
<td>P</td>
<td>Field</td>
<td>Brood cell production &amp; fecundity</td>
<td>THX</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Tafarella et al. 2018⁴</td>
<td>Apis mellifera</td>
<td>SS/P/N</td>
<td>Field</td>
<td>brood reproduction</td>
<td>CLT; IMD; THX</td>
<td>19,000 (N), 372,000 (P); 23,000 (N), 97,500 (P); 30,000 (N), 372,000 (P)</td>
<td></td>
</tr>
</tbody>
</table>

¹Exposure medium tested during study: pollen (P), nectar (N), sucrose solution (SS), or bee individual (B)
²Active ingredients analyzed: clothianidin (CLT), imidacloprid (IMD), and thiamethoxam (THX)
³Woodcock et al. 2017 summed the total of all three neonicotinoids found in nests
⁴Colony level study

When comparing between the lethal and sublethal effects of clothianidin, imidacloprid, and thiamethoxam, the sublethal toxicity was often one magnitude lower than the lethal toxicity for the three neonicotinoids (Table 4 and Table 5). From the literature review, there was a range of values found for lethal and sublethal endpoints. This was often due to the difference in methods used (laboratory vs. semi-field vs. field), different species used, exposure route (oral vs. contact), and exposure medium (nectar, pollen, sucrose solution, individual bee) evaluated. When comparing between the three bee species, there is still not enough studies on wild bee species and behavior studies to make an accurate comparison. A few meta-analyses have shown that honey bees are slightly more sensitive to pesticides than bumble or solitary bee species (Arena and Sgolastra 2014; Cresswell 2011; Heard et al. 2017). However, they also found that in some cases (for NOEC and LD₅₀) the bumble and solitary bees are more sensitive to neonicotinoids than honey bees (Alkassab and Kirchner 2017; Arena and Sgolastra 2014; Heard et al. 2017). Overall, the lethal and sublethal effects have shown that if neonicotinoid use continues to be used at the current rate, there will be a decrease in pollination services as managed and wild bee populations continue to decrease.
5.3. Risk Assessments

To determine the risk of pesticide toxicity to bee species, the U.S. EPA collaborated with the CDPR and Health Canada’s Pesticide Regulatory Agency to develop a risk assessment guidance process with a three Tier system (U.S. EPA 2014). The three tiers include, Tier I (laboratory studies), Tier II (semi-field studies on colony effect), and Tier III (full field studies) (U.S. EPA 2014). This guidance is to be used as an increasing step process to determine pesticide risks to pollinators, particularly bees. The first and most often used risk assessment conducted by the U.S. EPA is Tier I where laboratory studies are reviewed based on pesticide exposure risks (oral and contact) from foliar spray, seed treatment and soil application (U.S. EPA 2014).

Tier I is considered the screening level of the process to determine the risks to pollinators for both acute and chronic toxicity levels, which can be further refined if moderate or high risks are identified (U.S. EPA 2014). If risks are determined in Tier I, it is advised to identify mitigation actions to avoid risk. Mitigation measures are considered based on the route of exposure and risk, which can also be further supported during Tier II and Tier III assessments. For example, one mitigation measure to avoid direct pesticide exposure (potential bee kill) is to reduce pesticide application during blooming period and bee foraging times (California Department of Pesticide Regulation 2018). Each pesticide is reevaluated every 15 years (Durant 2020). The guidance on risk determination is to be used for all pesticide risk assessments, including for neonicotinoid insecticides.

Due to the increased use of neonicotinoids and studies identifying its potential toxic effects on pollinators, the California Environmental Protection Agency and CDPR conducted a risk determination for neonicotinoids on honey bee colonies (Tafarella et al. 2018). The determination expanded on the Tier I (laboratory) assessments by conducting Tier II assessments through semi-field studies to evaluate the effects of neonicotinoids that are applied to agricultural crops on honey bee colonies (adults and larvae) (Tafarella et al. 2018). The NOEC of neonicotinoids to honey bee colonies were identified for four neonicotinoid active ingredients (imidacloprid, thiamethoxam, clothianidin, and dinotefuran) to determine the risk for numerous agricultural crops.
During the risk determination, the NOEC was used for nectar and pollen residues instead of LD₅₀ or LC₅₀ values. Most risk assessment studies evaluate the LD₅₀ or LC₅₀ values to determine the amount where 50% of the population perishes (Arena and Sgolastra 2014; Heard et al. 2017; Sanchez-Bayo and Goka 2014; Uhl et al. 2019; Woodcock et al. 2017). However, during Tier II assessments sublethal effects were assessed. The NOEC identifies the concentration below even the lowest observed effect, which helps identify the sublethal levels of neonicotinoids. As mentioned in the sublethal toxicity section above, the NOECs found from the risk determination identifies the safest concentration amount that honey bee colonies can be exposed to with no effects observed based on the semi-field studies.

As previously mentioned, the NOEC for the four neonicotinoids (imidacloprid, thiamethoxam, clothianidin, and dinotefuran) ranges from 97.5-372 μg/kg for pollen and 19-71 μg/kg for nectar (Tafarella et al. 2018). These values are used to help determine the product use instructions and to update product labels noting the residue amount allowed for each individual active ingredient. During the risk determination, exposure route was also assessed for the application to a particular agricultural crop. Both oral (nectar/pollen) and contact (pollen) exposures were assessed for honey bee colonies during, which provided residue and risk assessments for each agricultural crop favored by bees (Tafarella et al. 2018). This risk determination provides further clarification on pesticide exposure, risk, and guidance to protect bee species from neonicotinoid insecticides.

As mentioned, standard risk assessments for honey bees are conducted by the U.S. EPA and California Environmental Protection Agency, but risk assessments have also been conducted in individual studies for the three bee species discussed (Blacquière et al. 2012; Sanchez-Bayo and Goka 2014; Sgolastra et al. 2019; Uhl et al. 2019). Several risk assessments have been conducted for each species or comparing two species together (e.g., honey bee vs. solitary bee or honey bee vs. bumble bee). However, few studies have been conducted to compare neonicotinoid risks (LD₅₀/LC₅₀) between all three species for most neonicotinoid active ingredients (Arena and Sgolastra 2014; Heard et al. 2017). Heard et al. (2017) conducted an oral toxicity comparison (LC₅₀) for clothianidin between the three bee species at 48-, 96-, and 240-hour increments. They found that the bumble bees (Bombus terrestris) and solitary bees (Osmia
**bicornis** were more sensitive to clothianidin than the honey bees (*Apis mellifera* spp.) at 48 hours, but gradually became equally or less sensitive than honey bees at 240 hours. Due to the change over time, these results do not provide a clear indication which bee species is more sensitive or at risk to the neonicotinoid active ingredient, clothianidin.

Another study that compared the three species was conducted by Arena and Sgolastra (2014). They conducted a meta-analysis to determine if honey bees are more sensitive than other bee species. The results determined that when a factor of 10 is added to the LD$_{50}$ of honey bees, then *Apis mellifera* is a good surrogate to protect other bee species. However, the study did not provide enough detail on which active ingredients of neonicotinoids were assessed for each bee species. Additionally, neither of these risk assessment studies evaluated the risk of behaviors affected during sublethal exposures. This is important to consider, especially if levels of sublethal toxicity are approved for use on plants, as seen in the risk determination by CDPR. Overall, more risk assessments, especially Tier II and III, comparing these three managed and wild bee species in the field need to be conducted for each neonicotinoid active ingredient at both the acute and sublethal level analysis.

