

Spatiotemporal Patterns of Insecticide Usage in Public Pennsylvania Forests

by

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Abstract

Pesticide trends and patterns are key to informing pest management strategies and understanding implications for non-target organisms like pollinators. These trends and patterns vary across different land uses. A recent study established a method to estimate and map pesticide use in agricultural lands. However, a literature search reveals that pesticide application trends in forestlands have been understudied. My study describes insecticide applications targeting pests in Pennsylvania state forestland from 2010 to 2022. Currently, the Pennsylvania Department of Conservation and Natural Resources (PA DCNR) treats for the following insect pests to reduce defoliation and stress in public forests: *Lymantria dispar* (spongy moth; SM), *Adelges tsugae* (hemlock woolly adelgid; HWA), and *Agrilus planipennis* (emerald ash borer; EAB). First, I cleaned and processed PA DCNR insecticide application records and then conducted background research on insecticide labels and active ingredients (AI). Information from insecticide labels was joined with application records and applications were translated to lethal doses to honeybees, providing insight into toxicity toward non-target organisms. Using a series of plots and maps, I examined the type and amount of insecticides applied yearly to understand the spatiotemporal relationships and generated summary statistics to compare the extent, intensity, and bee hazard of forest insecticide usage to agriculture. I found SM treatments make up the majority of acres treated, and AI applied, but pose the least bee hazard. HWA and EAB treatments were driven by neurotoxins, posing more hazard to bees and possibly other pollinators. With only about 2% of PA DCNR forestland treated each year, my results suggest that public forests serve as an important refuge for pollinators from insecticide exposure.

Introduction

Forests provide economic vitality, with wood products contributing approximately 2% to the world's gross domestic product (FAO 1995a). They also supply pollinators with diverse floral resources and nesting habitats, essential to pollinator success (Ulyshen et al., 2023). Conversely, pollinators support plant reproduction and forest health by pollinating approximately 90% of flowering species (Tong et al., 2023). Insecticide usage, however, poses a risk to this mutualistic relationship (Sponsler et al., 2019). Insecticides are an important pest management strategy and are used in forests to control pests, improve health, ensure timber productivity, and increase social and economic benefits (Waters & Stark, 1980). However, they often have non-target impacts on organisms like pollinators (Biddinger & Rajotte, 2015; Sponsler et al., 2019). Insect pollinators are especially susceptible since they are evolutionarily similar to forest pests, and insecticides act on their physiology (Scharf & Scharf, 2009).

Pollinators nest and forage across different regions, making land use an important factor when assessing potential hazards (Mailly & Lihoreau, 2025). Recent work established a method to estimate and map pesticide use in agricultural lands and another suggested neonicotinoid insecticides are particularly hazardous to pollinators (Douglas et al., 2022; Douglas et al., 2020). However, a literature search reveals that pesticide application trends in forestlands have yet to be studied to that degree. Pimental & Levitan (1986) suggest that less than 1% of forestlands are treated with insecticides. Although forests are predicted to have a relatively low insecticide footprint compared to other land uses, I am interested in corroborating this claim with empirical evidence and investigating the spatiotemporal extent of these treatments.

In Pennsylvania, the dominant land cover is forest, making up 16.6 million acres, or ~58% of the state (Albright et al., 2023). From 1968 to the present, the PA DCNR monitored,

managed, and treated three insect pests including SM, HWA, and EAB on 4.1 million acres of public state forest lands including state parks, forest, and game lands (Fengyou Jia, personal communication, October 23, 2023). SM defoliated ~440k acres in 2023; HWA and EAB destroyed 13% of eastern hemlock and 16% of white ash trees in PA respectively in 2019 (Spongy Moth Daily Spraying Status, n.d.; Albright et al., 2023).

Pest Natural History and Management:

Native to Europe and Asia, SM was introduced to the US and Canada in 1869 as an efficient silk producing species (Areces-Berazain, 2022; Smithsonian Institution, 1999). As a generalist species, they target and defoliate hardwood trees like oaks and maples (Areces-Berazain, 2022). The larvae feed on the leaves and weaken trees, making them susceptible to other diseases and parasites (Areces-Berazain, 2022). Over a 1-year period, SM transitions between four life stages: egg, larva, pupa, and adult (Areces-Berazain, 2022). Female adults lay egg masses consisting of ~500 to 1000 eggs in August; eggs overwinter and hatch in March and April and larvae are dispersed by wind (Liesch & Williamson, 2022). Insecticides are often applied via foliar spray during April and May to target larvae when they are most vulnerable (Liesch & Williamson, 2022).

Native to Japan, HWA was accidentally introduced to the West Coast in the 1920s (Orwig et al., 2003). This adelgid targets Eastern and Carolina hemlock trees by extracting the tree sap and leaving a wax-like substance to hydrate and protect HWA instars from predators; trees die within five years of infestation (Young et al., 1995; Vose et al., 2013; McClure, 1987; Duerr & Mistretta, 2013). HWA has an overwintering and spring generation each year, where the eggs hatch and molt between four instars before becoming an adult (McClure, 1987). Insecticidal soaps are most effective before the adelgids develop a wool coating in late March to early April

or in September (Jackson, 2021). Chemical insecticides, however, are injected via soil or trunk injections and are applied after the flowering season to reduce nontarget impacts on beneficial insects (Jackson, 2021).

Native to Eastern Russia and Asia, EAB was introduced in 2002 through wood cargo (Haack et al., 2002; Poland & McCullough, 2006). As a specialist species, EAB targets all 16 ash species, causing trees to lose most of their foliage within two years of infestation and die within three to four years (Albright et al., 2023; Poland & McCullough, 2006). Similar to SM, EAB also transitions between four life stages: egg, larva, pupa, and adult over a 1-to-2-year period (Poland & McCullough, 2006). Females lay 60 to 90 eggs in June or July and eggs hatch within the one to two weeks (Jackson, 2023). The first instars feed on the phloem of the tree, ultimately disrupting its ability to absorb and transport nutrients (Jackson, 2023). Like hemlock, ash trees are also treated repeatedly via trunk injections in May and early June, primarily as a preventative measure (Jackson, 2023).

Objective:

To describe insecticide patterns and hazards to pollinators, I adapted the framework from Douglas et al. (2022) to examine the *extent*, or where the insecticides are applied, *intensity*, or how much AI is being applied, and *quality*, which assesses toxicity to bees specifically. Native bees are particularly adept - singlehandedly pollinating 67% of all flowering plants (Axelrod, 1960; Tepedino, 1979). Due to the lack of toxicological research concerning native bee species, I used honeybees as a proxy for wild bee species (Pollinator Risk Assessment Guidance, 2025; Arena & Sgolastra, 2014). These methods can be applied across different land uses and geographies to assess the dynamic environments in which bees live. As predictions, I expect SM, a generalist species, to have the largest footprint among all three pests. Compared to

agriculture, I suspect forestlands are treated less frequently and are less hazardous to bees, thus serving as a refuge. This project will support ongoing work to quantify insecticide use in the landscape and predict hazards to wild pollinators.

Methods

This project aimed to describe insecticide usage patterns and estimate potential hazards to bees in Pennsylvania forests. The main outcomes included several plots to assess the temporal dynamics of the types and amount of AI applied and hazards to bees and a map to visualize the spatial dimension and treatment hotspots of each pest. This data will be standardized and compared to insecticide patterns in agriculture.

Data Inputs:

My study encompassed public forestlands managed by the PA DCNR (Figure 1). Public forestlands included state forests, parks, and game lands and made up 4.1 million acres (13.7%) of PA (Fengyou Jia, personal communication, October 23, 2023).