### 6. Alternative Actions to Neonicotinoid Use

One way to help control the use and toxicity of neonicotinoid insecticides is to encourage more sustainable (non-chemical) practices in agriculture and urban environments. Recently, European countries have taken action to reduce the use of neonicotinoid insecticides on agricultural landscapes. Starting in 2013, the European Union restricted the use of three highly toxic neonicotinoids (clothianidin, imidacloprid, and thiamethoxam) on agricultural flowering crops (e.g., oil seed rape, sunflower, and corn), and in 2018 they brought it a step further and banned use on all agricultural field crops (Jactel et al. 2019; Kathage et al. 2018; Nicholls et al. 2018). These restrictions were based on scientific findings of the negative effects on pollinators (specifically bees).

With these new restrictions, alternative actions must be taken to continue an efficient crop yield. A few studies have been conducted to evaluate the alternative actions farmers may use under the bans. Some are taking a more holistic approach through integrated pest management, while others continue to utilize unrestricted pesticides in soil and treated seeds.
to combat against continued pest pressure. The subsections below discuss the actions available to farmers post-restriction implementation with a specific focus on integrated pest management and a case study of more sustainable alternative actions conducted for corn fields and forests.

6.1. Post-restriction Actions

After the first restrictions on neonicotinoids were put into place in 2013, European farmers needed to transition to alternative actions to control pests. However, determining the most efficient and cost-effective alternative actions is a challenge since pest control is site specific. One study conducted in France assessed potential alternative practices available to farmers to best control pest pressure that neonicotinoids focused on (Jactel et al. 2019). Jactel et al. (2019) analyzed peer-reviewed literature, categorized them by eight alternative action categories, and evaluated each by efficacy, durability, applicability, and practicability compared to neonicotinoids.

The eight alternative actions categorized included: 1) other synthetic insecticides, 2) biological control by large predators, 3) biological control by microorganisms (e.g., fungi and bacteria), 4) biological control through different planting methods (e.g., hedgerows); 5) semiochemicals (e.g., trapping or disrupting mating); 6) physical (e.g., altering plants, trapping), 7) genetically modified plants, and 8) eliciting natural plant defenses (e.g., biocide). A semi-quantitative score was given for each evaluation between 1 to 3, with 3 being the highest score. High efficacy meant that there was no yield loss and low pest damage; high durability meant the alternative had a low risk of pest resistance; highly applicable alternative meant the method was already being used in France; while a high practicable score was given if the alternative was easy to implement on farms (Jactel et al. 2019).

After analyzing and categorizing the literature, they found that at least one non-chemical alternative was available instead of using neonicotinoids in 78% of cases evaluated. Jactel et al. (2019) determined the most substitutable non-chemical alternatives were the use of physical practices (65%) and microorganisms (54%). Physical practices include but are not limited to, crop rotation, changing sowing rates, installing barriers, altering the plants (i.e., uprooting or pruning), or trapping. However, due to a high applicability, practicability, and
efficacy score, the most popular alternative method that farmers utilized was another chemical control (98%), such as pyrethroid insecticides (Jactel et al. 2019).

Similar findings were noted by Kathage et al. (2018) when surveying European farmers post-ban. Corn, oilseed rape, and sunflower farmers (800 in total) were surveyed after neonicotinoids were banned to evaluate the alternative practices they adopted. The most popular alternative among farmers was the use of pyrethroids in replacement of neonicotinoids. The only non-alternative method that farmers used was altering their sowing methods (e.g., sowing earlier and increasing the sowing density) (Kathage et al. 2018). Farmers often stated they felt that pest pressure increased, and the alternative insecticide was not as effective.

While alternative non-chemical methods are available and substitutable for neonicotinoids, farmers are currently not putting them into practice. Biocontrol and physical methods seem to be the most promising alternatives to neonicotinoids. However, every alternative is dependent on what type of pest control is needed (e.g., pests on roots, leaves, soil, or bark). This is where the practice of integrated pest management can be utilized and encouraged within agriculture and urban land uses.

6.2. Integrated Pest Management

Integrated pest management (IPM) is the practice to control pests in a more ecologically friendly way. It is defined by the University of California Statewide IPM program as a multiple strategy effort to control pests by limiting pesticide use and utilizing biological control, habitat management, culture, and sowing resistant plant varieties (Epstein and Zhang 2014). IPM can be used in any landscape setting. It provides a holistic approach to monitoring and understanding the landscapes, pests present, and encouraging beneficial insects to provide pest control and encourage pollination and other ecosystem services. It is also thought of as a main strategy to limit pesticide use.

At the urban scale, IPM practices are required to be implemented through Municipal Regional Stormwater National Pollutant Discharge Elimination System (NPDES) Permits (California State Water Resources Control Board 2021). Municipal staff and contractors are required to be trained annually on non-chemical pest controls, and how to best apply an
approved chemical if all other options have been exhausted. These are only to be used when non-chemical alternative methods are unavailable. Additionally, outreach is provided to the community to inform residents when not to apply pesticides on their property, which limits potential contamination into local waterways and encourages the use of non-chemical practices and beneficial bugs to help control pests.

When incorporated, integrated pest management practices have been a proven effective method of controlling pests. Appropriate monitoring and applying best management practices to control pests or weeds based on what is occurring on the landscape is the most sustainable practice for the environment. However, the methods used do not always have pollinators in mind or benefit them. Egan et al. (2020) introduces a new concept to combine integrated pest management with a stronger pollinator focus to further protect bees, called Integrated Pest and Pollinator Management. The goal of the Integrated Pest and Pollinator Management is to increase pollinators, decrease pests, and increase plant yields (Egan et al. 2020). The authors proposed a framework of practices to prioritize (e.g., habitat diversification and pest-resistant/pollinator-attractive plants) and ones to be used as a last case scenario (e.g., synthetic pesticides) (Figure 10). This strategy follows similar methods as proposed by IPM but provides more support for pollinators by encouraging more pollinator friendly controls.

Figure 10. Integrated Pest and Pollinator Management framework: Displaying most desirable management actions to control pests and benefit pollinators at the bottom of the pyramid to the least preferred management technique at the top of the pyramid (e.g., conventional pesticides) (Egan et al. 2020).
6.3. IPM case studies in Italian agriculture and Canadian forests

One study analyzed several case studies in Italy and Canada on effective IPM strategies for agricultural crops and forests instead of using neonicotinoids (Furlan and Kreutzweiser 2015). Furlan and Kreutzweiser (2015) discuss alternative methods focusing on the main pests that need to be controlled in maize fields in Italy and forests in Canada. The pests analyzed for corn fields are wire worms (*Agriotes spp*), Western corn root worm (*Diabrotica virgifera virgifera*), and black cutworm (*Agrotis ipsilon*). For forests the main pest assessed was the emerald ash borer (*Agrilus planipennis*). While the forest case study focused on more rural areas of Canada, the pest described is also found in urban trees (Mach et al. 2018).

For each pest discussed in the Italian maize agriculture studies, different strategies were suggested to best control each. It was determined for all three pests that monitoring with pheromone traps is the first recommended alternative action to evaluate population size and when to begin implementing subsequent non-chemical actions. While for wire worms and corn rootworm, crop rotation was the first control action suggested (found to be most effective for corn rootworms), followed by biocontrol efforts (Furlan and Kreutzweiser 2015). However, the biocontrol action suggested for wire worms was more focused on biocidal plants (i.e., natural chemical compounds occurring in plants that will deter or kill a pest), while fungal pathogens was the biocontrol suggested for corn rootworms. Lastly, if non-chemical actions are ineffective, the alternative available pesticides include pyrethroids and phosphorganics. Additionally, to replace synthetic insecticides Furlan and Kreutzeriser (2015) suggest using crop insurance from mutual fund insurance agencies as a supplement with IPM practices. This provides an eco-friendly alternative to neonicotinoid use and gives farmers a peace of mind if their crop yield is reduced.

The three main alternatives discussed to control emerald ash borer in Canadian forests, include biocontrol through macroorganisms (exotic and native insect parasites), biocontrol through microorganisms (fungal pathogen), and non-persistent systemic insecticides (azadirachtin). The exotic and native insect parasites are currently being studied and more tests need to be conducted. However, the parasitic wasps (exotic and native) seem to have promise as a biocontrol for the emerald ash borer as long as they are reared and released in a controlled
setting. The fungal pathogen seems to be the least effective alternative since it is difficult to implement on a large scale and does not readily attach to a specific host. This characteristic may increase the risk of it attaching to non-target species. Finally, a non-persistent systemic insecticide was successfully used to control the emerald ash borer when injected into trunks of infected trees. Although it is systemic like the commonly used neonicotinoid, imidacloprid, it was not found to be persistent in the environment or cause harm to decomposer invertebrates (aquatic or terrestrial) after application or during leaf fall.

These IPM practices show promising results to control common pests found in agriculture (specifically maize) and forest environments without using neonicotinoids. However, oftentimes multiple methods, including good monitoring, is recommended to be implemented at the same time to achieve adequate pest control. While these methods can be more engaged and take a little more time, they are much more sustainable practices that will keep ourselves and the environment healthier. Additionally, using an insurance program to subsequent IPM practices will allow farmers to have financial stability even if their crop yields are lower, but still reducing pesticide use on agricultural lands.

7. Pesticide Policies

Pesticide regulation has been in place since the early 1900s. One of the first federal pesticide regulations was the Insecticide Act of 1910, which was established to protect humans from toxic pesticides (Sponsler et al. 2019). Then subsequent acts progressively became more focused on overall human health and the health of the environment (e.g., Federal Insecticide, Fungicide, and Rodenticide Act and Federal Environmental Pesticide Control Act) (Sponsler et al. 2019). These federal regulations focus on pesticide registration, fees, tolerances, exemptions, and protecting endangered species. The state of California also has several regulations related to pesticide use in the California Code of Regulations and Food and Agricultural Code. However, these laws are more focused on general pesticides, especially related to application in agricultural settings and apiaries.

Recently, due to pollinator decline there has been a recent spike in enacting conservation policies for pollinators in the United States. Hall and Steiner (2019) identified and analyzed conservation policies that have been enacted in the United States. They found 110
pieces of legislation to help conserve pollinators in several areas, including pesticide use. They also identified areas where policies have missed target conservation efforts for pollinators. However, there are still limited legislation pieces, federally and within the state of California, that are specific to pollinator conservation and pesticide use. Several articles discuss stakeholder involvement, knowledge gaps, and potential policy approaches that may help further protect pollinators from neonicotinoid insecticides in future pieces of legislation. The following subsections describe current pesticide regulations in the United States, State of California, and local government agencies, as well as current stakeholders and knowledge gaps.

7.1. Federal

The U.S. EPA is the primary authority to regulate and register pesticides in the United States. This agency is granted authority under several federal statutes: Federal Insecticide, Fungicide, Rodenticide Act (FIFRA), the Federal Food Drug and Cosmetic Act, Federal Food Drug and Cosmetic Act, the Food Quality Protection Act of 1996, Pesticide Registration Improvement Act, and the Endangered Species Act (ESA) (U.S. EPA 2021). These pieces of legislation are all implemented by the U.S. EPA Office of Pesticide Programs. Out of these five statutes, the FIFRA and ESA have the greatest relevance for pesticides and pollinators. The other remaining statutes are more specific to human health and chemical registration information, including determining tolerances of pesticide residues on food and the timeline and fees to register products.

The FIFRA drives and dictates the registration and evaluation of pesticides by the U.S. EPA, while the ESA protects threatened and endangered species and their habitats from pesticides (U.S. EPA 2020a; U.S. EPA 2020b). Under the ESA, the U.S. EPA conducts an Ecological Risk Assessment Process to determine the pesticide threats to listed species. This is an important process, but currently problematic as only eight bee species are listed under the ESA (U.S. Fish and Wildlife Service 2020). Only one of those species resides in the continental United States (Bombus affinis), while the remaining seven are Hylaeus species that are only found in Hawai’i (U.S. Fish and Wildlife Service 2020). There was a recent petition to list several bumble bee species under the California ESA but has not been approved (California Fish and Game Commission 2019). A recent court case, which is under appeal, determined that the California
ESA lacks the authority to list these species (Xerces Society for Invertebrate Conservation 2021a). Without the ability to list species, regulation of pesticides that are deemed toxic to bees will be even more difficult to regulate or eliminate.

Under the FIFRA, the U.S. EPA has created codes and policies related to pesticide use, registration, labeling requirements, reporting, and risk evaluation to protect pollinators. To enhance these policies, the U.S. EPA created proposed and current actions to protect pollinators. For instance, the U.S. EPA developed a policy to mitigate the acute risk of pesticide products to bees (U.S. EPA 2017). This policy applies to any managed bee under contract for pollination services on agricultural land, pesticides applied via foliar spray or in powder or granule form, and provides recommended language for pesticide labels to reduce exposure. A list of pesticides that are considered most acutely toxic to bees is also provided. The top three neonicotinoids (clothianidin, imidacloprid, and thiamethoxam) are included in this list, but it is important to note that it only relates to foliar or dust applications. Currently, neonicotinoid seed treatments are considered exempt under 40 CFR § 152.25(a) and are subsequently not registered or regulated as pesticides by the U.S. EPA (U.S. EPA 2000). This oversight is extremely problematic, because it does not adequately account for neonicotinoids being used in landscapes. An additional requirement from this policy is for State and Tribes to develop a Managed Pollinator Protection Plan. The California Managed Pollinator Plan is further discussed in the following subsection below.

Two other actions the U.S. EPA created to protect pollinators are specifically related to neonicotinoids. First, is the updated labeling requirement enacted in 2013 for all outdoor registered products for foliar use. This includes a “Bee Advisory Protection Box” required for all labels as well as specific application requirements and limits, such as only applying when bees are not foraging (Figure 11). This labeling is required in 40 CFR § 156.85(a) Environmental Hazards statements for pollinators (U.S. EPA 2012). The second action is a proposed interim decision on neonicotinoids to reduce risks to bees and applicators. These interim decisions reevaluated the registration and proposed future restrictions on use, expanding label language, and utilizing personal protective equipment for applicators. Clothianidin, imidacloprid, and
thiamethoxam were reviewed and the proposed decisions and pre-publication to the Federal Register was submitted in January 2020 (U.S. EPA 2020c; U.S. EPA 2020d).