Public Forestlands in PA

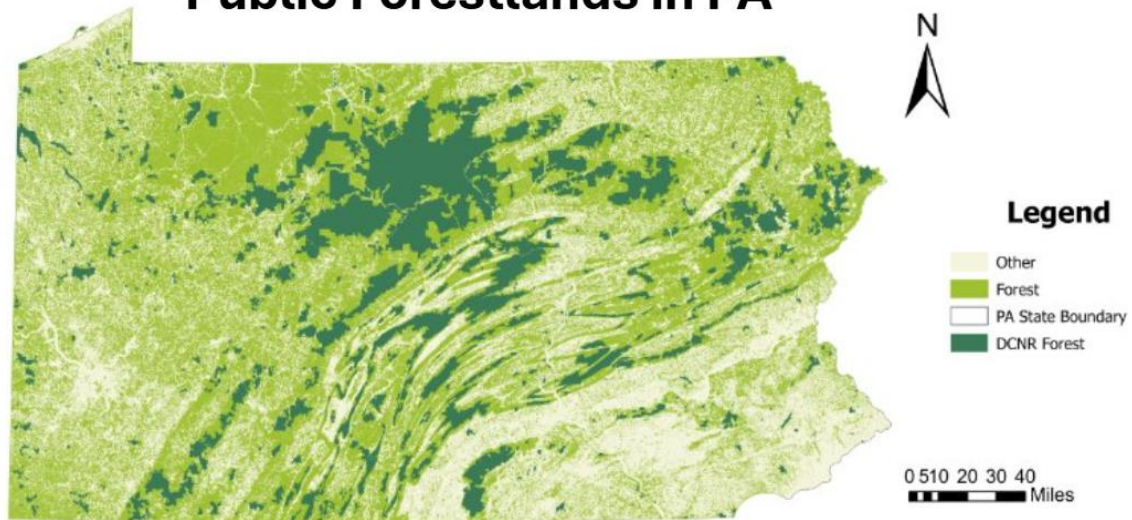


Figure 1. A reclassified map of PA with forests encoded in light green and DCNR managed lands in dark green. All forestland shapefiles were from NASS, 2024 and DCNR forest shapefile was from the Pennsylvania Department of Conservation and Natural Resources (PA DCNR) (personal communication, [October 23, 2023]).

Data on insecticide applications targeting SM, HWA, and EAB were collected and shared by the PA DCNR from the period 1996 to 2023. Data for earlier years were inconsistent or incomplete and were thus filtered to only include 2007 to 2022 for SM and 2011 to 2022 for HWA and EAB. (Table 1)

Table 1. Overview of data availability for spongy moth, emerald ash borer, and hemlock woolly adelgid. Green is available, yellow has few entries or incomplete, and grey is missing.

	SM	EAB	HWA
2007	Green	Grey	Grey
2008	Green	Grey	Grey
2009	Green	Grey	Grey
2010	Grey	Yellow	Yellow
2011	Grey	Green	Green
2012	Grey	Green	Grey
2013	Green	Green	Green
2014	Grey	Green	Green
2015	Green	Green	Green
2016	Green	Green	Green
2017	Green	Green	Green
2018	Green	Green	Green
2019	Green	Green	Green
2020	Grey	Green	Green
2021	Green	Green	Green
2022	Green	Green	Green
2023	Yellow	Grey	Grey

Data Structure:

Treatment data for each pest was stored and managed differently (Appendix A, B, and C). For SM, each record represented an aerial treatment at a site. For HWA, each record represented a treatment across multiple trees at a site on the same date. For EAB, each record represented a treatment to a unique tree, and each tree belonged to a site. These sites are managed areas repeatedly treated over time and are associated with spatial data. While organized differently across the three datasets, the key pieces of input information remain the same. (Table 2)

Table 2. Overview of key variables among pest datasets. Variables marked with asterisks are required to extrapolate the total active ingredient (in kg) estimates.

variable	description	structure	which pest?
year	year treated	character	<i>SM, EAB, HWA</i>
insecticide	common name of formulation	character	<i>SM, EAB, HWA</i>
active ingredient	substance with effects	character	<i>SM, EAB, HWA</i>
rate *	rate at which insecticide was applied	numeric	<i>SM, EAB, HWA</i>
acres *	area of the site	numeric	<i>SM</i>
dbh *	diameter at breast height of treated trees	numeric	<i>EAB, HWA</i>
ownership	land ownership (public vs private)	character	<i>SM, EAB, HWA</i>
site	management area	character	<i>SM, EAB, HWA</i>
number_of_trees	Number of trees treated	numeric	<i>EAB, HWA</i>

Data Processing:

For SM, I merged yearly data layers to generate a temporally complete data frame. For HWA and EAB, I excluded repeat site IDs and tag numbers from the baseline shapefile to ensure a unique set of management sites and trees treated. I then performed a left join to relate the insecticide application details with the spatial component for analysis and visualization. Among all three datasets, I filtered to include only treatments on public forests and exclude rows that were missing key variables in Table 2. For the HWA dataset, I extrapolated the missing rows of total trees treated per management site by dividing the total diameter at breast height (DBH) of all trees treated by an estimate of 20 in DBH per tree (affected 11 of 376 rows (3%)). The

majority (~2/3) of the SM treatments were excluded since most were applied on private lands. After filtering, 1271 of 3946 (32%) of rows remained for SM; 3955 of 4257 (93%) of rows remained for EAB; 368 of 376 (98%) of rows remained for HWA.

AIs, acres, rates, and information from the insecticide labels served as the basis for the insecticide key (Table 3). This key stored information on AI and conversion factors to derive the amount of AI in each formulated product. This key also included toxicity metrics specific to *Apis mellifera* (honeybees) and were derived from Douglas et al., (2022) and the Bio-Pesticides DataBase (BPDB). Contact and oral toxic loads were generated by dividing the total AI applied by the lethal dose of each AI and summed by target pests. The complete key provided a standard way to quantify the weight of AI and compare the toxicity of each insecticide.

Table 3. Key information extracted from labels and online sources for each insecticide.

variable	description	structure
active ingredient	substance with effects (kg)	character
ai_percent	percent of AI in formulation	numeric
class	insecticide category based on mode of action	character
appearance	liquid/solid/tablet	character
label_conversion	value to convert from liquid to solid	numeric
ld50_oral	µg AI to kill 50% of population via oral ingestion	numeric
ld50_contact	µg AI to kill 50% of population via contact	numeric
unit_conversion	convert from one unit to another	numeric

The insecticide key was joined to the pest specific data frame using AI. The complete data frame was used to generate statistics to understand the extent, intensity, and bee hazard of the insecticide patterns. Formulated product was translated to amount of AI using the following equations:

- For dry/powder insecticides:
 - Total applied (AI kg) = dosage * ai_percent * unit_conversion
- For wet insecticides:
 - Total applied (AI kg) = dosage * label_conversion * unit_conversion

Mapping:

Although insecticides targeting EAB and HWA were injected on a per tree basis, they belonged to a site polygon and the sites were associated with acres data. To estimate the total acres of lands treated, relative to DCNR-managed lands, I calculated the average percent of DCNR-managed land treated per year using the following steps:

1. Group insecticide treatments by year
2. acres: Sum acreage of unique sites
3. pct_dcnr_trted: Divide acres treated by the total acres of DCNR-managed lands calculated from the shapefile (~4151710 acres)

To examine the temporal and spatial dynamics of lands treated, I quantified the number of times a management site was treated over the study period, as follows:

- a. For SM, I combined the shapefiles across all years and used the Count Overlapping Features on ArcGIS Pro to generate the number of repeat treatments per polygon.
- b. Because EAB data were stored via trees instead of polygons, I generated a new criterion; if at least one tree per management site was treated, then the entire site was marked as treated for the year. I grouped the cumulative dataset by *Location Name* and *year*, extracted distinct combinations, and joined it to the site shapefile for mapping. Although this is likely an overestimate, it created common ground to compare the results.
- c. For HWA, I grouped the cumulative dataset by *Location Name* and *year*, extracted distinct combinations, and joined it to the site shapefile for mapping.

Each data frame then contained information on the number of times each polygon was treated, number of unique years treated, and the spatial coordinates. The following steps were completed on ArcGIS Pro:

1. Loaded all shapefiles (3 total).
2. Generated a new column titled ‘percent of years treated’, using times treated/total years for each shapefile.
3. Created a choropleth map, color coded by pests, shaded by percent of years treated over the study period.

The cumulative choropleth map depicted the spatial distribution and treatment hotspots of the percent of years in which a particular piece of land was treated across a 12-year period.

Summary Statistics:

The table aggregated the following factors by pest to assess the extent and intensity and hazard of treatments for each pest and total footprint among all insecticides applied in public PA forests. All entries (besides years treated) were presented as per year means \pm standard deviation.