The proposed use restrictions include a ban the use of clothianidin on bulb vegetables, and use of imidacloprid on turf, bulb vegetables, and canola, millet, and wheat seed treatments. While thiamethoxam is not proposed to be banned, there are proposed reductions to the amount used on crops. This reduction also applies to clothianidin and imidacloprid. Additionally, enhanced personal protective equipment (i.e., gloves and double layering of clothes) for occupational handlers, label language stating that these products are for professional use only, and reduction of spray drift and runoff is required. Lastly, the proposed decisions encourage stewardship efforts and implementation of best management practices by applicators and beekeepers. The final publication to the Federal Register has not yet been submitted and is pending review of submitted public comments.

Figure 11. Bee advisory box to label bee-toxic pesticides and provide further application guidance and restrictions (U.S. EPA 2013).

In a recent analysis by Hall and Steiner (Hall and Steiner 2019), only four bills on the national level were found to be passed within a 17-year period (2000 to 2017): 1) Food, Conservation, and Energy Act of 2008, 2) Agricultural Act of 2014, 3) Fixing America’s Surface Transportation Act of 2015, and 4) amendment (2013) to the Federal Agricultural Reform Act (Hall and Steiner 2019). Respectively, these pollinator conservation pieces mainly focused on conducting research for honey bee health (including evaluating sublethal effects of pesticides), appropriating funds to conduct research for pollinators, increasing pollinator habitat along transportation areas, and improving federal coordination to protect managed and wild pollinators. However, none of these were categorized to respond to the crisis of declining managed and wild bee populations. Additionally, Hall and Steiner (2019) analyzed the state level legislation passed within the same period. They identified 110 policies related to pollinator conservation created by state legislatures and categorized them into five main areas:
apiculture, pesticide use, habitat development, research, and awareness. Seven of these policies were created by the state of California.

### 7.2. California

The main regulatory agencies involved with bees and pesticide regulation include the CDPR and the California Department of Food and Agriculture. The CDPR, under the California Environmental Protection Agency, is responsible for enforcing pesticide use and regulation of registered products in the State of California. The California Department of Food and Agriculture is responsible for the state’s agriculture industry, including apiculture (California Department of Food and Agriculture 2021). The main laws and regulations related to bees and pesticide use are regulated under the Food and Agricultural Code and California Code of Regulations (California Department of Food and Agriculture 2021; California Department of Pesticide Regulation 2021b). These regulations have specific laws to protect pollinators, but are focused primarily on pesticide use in agricultural landscapes and for managed honey bees only. For instance, the Food and Agricultural Code has specific laws for Bee Management and Honey Production under Division 13, including for pesticide use on agricultural lands (13 Food and Agricultural Code 7 § 29100 – 29103). However, when closely reviewed, most of the language within this code is specific to beekeepers registering their hives to be appropriately notified of nearby pesticide application.

Similarly, the California Code of Regulations provides regulation on what pesticides are considered toxic to bees, the timing of when bees are considered inactive (opportunite time to apply pesticide), and description of residual toxicity time based on the pesticide product’s label (3 CCR § 6650). Also, under the California Code of regulations, beekeepers are required to register their apiary location, while pesticide applicators are required to submit adequate notification to beekeepers before application and report pesticide use monthly to the County Agricultural Commissioner (3 CCR § 6652 and 6654; 3 CCR § 6600-6628). While these laws and regulations are important to ensure the protection of bees in agricultural lands, there are not adequate laws and regulations specific to neonicotinoid applications in all land settings. Currently, the application of neonicotinoids is only regulated through spray and soil application, but not seed treatments (California Department of Pesticide Regulation 2018).
Under the U.S. EPA policy to mitigate risks to pollinators, States and tribal areas were instructed to create their own Managed Pollinator Protection Plans (California Department of Pesticide Regulation 2018; U.S. EPA 2017). California’s Managed Pollinator Protection Plan has specific requirements and guidance for honey bee apiaries and how bee keepers and growers can protect them. There are multiple stakeholders involved including, CDPR, California Department of Food and Agriculture, the Almond Board of California, and beekeepers. The three main goals of the plan are cooperation, communication, and collaboration between all stakeholders. Communication between the growers and beekeepers is one of the most important sections of the plan. Managed bees have a greater risk of direct exposure without appropriate communication of pesticide use and location of apiaries. California’s Managed Pollinator Protection Plan reiterates California’s laws and regulations related to bee management and protection. This includes farmers notifying beekeepers, beekeepers registering apiaries, and decreasing pesticide use during bloom periods or when bees are most active.

Pesticide applicators must provide notification to any apiary within a one-mile radius prior to application of pesticides (3 CCR § 6654); especially ones identified as toxic to bees. However, it is the beekeeper’s responsibility to register with the state and request notification of pesticide application (3 CCR § 6652; 13 Food and Agricultural Code 4 § 29040 – 29056). Once notification is received it is the beekeeper’s responsibility to relocate potentially affected hives (13 Food and Agricultural Code 7 § 29103). Additionally, the plan reiterates use restrictions based on the product label and encourages integrated pest management practices. However, the downside of California’s Managed Pollinator Protection Plan is that it is heavily focused on beekeepers registering their hives and signing up to be notified of any potential application. It does not limit the application of pesticides but provides a plan for notification and how to limit or restrict pesticide use to protect bees (e.g., do not apply when bees are foraging or may be foraging). While California’s Managed Pollinator Protection Plan provides a good starting point, it does not emphasize alternative management strategies enough or provide information of how wild bee species may be exposed or protected.
As previously mentioned, Hall and Steiner (2019) analyzed state legislation related to pollinators passed between 2000 and 2017. Five main themes were identified and categorized the state policies passed. In California, seven policies related to pollinators were passed during the analysis period and two fell under the pesticide use category: Assembly Bill 1789 and Senate Bill 826. The remaining policies fell under the apiculture, research, and habitat category. Assembly Bill 1789 was passed in 2007 and required the CDPR to conduct a risk determination on neonicotinoids by July 1, 2018 (Hall and Steiner 2019). While Senate Bill 826, also known as Budget Act of 2016, was created to appropriate funds for several areas in the State of California, including for the Department of Pesticide Regulation (Hall and Steiner 2019). While some funds were geared toward the pesticide programs there was no direct funding related to neonicotinoids.

Neonicotinoids are becoming a more prominent issue discussed in California legislature. In February 2021, a new assembly bill specific to neonicotinoids was proposed. Assembly Bill 567 proposes that after January 1, 2024, all neonicotinoids used on seeds will be prohibited (California Legislature 2021). If passed, this would be added onto Chapter 3 of Division 7 of the Food and Agricultural Code (restricted materials). This would be the first legislation specific to controlling the use of neonicotinoids in California, which has been found to be toxic to bee species. A previous legislation (Senate Bill 1282) was proposed in 2016 to amend portions of the Food and Agricultural Code to require products with neonicotinoids to be labeled and restrict non-commercial use of neonicotinoids (California Legislature 2016). However, it was denied passage and its reconsideration unfortunately died in the inactive file. Hopefully, Assembly Bill 567 has a better chance to be approved, providing a positive step towards restricting use of neonicotinoids in California.

7.3. Local

Federal and state legislation related to neonicotinoids is being discussed more frequently, but action can often be taken quicker through the local level with appropriate education and outreach. Most frequently, there are local ordinances in California municipalities related to pesticide use based on the current state and federal laws and regulations. However, these ordinances are usually reflective to the application and implementation of IPM programs.
Specifically, IPM policies have been adopted by cities in compliance with the Municipal Regional Stormwater (NPDES) Permit (California State Water Resources Control Board 2021). Municipal agencies have adopted IPM policies to provide general agency guidance on pesticide use, response to public concerns, and reduce the use of pesticides in urban environments (Flint et al. 2003).

Unfortunately, there are limited local policies currently in place specifically for neonicotinoid insecticides. When searching for local ordinances, there were only a few local agencies in the United States that created resolutions and ordinances to reduce neonicotinoid use and purchase in their jurisdictions. Within California, only three cities were found to have implemented local authority against the use and purchase of neonicotinoids: City of Oakland, City of Encinitas, and City of San Francisco (City of Encinitas 2019; City of Oakland 2019; San Francisco Department of the Environment 2020). City of Oakland and City of Encinitas have both incorporated prohibition of neonicotinoid use into their local policies. The City of Oakland, California most recently adopted an ordinance to prohibit the use of neonicotinoids on city property, urge state and federal authorities to restrict neonicotinoid use, and discourage Oakland retailers from selling products with neonicotinoids (City of Oakland 2019). The City of Encinitas, California also amended their IPM policy to incorporate prohibiting the use of pesticides with neonicotinoids on any property owned or operated by the city, unless exempt under the Special Use category (City of Encinitas 2019). While the City of San Francisco does not have an explicit ordinance in place, since 2014 they have stopped all use of neonicotinoids on city and county property (San Francisco Department of the Environment 2020).

Local ordinances are a great step to quickly prohibit use of toxic pesticides, such as neonicotinoid insecticides. Local policies are often faster to implement than state or federal regulations and can make a greater impact on the local scale. Local ordinances on neonicotinoids are also encouraged by non-profit organizations such as Xerces Society (Xerces Society for Invertebrate Conservation 2021b). They have developed a model ordinance to encourage adoption of these policies at the local level to help control and limit the use of neonicotinoid insecticides in the urban landscapes. A model ordinance provides a simple guide for municipalities to streamline development and adoption process. This model ordinance has
been used by the City of Boulder, Colorado (Xerces Society for Invertebrate Conservation 2021). Prohibiting use along with local engagement through education and outreach, can help reduce knowledge gaps and guide changes to policy approaches at higher government levels.

### 7.4. Stakeholders and knowledge gaps

When developing pesticide policies, it is important to understand the stakeholders involved. Stakeholders often include chemical companies, scientists, conservationists, government agencies, non-profit groups, farmers, and beekeepers (Dicks et al. 2013; Durant 2020; Nicholls et al. 2020). Each have different goals, but also knowledge and field expertise to contribute. Understanding stakeholder knowledge is important in forming policy decisions but is often unaccounted for since the U.S. EPA is considered the knowledge source of pesticide toxicity on landscapes and non-target organisms (Durant 2020). However, stakeholders still have an important role in the adoption of proposed regulations. Nicholls et al. (2020) evaluated public comments (mostly from farmers and beekeepers) on the Ontario Pollinator Protection Plan proposed in 2014 and found gaps in knowledge in other bee species, but broad support to protect the environment and pollinators from neonicotinoids. Despite the broad support between the public and stakeholders, there was a discrepancy in the stakeholder group support for the proposed regulations. Farmers were less likely to support more restrictive regulation against neonicotinoids and pesticides in general, while beekeepers were more likely to support stricter regulations (Nicholls et al. 2020). This discrepancy is problematic in enforcing conservation policy for pollinators and highlights the power skew between farmers and beekeepers at a regulatory and social level.

Beekeepers are often seen as serving farmers, due to fear of losing contracts, even though they provide important pollination services to the crops. Beekeepers need to be activists for their managed bees but are often disengaged by the regulatory process. For instance, if they do not register their hives, they will receive a fine. This lack of registering is problematic because if a bee kill occurs on an unregistered hive, they will most likely not report it for proper investigation due to fear of a being fined. While current policies provide guidelines for pesticide use and restriction for applicators, they are still able to apply bee-toxic pesticides with 48-hours notification to commercial beekeepers and following application guidelines to
reduce risks to bees (Durant 2020). Additionally, beekeepers are disincentivized to report bee kills due to the current investigation process. State and county regulators follow the guidelines provided under FIFRA and the Food and Agricultural Code, which does not allow for samples to be sent for investigation unless it was a pesticide labelled as bee-toxic (Durant 2020). This lack of investigation and reporting of pesticides that have chronic or sublethal toxicity or has not been evaluated for bee toxicity yet has created an ignorance on what pesticides, including neonicotinoids, are toxic to bee species.

Due to the current stakeholders involved, honey bees are the main non-target species of concern related to pesticide policies. While honey bees are an important managed pollinator, they can inhibit biodiversity by outcompeting native or wild species and encourage non-native plants (Colla and Maclvor 2017). The public does not often think about other bee species and their importance for pollination services and biodiversity. An increase in education and public outreach on conservation policies for wild bees and their importance to biodiversity could help create more policies to protect them. However, it is important to consider specific conservation policies for managed and wild bee species. We cannot rely on the umbrella effect to protect all managed and wild pollinators when there is a lack of pesticide reduction or encouragement of alternative practices on agricultural and urban landscapes. For instance, several policy targets (including incorporation of IPM) are not included in current pollinator legislation in the United States (Hall and Steiner 2019).

8. Management Recommendations

As bee populations continue to decline, it is important to evaluate and act against the main threats to these vital pollinators. Neonicotinoids are a systemic insecticide that have been found to have lethal and sublethal toxicity effects to both managed and wild bee species. However, despite their toxicity they are still applied to both agricultural and urban landscapes. To help reduce neonicotinoid toxicity to bees in California, several policies and actions must be implemented for both urban and agriculture landscapes at the federal, state, local, and stakeholder level. While these recommendations must be implemented at the federal and state level, there are several local actions that may be executed faster. The management recommendations for agriculture and urban landscapes described below can be completed by
developing more strict policies to regulate neonicotinoids, adopting new policy approaches, enhancing pesticide risk assessment criteria for bees, requiring implementation of alternative actions (i.e., IPM), and participating in pollinator protection certification programs.

8.1 Agriculture Recommendations

To protect bees in agriculture landscapes, there are several management actions that need to be enhanced and implemented. First, neonicotinoid-coated seeds need to be regulated and prohibited. They are currently unregulated due to an exemption, but their use and residues cause sublethal harm to non-target species (U.S. EPA 2000; Woodcock et al. 2017). Since they are unregulated, their use on California landscapes is not monitored. It is recommended for additional studies to be conducted to determine the actual amount applied on farmlands. California has a robust pesticide accounting system through CDPR’s Pesticide Use Reporting (PUR) database. However, since neonicotinoid-coated seeds are exempted, they are currently not accounted for in the database. Accounting for seed application will provide a better understanding of the amount of neonicotinoids applied in the environment.