1. Years treated
2. Acres treated
3. Percent of DCNR lands treated
4. Trees treated (HWA and EAB only)
5. AI applied (in kg)
6. LD₅₀ toxic load for honeybees

7. LD₅₀ toxic load for honeybees

An additional table was generated to compare the extent, intensity, and bee hazard of public PA forests to PA agricultural lands. For forestlands, I used the per year estimates from the previous table and divided the total acres treated, AI applied, and bee toxic load by the total public forestlands (4151710 acres derived from shapefile) for a yearly per total public forestlands estimate. For agriculture, I generated similar estimates using insecticide data from Douglas et (2022) and total agricultural lands data from USDA NASS. All entries were scaled to per year means \pm standard deviation.

1. % of lands treated
2. Total AI Applied (in kg) per Ac
3. Contact lethal doses (in mil) per Ac
4. Oral lethal doses (in mil) per Ac

Results

Extent of insecticide usage: Among all three pests, there was variability between the number of trees and acres treated each year (Figure 2 & 3). SM treatments made up the majority of acres treated and followed a cyclical pattern, peaking roughly every 5 years (Figure 2a). More hemlock trees were treated on average compared to ash trees; they were largely treated in state parks (Figure 3b). EAB treatments had the smallest spatial footprint and were primarily applied in state forests (Figure 2c & Figure 3c).

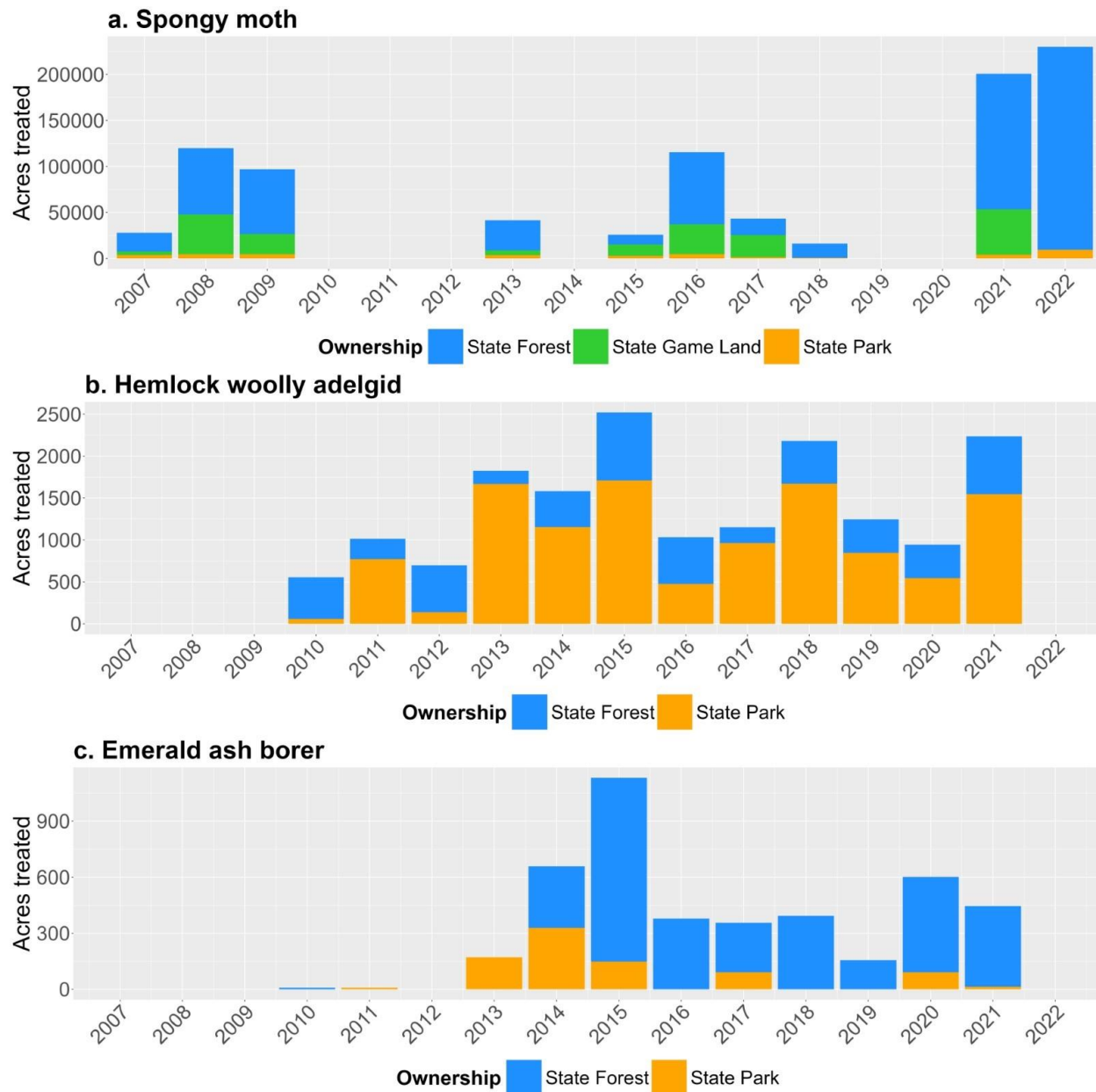


Figure 2. Bar plot visualizing the total acres treated by insecticides in PA DCNR-managed forestlands for the following forest pests: (a.) spongy moth, (b.) hemlock woolly adelgid, (c.) emerald ash borer. Hemlock woolly adelgid and emerald ash borer treatments were applied via tree or soil injection within a management site. Duplicate treatments per site each year were excluded in this plot.

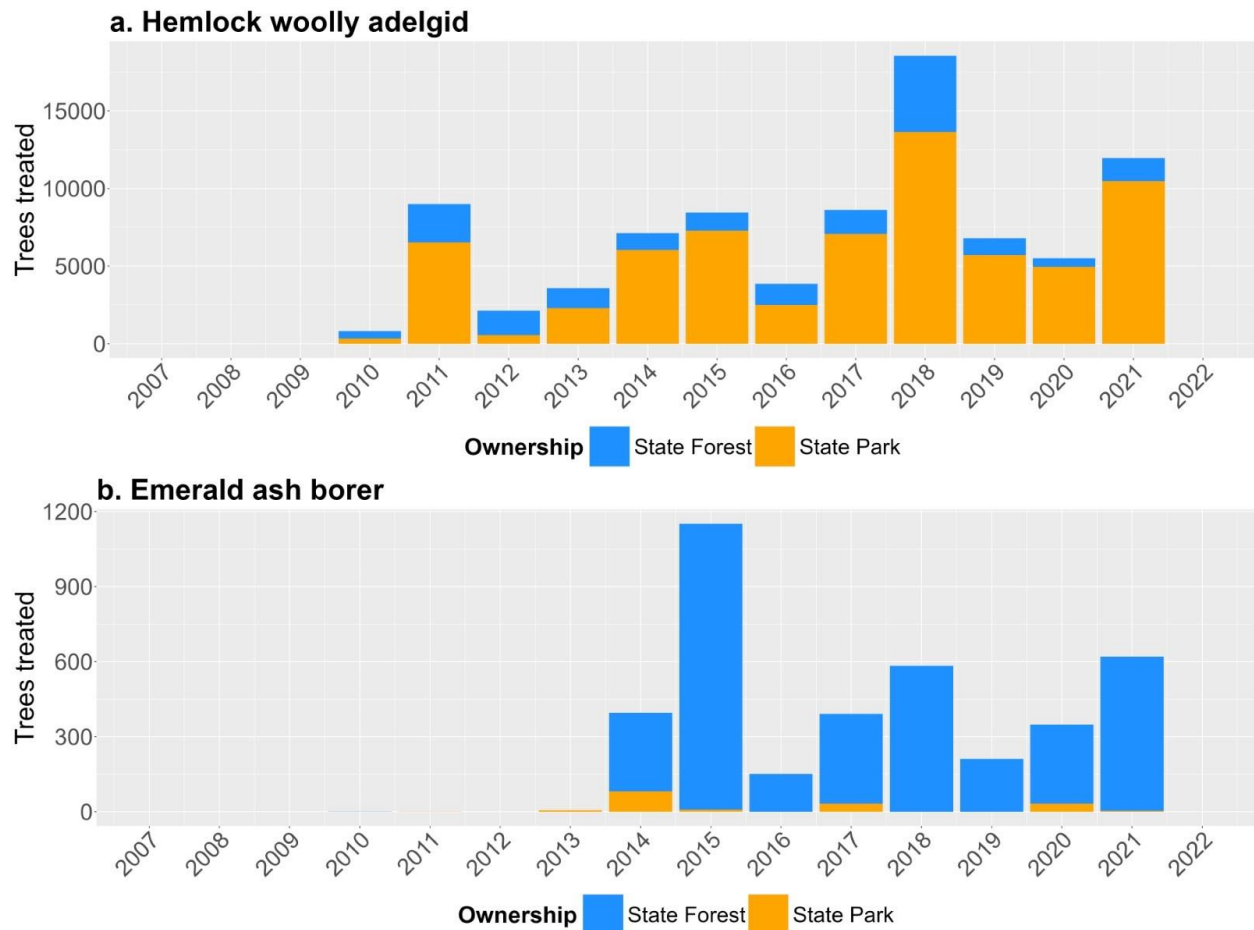


Figure 3. Bar plot visualizing the total number of trees treated by insecticides in PA DCNR-managed forestlands for the following forest pests: (a.) hemlock woolly adelgid and (b.) emerald ash borer. No plot for spongy moth since treatments were applied via foliar spraying.