For this to be effective, policies regulating neonicotinoid-coated seeds need to be implemented at the federal and state level. Encouragingly, there is a policy (Assembly Bill 567) proposed by the California state legislature to prohibit neonicotinoid-coated seeds by January 1, 2024 (California Legislature 2021). Additional policies related to all neonicotinoid application methods that need to be enhanced include but are not limited to: increasing restriction of use, enforcing label language, providing more support to beekeepers, and encouraging more thorough investigations of bee kills when pesticides are not labeled bee-toxic.

To help achieve better conservation policy and reduce pesticide toxicity to managed and wild bee species, a more “context-sensitive” approach to policy is needed (Suryanarayanan 2015). A context-sensitive approach will help mend the divide between farmers and beekeepers by encouraging stakeholders to provide their knowledge and expertise to protect pollinators from pesticide applications, including neonicotinoids (Durant 2020; Suryanarayanan 2015). Currently, most policies favor farmers more than beekeepers, including reprimanding beekeepers if they do not register their hives. More policy support needs to be given to beekeepers to eliminate the divide between farmers and beekeepers. For instance, beekeepers
should be given more than a 48-hour notice before application of pesticides and support to relocate their bees until after application and residual toxicity has diminished. Increasing the voice of other stakeholders (i.e., beekeepers) and responding to the context of the situation allows for better communication and coordination to protect non-target species and encourages problem-solving.

Additionally, implementing this context-sensitive policy approach encourages more reactive policies, as seen in the European Union, where restrictions on neonicotinoids were prohibited based on the harm seen (context) even with some uncertainty identified (Suryanarayanan 2015). Pieces of legislation with a more responsive action to notably harmful chemicals to pollinators needs to be implemented to encourage the conservation of managed and wild bees. For example, even though neonicotinoids have been labeled as bee-toxic, they can still be used as long as they are not applied during foraging or in-flight periods. Taking immediate action when harm is identified provides more power to the community and less to chemical companies. A more context-dependent and sociological approach to policy will help reduce exposure of neonicotinoids to bees (Sponsler et al. 2019; Suryanarayanan 2015).

The next recommendation is to enhance pesticide risk assessment criteria to include sublethal effects, potential for synergism, and wild bees. Currently, risk assessments conducted by the U.S. EPA do not include the evaluation of sublethal effects (e.g., behavior changes), synergistic or additive effects from multiple chemicals found in the field, or difference in life history traits between species. More behavioral studies need to be conducted for sublethal effects, especially for solitary bees which are understudied. The difficulty to study them is often because they do not thrive in controlled environments under Tier I risk assessments. However, they have a greater risk to pesticide exposure due to their solitary lifestyle, small hives, low fecundity, singular floral preferences, and nesting habits. Due to the difference in life history traits and risks to pesticide exposure, bumble bee and solitary bee species should be included in risk determinations separate from honey bees.

Additionally, more field studies on the synergistic effects of neonicotinoids with other pesticides needs to be conducted for each bee species and across landscapes. Current risk assessments only evaluate one pesticide in a controlled setting. However, in real field settings
pollinator species are more likely to interact with multiple types of pesticides during their life cycle. Fungicides have already been noted to have a synergistic effect with neonicotinoids, but this is not accounted for in risk assessments (Main et al. 2020). The lack of understanding of how pesticides react to each other needs to be better studied and accounted for before approving registration of pesticides. This should be incorporated into the U.S. EPA’s policy to mitigate risks to bees.

Finally, integrated pest management (IPM) programs, specifically integrated pest and pollinator management framework, in both agriculture and urban landscapes needs to be required through policy. These programs provide effective non-chemical alternatives to control pests from all landscapes. It is a holistic approach to understand the landscape, associated pests, and how to control these pests in non-toxic ways. Chemical controls (i.e., neonicotinoid insecticides) should only be used as a last resort when all other methods are no longer effective. Local municipal agencies are currently required to implement IPM strategies in urban settings under the Municipal Regional (NPDES) Stormwater Permit. However, agricultural applicators are not required to implement these practices instead of using pesticides.

Requirements can be fulfilled at a similar level taken by local agencies and the non-profit organization, California Certified Organic Farmers. During their certification process, the California Certified Organic Farmers ask farmers to describe their plans before using chemical alternatives (personal comm. Barajas 2021). Accountability could also be incorporated at the state and County Agricultural Commissioner level by requiring farmers to report IPM practices to a database like the PUR. Along with reporting approved pesticide application, farmers would be required to report the IPM practices used. Additionally, California’s Managed Pollinator Protection Plan should provide a greater emphasis and requirements to implement IPM programs and using chemical substances as a last resort. Currently, there is only a short paragraph describing IPM within California’s Managed Pollinator Plan. Following the California Certified Organic Farmers example, California’s Managed Pollinator Protection Plan should require all farmers (conventional and organic) to provide IPM plans before using any chemical controls. To support this effort, California has a statewide IPM program run by the University of California Agriculture and Natural Resources (University of California 2021). This statewide IPM
program provides resources for pest control across all landscapes and applicators. They even provide training and workshops to encourage IPM practices and pesticide application safety trainings. Farmers and applicators should be required to utilize these resources. Requiring IPM programs and practices will lead to a more sustainable behavior change for pest control, which will greatly benefit pollinators.

If policies on restricting and prohibiting neonicotinoids are implemented, IPM programs need to be required to reduce utilizing previously applied pesticides. For instance, after the neonicotinoid ban in Europe, farmers resorted to alternative pest control methods. Unfortunately, the majority reverted to previously used alternative chemical methods (e.g., pyrethroids), which are both toxic to invertebrates and vertebrates due to its ease of application and effectiveness. The goal should be to remove harmful chemicals completely and not replace it with another harmful pesticide. To eliminate this potential, states and local agencies need to require IPM practices and provide crop insurance funding programs. As encouraged by Jactel et al. (2019) and Furlan and Kreutzweiser (2015), insurance programs provide a safe way for farmers to implement non-chemical pest control actions while ensuring they do not experience economical losses from potential reduced crop yield. This could be further incorporated into California’s Managed Pollinator Protection Plan.

To further benefit pollinators, IPM can be taken a step further by adopting an integrated pest and pollinator management framework for agricultural and urban landscapes. This framework encourages the creation of pollinator habitat and prioritizes non-chemical pest controls, which greatly benefits bee species in both landscapes. The framework also encourages increased monitoring, which will lead to a more sustainable understanding of the land and how to control pests. Farmers can show their dedication and prioritization to implement bee conservation practices by becoming certified through two separate non-profit agencies: Xerces Society and Pollinator Partnership (Pollinator Partnership 2021; Xerces Society for Invertebrate Conservation 2021c). Farmers can become certified through these programs to demonstrate their commitment to pollinator conservation efforts and give consumers confidence in the products they purchase. Certified farms will place a Bee Certified or Bee Friendly Farm logo on
their products. This helps customers make better informed decisions and support producers that are dedicated to protecting pollinators.

8.2 Urban Recommendations

To protect bees in urban landscapes, there are several management actions that the local governments, residents, and U.S. EPA can implement. Local policies can make a great impact and take less time to develop and execute than at the federal or state level. The first step is to encourage municipalities to incorporate policies to prohibit and restrict neonicotinoid use in urban areas. These policies should include prohibiting or at minimum discouraging retailers from selling products with neonicotinoids to residential owners. This is important as residential owners often apply 120 times more pesticides than agricultural users (Stokstad 2013). This is problematic since urban consumer level use is unregulated and unchecked compared to agricultural use.

Three local government agencies in California have recently implemented policies and ordinances, some tied with their IPM programs, specific to neonicotinoids. The policies include prohibiting the use of these pesticides on public property and encouraging retailers within their jurisdictions to not sell products with neonicotinoids (City of Encinitas 2019; City of Oakland 2019; San Francisco Department of the Environment 2020). However, this effort needs to be expanded across California cities. To better understand why more local governments have not implemented policies on neonicotinoids, it is recommended to contact cities throughout the United States that have adopted neonicotinoid policies and ordinances. Understanding the decision that helped these local policies become adopted, and the obstacles encountered while developing them, is important to encourage other cities to develop similar policies. Along with understanding the limitations, a model ordinance can be used to streamline the adoption process. Fortunately, a model ordinance against neonicotinoids has already been developed by the Xerces Society (Xerces Society for Invertebrate Conservation 2021). Local agencies can encourage behavior change through ordinances, other local policies, and community outreach programs.

While creating ordinances is a promising start, additional education and outreach is still needed for the public and local officials to increase awareness of these insecticides.
Fortunately, most municipalities already have resources in place to provide education to the community. While municipalities are already required to implement IPM programs for public spaces, residents need to be further encouraged and educated on the importance and effectiveness of non-chemical controls and native pollinators. Most urban residents are not aware of native pollinators and beneficial bugs that provide essential pollination and pest control services. Wild bees play an important role in the biodiversity of flora species through their pollination services. To support pollinator conservation, cities can become certified as a Bee City USA through the Xerces Society. This requires city officials to adopt a resolution and meet the following requirements: increase native plants on public and private property, increase nesting habitats, and reduce pesticide use (Xerces Society for Invertebrate Conservation 2021d). Cities can then annually renew their certification and show their commitment to protecting pollinators from pesticides. Becoming a certified city brings local solutions to a worldwide issue.

One additional way to increase public outreach is to improve the labeling requirements of products with neonicotinoid active ingredients. Then residents can make a more informed decision until its use is restricted at the federal and state level. The U.S. EPA is the main authority on pesticide registration in the United States. In 2013, they created a bee-advisory box to label bee-toxic products with neonicotinoid insecticides. However, this label is currently not included on the front of consumer products with active ingredients. Adding the bee-advisory box to consumer products will greatly increase public awareness and promote educated purchases.

Additionally, label language needs to be consistent and enforced across all pesticide products, especially when it comes to describing toxic substances to bees. Currently, many products are mislabeled on their acute and residual toxicity, which spreads misinformation to applicators. Also, bees are more likely to be affected at a sublethal level when the application instructions are appropriately followed for neonicotinoid insecticides. However, labels only provide the acute and residual toxicity which does not account for the more common sublethal effects to bees. The U.S. EPA needs to add sublethal effects on pesticide labels to better inform professional and home applicators in urban landscapes.
9. Conclusion

The prevalence of neonicotinoids in California landscapes may be far more abundant than currently recorded. It is not only a systemic insecticide (i.e., ability to be taken in by plants) but is found to be persistent in soils and vegetation for multiple years, including after it was banned from use on flowering crops (Nicholls et al. 2018; Wintemantel et al. 2020). Additionally, it has been found to spread easily across landscapes, even to areas where it has not been applied (David et al. 2016; Main et al. 2020). Both managed and wild bee species are subject to exposure through multiple routes including acute exposure (e.g., spray or dust particles) and chronic or sublethal exposure (e.g., residues in nectar, pollen, plant leaves, water, or soil). In California, there may be 77% more neonicotinoid contamination in agricultural lands than what is currently reported in the Pesticide Use Reporting database, due to seeds coated with neonicotinoids (Mineau 2020). Additionally, urban landscapes are equally subjected to high exposure of neonicotinoids through consumer products that treat pests for flowers, fruits and vegetables, trees, and lawns (Bucy and Melathopoulos 2020). These products are not currently labeled with a bee-toxic label to educate and notify non-commercial users of the product they are applying and the harm it would cause to bees.

Based on the literature reviewed, neonicotinoids are more likely to be found in agricultural landscapes. However, there was a lack of literature analyzing neonicotinoid use and effects on bee species in urban landscapes. For those few urban studies assessed, application was found at highly toxic levels to bee species (Botías et al. 2017; David et al. 2016; Larson et al. 2013; Lawrence et al. 2016; Mach et al. 2018). Additionally, if more urban studies and reports were conducted, residential areas may have greater contamination than what is currently known. For instance, 63% of products reviewed for label language was found to be used specifically for gardens and residential use (Bucy and Melathopoulos 2020). Knowledge of its use across landscapes and its persistence is important to determine the toxicity to bees and the environment.

Three bee species were analyzed and compared during this research: western honey bee (Apis mellifera), bumble bee (Bombus spp.), and solitary bee (Osmia spp.). The honey bee is most often used as a managed commercial pollinator for agricultural lands, while bumble bees
and solitary bees are more often found in the wild. However, there are instances of bumble and solitary bee subspecies that are also used as managed pollinators. Despite their pollination service as managed and wild pollinators, each bee species has slightly different life history traits that may make them susceptible to pesticides. This is important to note, as the honey bee is currently used as a surrogate species for all bees when conducting pesticide risk assessments. However, when comparing the lethal and sublethal toxicity of neonicotinoid active ingredients, honey bees are not always the most sensitive species.

The toxicity results were often mixed due to the difference in methodologies used in each study. When assessing neonicotinoids as a group, some found that honey bees are slightly more sensitive to neonicotinoids (oral LD$_{50}$ 4 to 20 ng/g) than bumble or solitary bee (oral LD$_{50}$ 20 to 30 ng/g) at lethal levels (Cresswell 2011; Iwasa et al. 2004; Sanchez-Bayo and Goka 2014; Uhl et al. 2019). However, depending on the active ingredient evaluated, wild bees were found to be equally or more sensitive than honey bees (clothianidin: LD$_{50}$ 20 ng/g [bumble bee.]; 22-40 ng/g [honey bee]). For sublethal levels, bumble and solitary bees (oral NOEL 0 to 9 ng/g; NOEC 0.001 to 0.02) were found to be slightly more sensitive to neonicotinoids than honey bees (NOEL 4.9 to 372,000 ng/g) (Cresswell et al. 2012; Cutler and Scott-Dupree 2014; Mommaerts et al. 2010; Ruddle et al. 2018; Stanley et al. 2016; Tafarella et al. 2018; Thompson et al. 2019; Woodcock et al. 2017). These mixed results may be due to a lack of studies on wild bee species and behavior assessments.