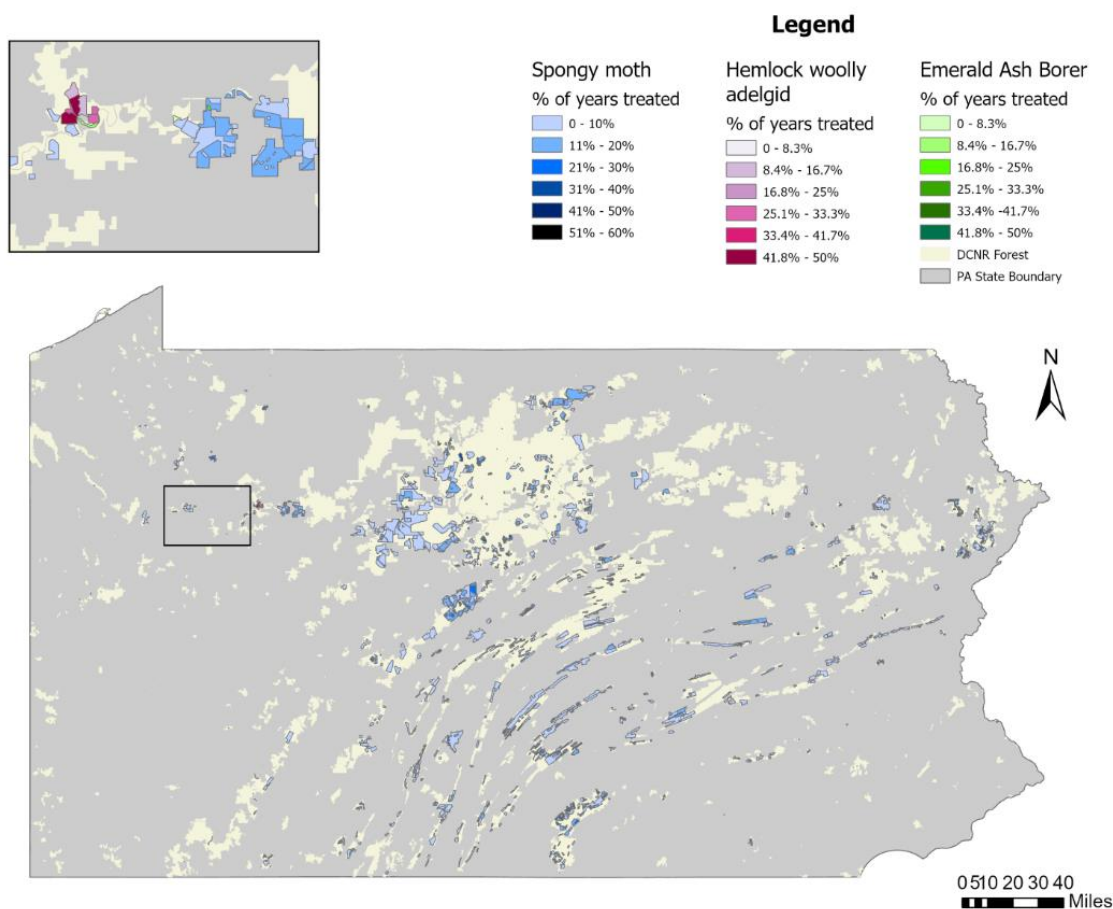


Figure 4. A choropleth map depicting the spatial distribution and hotspots of DCNR insecticide applications on DCNR-managed forestlands in PA for each forest pest. Hemlock woolly adelgid and emerald ash borer treatments were unique to an individual tree within a management site. If a tree within a management site was treated, the polygon was marked as treated for the year.

Between 2010 and 2022, ~23% of state forestlands were treated at least once. SM treatments made up most of the lands treated accounting for $\sim 2.21 \pm 0.003\%$ of state forestlands each year (Table 4). HWA and EAB treatments were both treated to a lesser extent, with $0.001\% \pm 0.002\%$ and $0.0005\% \pm 0.0007\%$ of DCNR-lands treated yearly, respectively. Sites treated for SM and HWA were treated one to three times on average, while sites for EAB were treated over 3 times for a quarter of the treatments (Figure 4).

Intensity of insecticide usage:

SM treatments were applied via aerial spray and were applied more intensively compared to HWA and EAB (Figure 5). In recent years, there was an increase in total AI applied and a shift toward tebufenozide, an insect growth regulator, from the biological insecticide, *Bacillus thuringiensis kurstaki* (Btk) strain. Dinotefuran and imidacloprid were neonicotinoids used to control HWA (Figure 5b). For HWA, the amount of AI applied peaked every two to three years, with imidacloprid making up the majority of the treatments. Emamectin benzoate, an avermectin, was the sole AI used to prevent and manage EAB populations and was applied in lower quantities in recent years (Figure 5c).

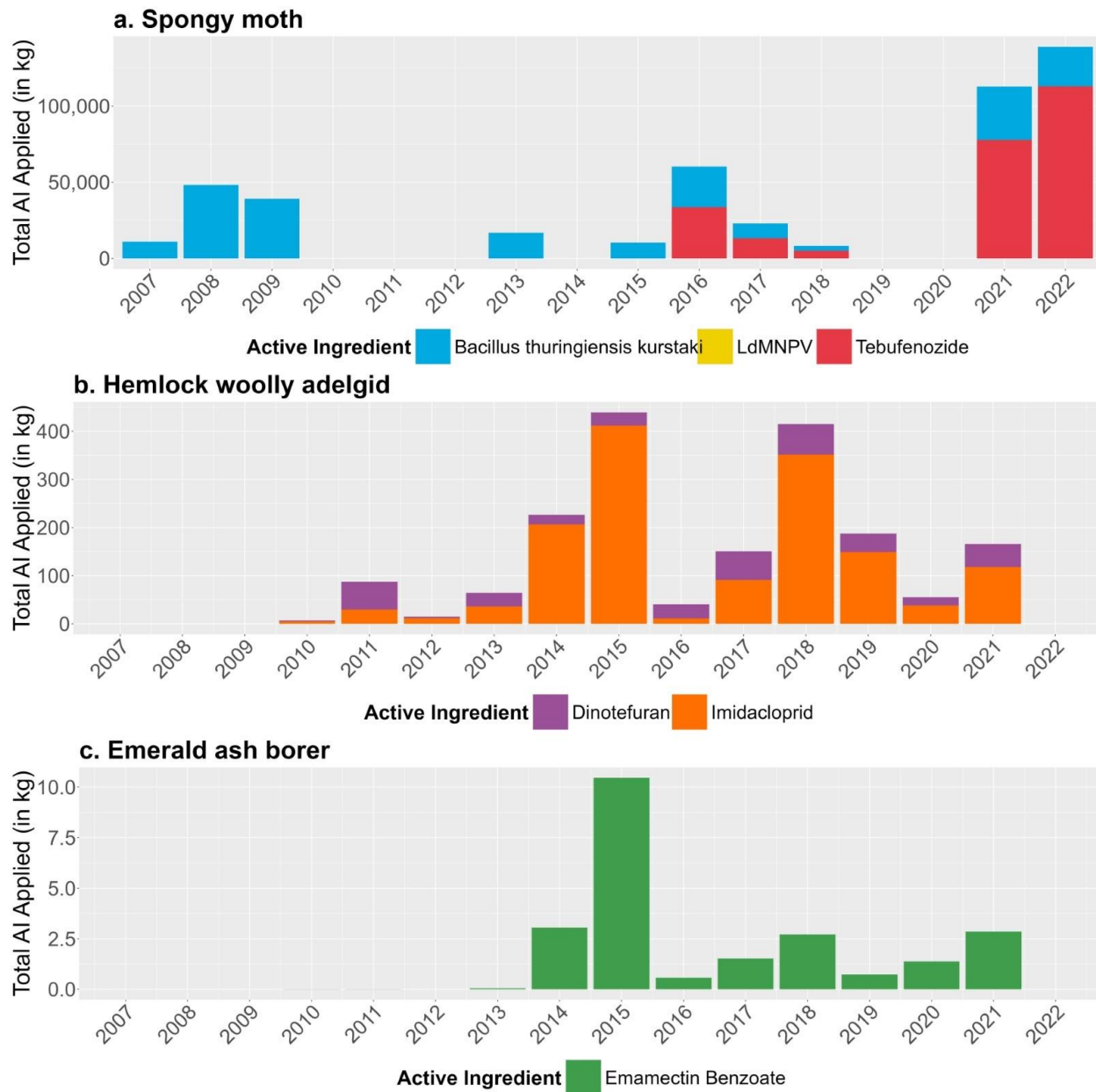


Figure 5. Bar plot visualizing the total active ingredient (kg) of formulated products applied in PA DCNR-managed forestlands for the following forest pests: (a.) spongy moth, (b.) hemlock woolly adelgid, (c.) emerald ash borer.

Bee Toxicity:

Although SM treatments were applied more intensively across a larger region (Figure 2a & 3a), they posed the least hazard to honeybees. On the other hand, HWA and EAB treatments made up a small fraction of land treated, and the AIs used but were more hazardous; they contributed approximately 2835 and 550 billion contact lethal doses respectively, and HWA treatments were ~16 times more hazardous when ingested (Figure 6 & 7; Table 4). With an LD₅₀ oral value of 0.0037 µg per bee, imidacloprid made up most of the oral toxic load for HWA treatments, suggesting greater potential threat to honeybees (Figure 7b).

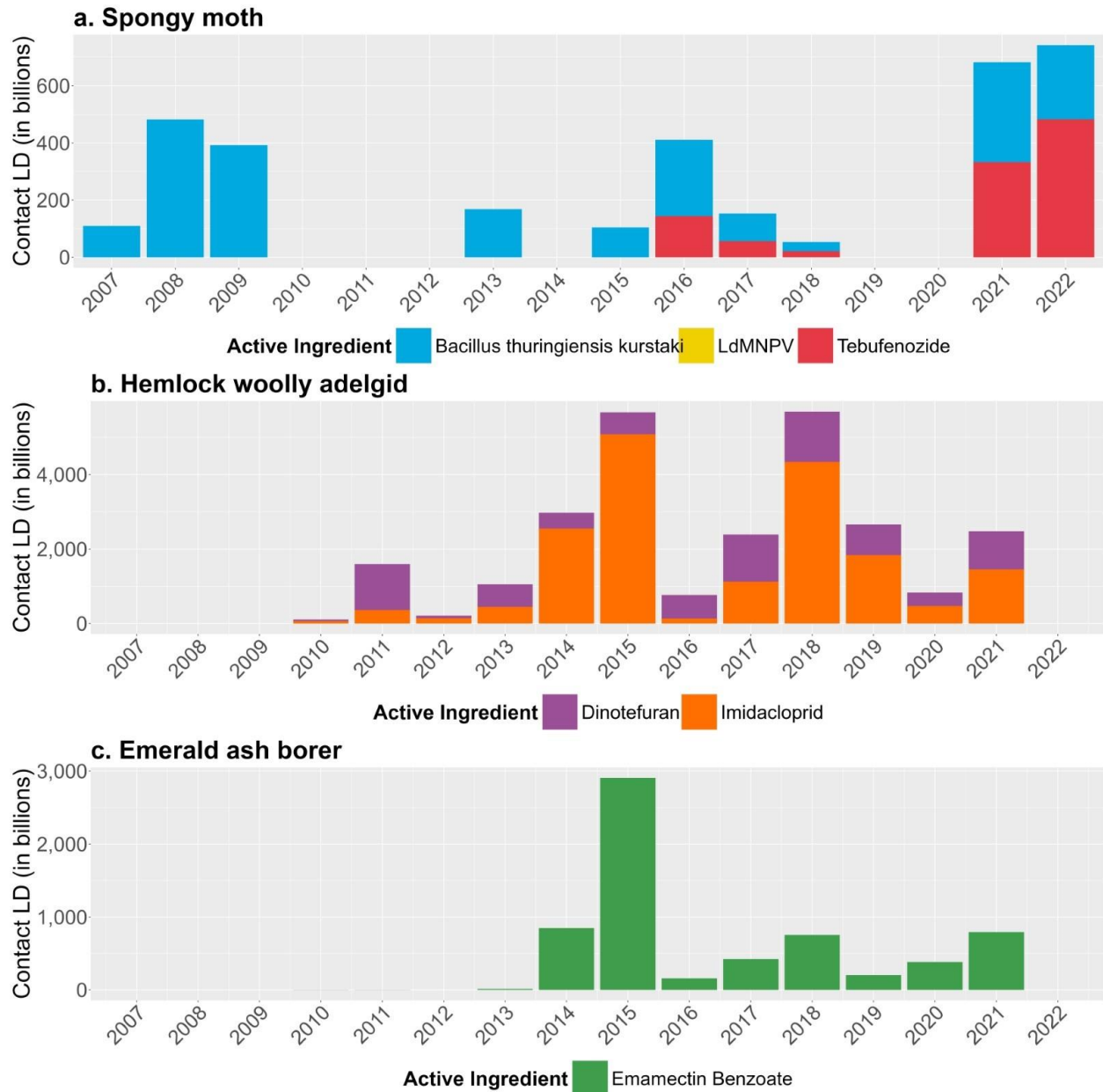


Figure 6. Bar plot visualizing total contact toxic load for honeybees based on insecticides applied on PA DCNR-managed forestlands for the following forest pests: (a.) spongy moth, (b.) hemlock woolly adelgid, (c.) emerald ash borer. Contact toxic load is a direct product of total active ingredient (AI) divided by bee lethal dose (LD_{50}) on a contact basis (pesticide is applied to the outside of a bee's body).