Additionally, honey bees may be less sensitive to neonicotinoids due to being a eusocial species, with large hives, good foraging ranges, and a perennial life cycle. Although they are exposed to high levels of neonicotinoids through pollen, nectar, and honey (adults and larvae), their sociality and large hives provide a buffer from becoming detrimental to the hive. While compared to the bumble and solitary bees, whose hives are less likely to persist after an exposure to neonicotinoids due to their smaller hives and sometimes solitary nature. These behavior and life history differences are important to note and are not currently considered during risk assessments. Bumble bees also have some traits that make them less at risk to neonicotinoid exposure: large body size and generalist floral preferences. However, it has also been found that bumble bees may not be able to metabolize certain neonicotinoid active
ingredients as well as honey bees can, making them more sensitive (Cresswell et al. 2012; Siviter et al. 2018).

Based on their life history traits, solitary bees seem to be the most sensitive to neonicotinoids (Brittain and Potts 2011; Sgolastra et al. 2019). However, there were a few studies that found that they were less sensitive to neonicotinoids than honey bees (Heard et al. 2017; Uhl et al. 2019). Unfortunately, there is a dearth of studies on solitary bees, which makes it difficult to compare species based on the difference in methods used. To clearly determine if honey bees are an adequate surrogate for all bees, more comparison studies at the lethal and sublethal level need to be conducted for wild bee species, especially in field settings. Additionally, current studies lack analysis of potential additive or synergistic exposure for neonicotinoids alongside the multitude of other pesticides applied to both agricultural and urban landscapes in California. For example, fungicides have been seen to cause synergistic lethal effects for wild bee species (Main et al. 2020). Overall an increase in risk assessments and studies focusing on wild bee species, sublethal effects, and potential additive or synergistic effects with other pesticides is needed across landscapes.

If neonicotinoid use was reduced through alternative pest control practices, there would be less of a need for more studies on the toxicity effects to wild species. There are alternative options to using neonicotinoids on landscapes. While most studies assessed alternative actions for agricultural settings, some may be applied to urban settings as well (Furlan and Kreutzweiser 2015; Jactel et al. 2019). After Europe banned the use of neonicotinoids in agriculture fields, farmers needed to determine adequate alternative practices. Out of the alternatives available, physical controls and microorganism biocontrol were found to be the most substitutable non-chemical actions instead of using these insecticides (Jactel et al. 2019). However, it was also found that the most popular alternative action used by European farmers was to apply a previously used chemical pesticide (i.e., pyrethroids). This is a troubling finding, as the goal should be to encourage non-chemical actions that will not harm humans or other non-target organisms. Despite physical and biocontrol actions being as effective as pesticide control, farmers were more familiar with the previous pesticide and it was not required for them to implement less toxic chemical controls.
There are several non-toxic chemical controls available in replace of using neonicotinoids. For instance, IPM programs provide a framework to implement a variety of ecologically friendly practices to control pests. These practices have been effective in both agricultural crops and tree species (Furlan and Kreutzweiser 2015). However, multiple non-chemical actions often need to be used at the same time. Additionally, while IPM is an ecologically safe way to control pests in agriculture and urban landscapes, it needs to be further modified to include benefits to pollinators. Some actions in IPM can be detrimental to pollinators since it does not consider adequate habitat or floral resources for bee species. Finally, when it comes to policies, there are none that require agricultural lands to practice IPM. However, urban landscapes are required to report on IPM practices conducted under the Municipal Regional (NPDES) Stormwater Permit (California State Water Resources Control Board 2021).

As a pesticide, neonicotinoids are included in the general pesticide sections in both federal and state regulations. The U.S. EPA is the main authority to regulate, assess, and register pesticides nationally under Code of Federal Regulations. FIFRA and ESA are the two main statutes that give the U.S. EPA the authority and guidelines on how to assess pesticide risk and register products. The U.S. EPA has recently taken further steps to protect pollinators than what is required under FIFRA, but there is still more that can be done regarding neonicotinoids. For instance, the U.S. EPA relies on studies conducted by pesticide product companies, which does not include behavior risks, wild bee species, and very limited sublethal toxicity data. Seed coating is also currently unregulated as a pesticide and is not tracked in the California Pesticide Use Reporting database. The U.S. EPA has also required specific label language (e.g., bee advisory box) for pesticides with neonicotinoid active ingredients, but this label language is often inconsistent across products and difficult for applicators to interpret (Bucy and Melathopoulos 2020). Additionally, the bee advisory box is not provided on consumer products.

The CDPR is the California authority to regulate pesticide products and use under the Food and Agricultural Code and California Code of Regulations. However, the current pesticide policies focus on agricultural landscapes and honey bee sensitivity to pesticides, since it has been deemed a surrogate for all bee species. There is also very limited pollinator conservation
policy that has been enacted in the last 17 years in the United States, with only two in California that are specific to pesticide use. However, some local governments are taking action against the use of neonicotinoids at a city level and encouraging the federal and state regulators to take further action to restrict the use of neonicotinoids. Three cities in California were identified to act against neonicotinoid use (City of Encinitas 2019; City of Oakland 2019; San Francisco Department of the Environment 2020). Also, a recent California legislation has been proposed to ban the use of neonicotinoid seeds, which may have been encouraged by local government ordinances (California Legislature 2021). If this is passed, it will greatly benefit pollinators and water quality.

Without the pollination services from managed and wild bee species, our food systems and floral biodiversity are in jeopardy. Biodiversity is an important component to pollination services, as multiple bee species allow for cross pollination of different flora species (Oliver et al. 2015). However, the toxic effects of neonicotinoids decrease the pollination services available, as bee populations decline. The toxicity in the environment may be even greater than currently understood, since the synergistic and additive potential with other pesticides is not currently accounted for or managed. Additionally, their persistence in the environment has detrimental implications for a variety of non-target species (e.g., aquatic invertebrates and birds) in addition to bees (Hladik et al. 2018). These effects create an even more troubling future for flora and fauna that create important ecosystem services (e.g., soil decomposition). We are in an urgent state to act against these pesticides that pose a main threat to bee species and biodiversity.

Luckily, we can take action to alter its use and application. As cultivators, consumers, and residents we can implement local changes. This includes restricting the sale of neonicotinoids by retailers and eliminating products with active ingredients from our backyards. This can be accomplished by checking the pesticide label for acetamiprid, clothianidin, dinotefuran, imidacloprid, thiacloprid, and thiamethoxam. There are also non-chemical pest control options available to replace neonicotinoids. Additionally, we can purchase food that is more sustainably cultivated and less toxic. By purchasing organic or foods that are certified to protect bees on farms by creating more habitat and reducing or eliminating
pesticide exposure. While California legislative bills that restrict the use of neonicotinoids have not yet been passed, they have been proposed several times in the last few years. This is promising but local governments can create a faster impact to alter behavior changes in the community and encourage state and federal legislators to adopt more policies to align with local interests. Lastly, supporting pollinator conservation efforts with non-profit organizations is extremely beneficial to the protection of bees. Since only eight bee species are currently protected under the ESA, it is important to support organizations that make it their mission to further protect and educate stakeholders and the community. When appropriately accounted for through application, restriction, enforcement, and increased education, the use of neonicotinoids can be reduced to protect managed and wild bee species across California landscapes.
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