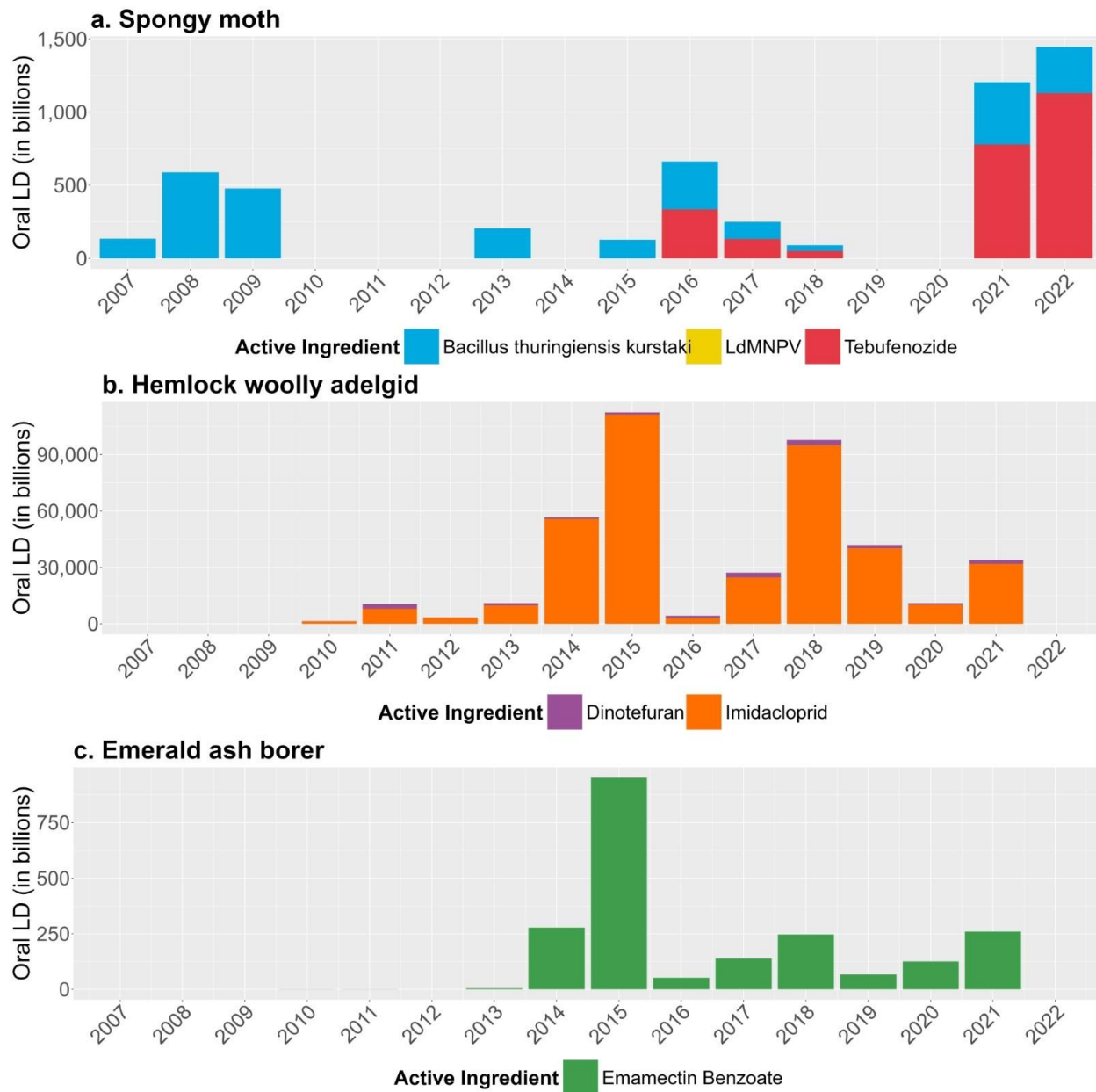


Figure 7. Bar plot visualizing total oral toxic load for honeybees based on insecticides applied on PA DCNR-managed forestlands for the following forest pests: (a.) spongy moth and (b.) hemlock woolly adelgid, and (c.) emerald ash borer. Oral toxic load is a direct product of total AI divided by bee lethal dose (LD_{50}) on an oral (ingested) basis.

Table 4. Yearly average and standard deviation of the extent, intensity, and hazard to honeybees of insecticide applications by forest pest using PA DCNR insecticide data from 2010 to 2022.

Pest	Years of data	Trees treated	Acres treated	% DCNR lands treated	Total AI applied (in kg)	Contact lethal doses (in bill)	Oral lethal doses (in bill)
Spongy moth	10	n/a	91699 ± 163	2.21 ± 0.003	46861 ± 102	330 ± 1	518 ± 1
Hemlock woolly adelgid	12	7514 ± 34	1507 ± 7	0.03 ± 0	166 ± 2	2835 ± 24	44141 ± 534
Emerald ash borer	12	330 ± 26	382 ± 3	0.009 ± 0	2 ± 0.004	550 ± 0.1	180 ± 0.03
Total	-	7844 ± 60	93588 ± 173	2.21 ± 0.042	47029 ± 104	3715 ± 25	44839 ± 535

Note: Trees treated, acres treated, AI applied (in kg), LD50 Contact (in bill), and LD50 Oral (in bill) are all a product of [var/years] treated for each pest.

% DCNR lands treated = [Acres treated / DCNR Lands (4,151,710 ac)] (Figure 1).

LD50 Contact and LD50 Oral measures were generated by converting total AI from kg to µg and divided by LD50 value per bee (Table 3). Bee lethal doses = [AI applied (in kg)/1,000,000,000]/LD50 per bee

SM dominated extent and intensity, but HWA and EAB posed a greater bee hazard given the bee-toxic nature of the products used to control them (Table 4). However, compared to agriculture, public forests were treated to lesser extent and intensity, with over 350 times fewer lethal doses per acre in the contact scenario and ~80 times fewer lethal doses per acre in the oral scenario (Table 5).

Table 5. Yearly average and standard deviation for extent, intensity, and bee hazard estimates relative to all state forest and agricultural lands. Forest estimates were from this study between 2007 and 2022. Agricultural estimates used acreage estimates the USDA NASS, and insecticide data from Douglas et al. 2022 between 2007 to 2014.

	% of lands treated	Total AI Applied (in kg) per Ac	Contact lethal doses (in mil) per Ac	Oral lethal doses (in mil) per Ac
Forest	2.24 ± 0.003	0.01 ± 0.00002	0.9 ± 0.006	10.8 ± 0.1
Agriculture	14.5 ± 0.07	0.025 ± 0.007	345 ± 79	828 ± 257

Note: Total AI Applied (in kg), LD50 Contact, and LD50 Oral are divided by all public forestlands and agricultural lands each year

Total Public Forestlands = 4,151,710 acres

Total Agricultural land = 6,570,945 acres

Discussion

Insecticides applied in public forestlands make up a small fraction of the total insecticide applied. Pimental & Levitan, (1986) estimated less than 1% of forestlands are treated with insecticides, with an average application rate of 3 kg of AI per ha. Focusing on the per acre estimate, Pimental's predictions exceed the amount of AI applied in public PA forests by ~2.5 times, further reinforcing the small footprint. Each year, a small percentage of public forestlands are treated for SM, HWA, and EAB. Of the three pests, SM is treated more widely and intensively but poses the lowest bee hazard. While HWA and EAB are both treated to a lower extent and intensity, the products used are neurotoxic and drive up the bee hazard estimates considerably.

Extent of insecticide usage:

Of the public forestlands treated, my results indicate that the total acres treated make up a small part of DCNR-managed lands. Among the three forest pests, SM treatments are applied most extensively, with ~2% of public forests treated yearly, because insecticides are applied via aerial spraying, whereas HWA and EAB treatments are applied via soil and tree injections, respectively. Since trunk and soil injections are tree specific, there is likely an overestimate of direct area treated. However, this overestimate can account for the insecticide contamination of surrounding environments.

In PA, state forests make up ~2.2 million acres, state game lands make up 1.5 million acres, and state parks make up 300k acres (State Forests, State Game Lands, State Parks, n.d.). Most insecticides are applied in state forestlands, compared to other state lands. State forests and parks are managed by two bureaus within PA DCNR, with an emphasis to maintain 'wild character' and 'biological diversity' and procure timber resources (State Forests and State Parks,

n.d.). State game lands are managed by PA Game Commission with the goal of protecting and restoring understory herbivory (Albright et al., 2023).

Temporal changes in insecticide usage:

Pest population dispersal and longevity of AI applied are two important factors that can explain the variability in insecticide applications applied on public forestlands (Tobin, 2013; *Adelges tsugae*, n.d.). In the SM treatments, there are few repeat treatments and variability in the areas treated since the moth ball or hang from silk threads and are dispersed by the wind. Once established, females lay egg masses consisting of more than 600 eggs (Tobin, 2013; Blackburn et al., 2024; Coleman et al., 2020). Flight capability and multiple pathway vectors like incidental transport of egg masses also help facilitate and accelerate dispersal and population spread (Tobin, 2013; Blackburn et al., 2024). HWA undergoes two generations each year and are dispersed in the spring by bird migration (McClure, 1987; Russo et al., 2019). Additionally, chemical AIs are applied via soil injections or drenches to the base of a tree and can prevent infestations for up to five to seven years, further explaining infrequent treatments (*Adelges tsugae*, n.d.). EAB populations spread via stratified dispersal, where insects travel short continuous distances and humans facilitate longer dispersals, specifically with firewood transportation (Herms & McCullough, 2014; Mercader et al., 2011; Shigesada & Kawasaki, 1997). This supports the combination of repeated and newly treated trees. The AI used is known to provide protection and coverage from EAB for two to three years, further contextualizing the cyclic nature of treatments (Herms et al., 2009).

Pest population and host tree life cycles can account for the cyclic patterns present in the number of acres treated and amount of AI applied (Tobin, 2013; Kappler et al., 2020). SM have distinct population dynamics where populations peak every five to ten years for two to three

years at a time and are consistent with the cycles present in pest treatments (Tobin, 2013). HWA are reliant on hemlock trees, and experts suspect tree health influences pest population cycles and dispersal (Thompson et al., 2023; McClure, 1991). Similarly, EAB is dependent on ash trees and population spikes are predicted to occur every ten years when ash matures from sapling into adult trees with a DBH > 3 in (Kappler et al., 2020). Since pest population and dispersal cycles often unfold over extended periods, a decade long study may miss the nuances in their dynamics.

Hazard of insecticide usage:

Among three forest pests, six distinct AIs across four insecticide classes were used to treat and reduce insect populations. Each insecticide has a mode of action (MoA), or how the AI in an insecticide kills the insect (Suiter & Scharf, 2009). Insecticides with various modes of action target different aspects of an insect's physiology (Suiter & Scharf, 2009). Btk and tebufenozide were the main insecticides used in SM treatments. Btk, a biological insecticide and tebufenozide, an insect growth regulator (IGR) both target lepidopteran larvae, destroying the gut lining and disrupting the molting process, respectively (Swadener, 1994; Blackburn et al., 2011). Even though both AIs may have low toxicity to adult bees, they may pose threats to lepidopteran pollinators (Blackburn et al., 2011). A study on insecticide toxicity on aquatic arthropods revealed that tebufenozide interferes with the molting process in mosquitoes and other arthropods, suggesting possible hazard to immature insects including pollinators (Song et al., 1997). In recent years, there has been a shift toward tebufenozide from Btk for SM treatments, to control areas at risk of severe defoliation that were not successful with Btk treatments (Yoo et al., 2024). While tebufenozide has a lower bee toxic load than Btk, it may pose a hazard to a broader range of insect larvae (Song et al., 1997).

Imidacloprid and dinotefuran are both neonicotinoids used to treat HWA. Neonicotinoids are a class of broad range neurotoxins that disrupt the nervous functions of insects (Suiter & Scharf, 2009). With an LD50 oral value of 0.0037 µg per bee, imidacloprid is effective and potent (BPDB, n.d.). It takes three to 12 months to fully absorb into the tree's system and provides four to six years of protection (Jackson, 2021). Comparatively, dinotefuran is more water soluble and absorbs more quickly (Jackson, 2021). While AIs are often applied together to capitalize on the efficacy and quicker intake properties, imidacloprid is applied more extensively than dinotefuran in HWA treatments. With a larger imidacloprid footprint, there will likely be a higher hazard to bees and other insect pollinators.

Emamectin benzoate belongs to the avermectin class and was the only AI applied to treat EAB. This AI targets a broad range of insects by suppressing muscle contractions and causing paralysis (PPDB, n.d.). The plot showed a significant reduction in total AI applied after 2016 and cyclic patterns of lower treatments thereafter. This was supported by a management decision to reduce the dose from 10 mL to 5 mL per in of DBH in 2020 since literature suggested a similar efficacy rate with lower dosage (Fengyou Jia, personal communication, September 26, 2023; Flower et al., 2015).

Implications for bees:

Contrary to the original hypothesis, tree and soil injections were far more hazardous to bees compared to aerial treatments. Although HWA is treated less intensively compared to SM, their associated treatments are nine times more hazardous in the contact scenario, indicating that neonicotinoids are far more potent than biologicals and IGRs. Similarly, EAB treatments are applied at a far less intensity and extent compared to SM but pose twice as much hazard to bees in the contact scenario. Although emamectin benzoate is more potent, compared to

neonicotinoids, with an LD₅₀ contact value of 0.0036 µg per bee, the sheer amount of AI applied for HWA treatments drives up the hazard estimate. Honeybees were used as a proxy for wild pollinators, since consistent toxicity data for other pollinator species are unavailable, highlighting an important limitation in my study (Pollinator Risk Assessment Guidance, 2025; Arena & Sgolastra, 2014).

When assessing bee hazard, insecticide drift is an important factor that influences whether or not an insecticide will reach a bee (Dhananjayan et al., 2019). A key determinant of insecticide drift is the method of application (Dhananjayan et al., 2019). For instance, spongy moth treatments were applied via aerial spraying which may result in direct insecticidal contact. About two to 25% of aerially applied insecticides can drift several miles from the source, contaminating waterways and bee habitats (Dhananjayan et al., 2019). Conversely, soil injections are absorbed in the tree's root system, reducing dermal drift but resulting in residues in leaves, soil, and groundwater sources (Steward & Horner, 1994; Fitzpatrick & Dowell, 1979). Over 70% of solitary bees live in the ground and use soil and leaves to build nesting habitats, making them more susceptible to pesticide residues in soils, compared to their non-ground-nesting bee counterparts (Fawcett et al., 2019; Willis Chan & Raine, 2020). In the HWA case, hemlock trees shade flowering plants and hemlock pollen are not typically used by pollinators, reducing direct contact risks to pollinators (Jackson, 2021). Trunk injections operate similarly, except insecticides are injected directly into the tree and absorbed into the phloem and leaf tissues, reducing both aerial drift and environmental contamination (Moura & Pereira, 2022, Flower et al., 2015). Emamectin benzoate is speculated to transport to tree foliage to target leaf feeding adults (Flower et al., 2015). Although there is no research now, this raises the concern of possible contamination and exposure to pollinators and via flower and pollen sources, since bees depend on ash pollen to start their nest for the season (Fawcett et al., 2019; Smitley et al., 2019).

Environmental fate is another important contributor when examining exposure and encompasses pesticide degradation and persistence (Kah et al., 2013). While all AIs used in this study are known to degrade with UV light exposure, neonicotinoids have the longest half-life, with 3.4 to 7000 days (Smith & Barry, 1998; Thompson, 2011; Liu et al., 2016; Zhu et al., 2011; Aseperi et al., 2022). Although a recent modeling effort to predict pesticide exposure to bees implies that pesticide degradation is not a significant factor (Lonsdorf et al., 2024), it may still contribute to the exposure in different families of bees.

Relevant Literature and Implications:

Consistent with predictions, my analysis suggests that agricultural lands are treated to a greater extent and yield more hazard to bees compared to forestlands. Of the 14.5% of agricultural lands treated each year, they are ~350 times more hazardous on contact basis and ~80 times more hazardous on an oral basis when ingested, compared to public forestlands. Agricultural areas are treated more extensively to produce crops and meat products and make up 5.5% of the world's GDP (Zahniser, 2024). On the contrary, PA public forestlands are primarily treated for timber production, natural resources conservation, and recreation purposes (Bureau of Forestry, n.d.). Although public forestlands are treated to a smaller extent, the average AI applied per year and per acre is more similar between both land uses. This likely reflects the potency of AIs used in agriculture like neonicotinoids and pyrethroids that require less quantity for the same performance (Schulz et al., 2021). Btk makes up the majority of AI applied in public forestlands and is applied in larger quantities to suppress pest populations (Swadener, 1994).

Public forestlands serve as an important refuge for bees from insecticide exposure since they are less hazardous than agricultural lands. PA DCNR conducts an aerial monitoring survey each year to assess pest damage and make informed management decisions (Forest Insects and

Diseases, n.d.). By tracking these trends, public land managers can implement targeted interventions, ultimately reducing the quantity of insecticides and acres treated (Forest Insects and Diseases, n.d.). The primary forest pests treated in PA include SM, HWA, and EAB (Fengyou Jia, personal communication, September 26, 2023). They are also ranked within the top 15 species responsible for biomass loss and forest damage within the US (Fei et al., 2019). This conveys the importance of ecologically sound and efficient pest management strategies to protect the health and longevity of forests.

While public land managers have a good strategy to manage pests and protect forest health and biodiversity, little is known about insecticide applications in private lands. The private sector owns ~69% of all forestlands in PA, and a recent survey shows that over 80% of private landowners are concerned with land and resource management and nonnative species, but only a few follow a structured plan (Albright et al., 2023). This suggests private forestlands may be treated to a lesser degree than public forestlands. However, there is no empirical data available to address this gap. Most forests are privately owned, illustrating the importance of filling this gap in understanding.

Future Directions:

Bees rely on diverse floral resources and interact with different land uses and geographies. Thus, it is important to expand this research to include insecticide application patterns in private forest and urban land covers over an extended period. In the same vein of generalizability, PA is one of many states that apply insecticides but one of few states that keep application records (Brink & Callahan, 2024). Of the states that document insecticide applications, I suspect that the number of acres treated depends on state specific management goals, but the application rate is likely consistent because of pesticide regulations. My analyses

suggest that specialist pest treatments will span a smaller area with high toxicity hotspots whereas, generalist species will cover larger areas with lower hazards. These patterns can provide a general estimate of bee hazard in areas without empirical data. Additional data, research, and generalizable patterns will provide us with a complete understanding of application trends over time and across a continuous land cover and ultimately support an ongoing modeling effort to predict bee hazards from insecticide usage and support pollinator conservation.

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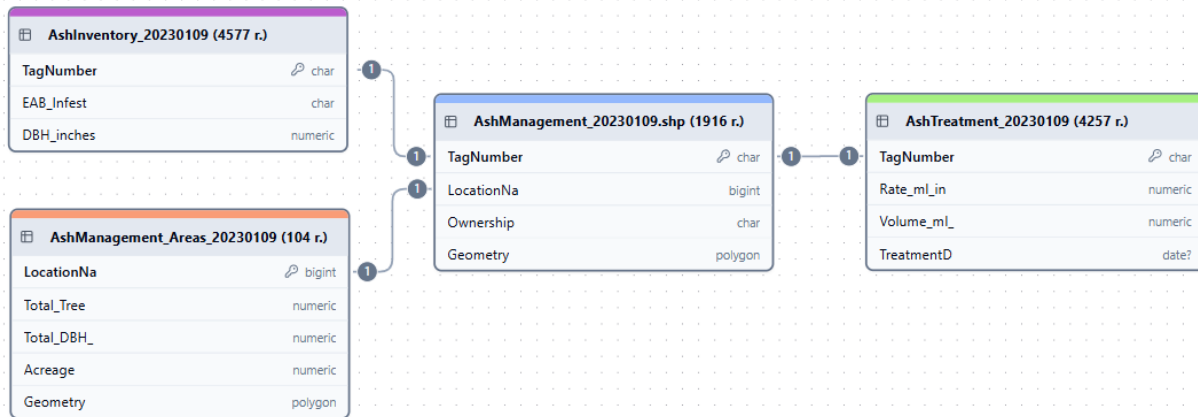
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Appendix

Appendix A. An example metadata file for the 2022 spongy moth shapefile. Each year is documented in a different shapefile and includes relatively similar variables. Each data frame includes a spatial polygon, represents a year, and will be appended to generate a complete data frame with all variables in Table 2.

GM_SprayBlocks_2022 (221 r.)	
2022	Description
OID_	ObjectID by ArcGIS
ACRES	Acres treated
Gallons	Amount of formulated product applied (in gal)
Insecticid	Formulated product
FPM_Area	Part of the state (northern, southern, etc.)
DistrictNu	District #
Ownership	Ownership of land
Owner_Code	Ownership encoded
Municipali	Township
County	Counties in PA
County_Cod	County code
Year	Treatment year (also in name of file)
Site_Name	Name of site
Population	# of egg masses/Ac
Trend	Population trend

Appendix B. Database schema for emerald ash borer files. Blue and orange files represent tree points and site polygon shapefiles. Purple and green files contain application information (rate, volume) and tree info (DBH) respectively. LocationNa corresponds to individual sites and relates the two spatial files. TagNumber corresponds to the individual trees and relates the tabular data with points shapefile. Metadata for each data frame with variable interpretations below.



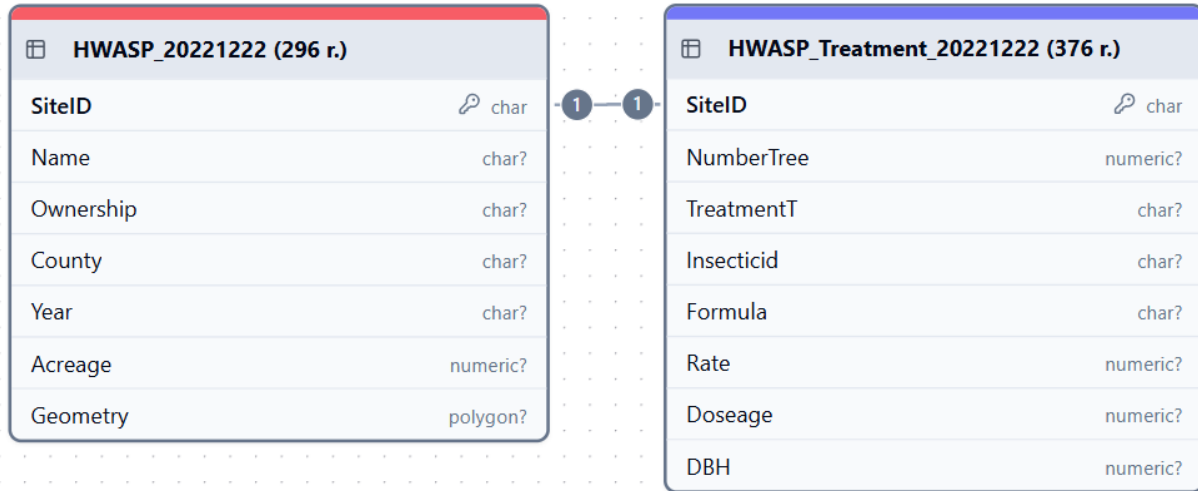
AshManagement_20230109 (1916 r.)	
Column Name	Description
OID_	ObjectID by ArcGIS
OBJECTID	ObjectID by DCNR
TreeNumber	Unique ID for each tree
TagNumber	Unique ID for each tree (KEY)
DistrictNu	District #
LocationNa	Site name (KEY)
Ownership	Ownership of site
Latitude	Latitude
Longitude	Longitude
ElevationF	Elevation (by feet)
Aspect	Cardinal directions
SlopePosit	Slope position
AshSpecies	Type of ash
TreeGender	Tree gender
AshPercent	% of ash in forest
StandSize	Size of grove
ForestType	Type of forest
EAB_Infest	Date of infestation

AshManagement_Areas_20230109 (104 r.)	
Column Name	Description
OID_	ObjectID by ArcGIS
OBJECTID	ObjectID by DCNR
LocationNa	Site name (KEY)
DistrictNu	District #
County	Counties in PA
Total_Tree	# of trees in each site
Total_DBH_	Diameter at breast height (in inches)
Acreage	Size of site in acres

AshTreatment_20230109 (4257 r.)	
Column Name	Description
OBJECTID	ObjectID by DCNR
TagNumber	Unique ID for each tree (KEY)
Treatment	Date of treatment
Treatment	Method of application
Rate_ml_in	Application rate (in mL/in)
Volume_ml	Total formulated product applied
Number_Inj	Total # of injections
Weather	Weather patterns

AshInventory_20230109 (4577 r.)	
Column Name	Description
OBJECTID	ObjectID by DCNR
TagNumber	Unique ID for each tree (KEY)
Inspection	Date of pest inspection
EAB_Infest	Whether tree is infested or not
AshHeight	Height of tree in feet
TreeCondit	Dead vs. alive
DBH_inches	Diameter at breast height (in inches)
Weather	Weather patterns

Appendix C. Database schema for hemlock woolly adelgid files. Red file represents the site polygons shapefile. Blue file represents tabular application information. SiteID corresponds to individual sites and relates the tabular data with the site polygons. Metadata for each data frame with variable interpretations below.



HWASP_20221222 (296 r.)	
Column Name	Description
OID_	ObjectID by ArcGIS
OBJECTID	ObjectID by DCNR
SiteID	Unique ID for each site (KEY)
Complex	Location Name
Name	Location Name (specific)
FPMArea	Part of state (northern, southern, etc.)
Ownership	Ownership of land
County	Counties in PA
Year	Year of treatment
Acreage	Size of site in acres

HWASP_Treatment_20221222 (376 r.)	
Column Name	Description
OBJECTID	ObjectID by ArcGIS
SiteID	Unique ID for each site (KEY)
NumberTree	# of trees in site
Treatment	Method of application
Insecticid	Active ingredient
Applicator	Person who applied treatment
PDA_Licens	Lead applicator certification number
Manufactur	Manufacturer
Formula	Formulation name
EPA_Number,C,20	EPA registration #
Rate	Application rate
Dose	Rate * DBH
DBH	Diameter at breast height (in inches)
Treatment	Date of treatment

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