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Preventing Defoliation by Spongy Moth (*Lymantria dispar*) with Systemic Insecticides and Their Interaction with Nitrogen Supplementation

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Abstract. Background: Spongy moth (*Lymantria dispar* L.) is an exotic, outbreak pest in North America, where it causes defoliation and mortality of trees. The management tools for this insect on residential and commercial properties as well as small woodlots include the use of systemic insecticides to protect against severe defoliation during an outbreak. Methods: We evaluate the ability of acetamiprid (TriStar® 8.5 SL; Nufarm, Alsip, IL, USA) applied as a bark spray in the spring; acephate applied as either a soil injection (Lepitect™; Rainbow Ecoscience, Minnetonka, MN, USA) or root flare injection (Lepitect Infusible™; Rainbow Ecoscience) in the spring; and emamectin benzoate (Mectinite®; Rainbow Ecoscience) applied as a root flare injection either in the previous fall or spring to prevent defoliation of mature northern red (*Quercus rubra*) and white (*Q. alba*) oaks during a spongy moth outbreak. We also evaluated any potential influences of nitrogen (N) supplementation on the efficacy of acetamiprid and fall emamectin benzoate treatments to prevent defoliation by spongy moth. Results: No effect of N supplementation on foliar N levels or insecticide efficacy was detected. All insecticide treatments, except for bark-applied acetamiprid, were able to significantly reduce spongy moth defoliation relative to nontreated controls, though there were statistical and numerical differences between treatments. Conclusion: These results demonstrate that N supplementation requires further study but did not influence insecticide efficacy in our study and that acephate and emamectin benzoate are both effective at preventing defoliation, but due to variation between treatments, considerations should be made regarding the timing and method of application.

Keywords. Defoliation; Nitrogen Fertilization; Spongy Moth; Systemic Pesticide.

INTRODUCTION

Spongy moth, *Lymantria dispar* L. (Lepidoptera: Erebidae), is a destructive defoliating pest in its invaded range in North America where it was introduced in 1869 (Liebhold et al. 1989; Beninger and Abou-Zaid 1997; Davidson et al. 1999). Spongy moth caterpillars are polyphagous with an extensive host range (Liebhold et al. 1995) but are most notable for the defoliation of oaks (*Quercus* spp.) in natural and urban areas of their invaded range (Mcmanus and Csóka 2007; Hilmers et al. 2023).

Managing spongy moth defoliation of trees at the individual or stand level in urban environments and small woodlots can be achieved with the application of insecticides, which can be applied directly to the canopy/foliage or systemically through the vascular system. Active ingredients that are registered under various trade names for the management of spongy moth in these environments include systemic insecticides such as acephate, carbaryl and emamectin benzoate, and foliar-applied insecticides such as *Bacillus thuringiensis kurstaki* (Btk), bifenthrin, chlorantraniliprole, permethrin, pyrethrins, and spinosad (e.g., Liesch and Williamson 2022). Notably, alternative or value-added management approaches such as the targeting of egg masses during the dormant season are still under development (e.g., Chase et al. 2023). Financial, environmental, and/or logistical considerations can often prevent the utilization of certain products and application procedures in some scenarios. For example, product acreage limits, proximity to water or structures (e.g., houses), the number and

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density of trees, total diameter inches to be treated, and/or accessibility of trees can all be factors when choosing a management approach. Systemic products are usually preferred when trees are large and/or in urban areas to avoid or limit concerns such as drift (Tatter et al. 1998; Davis and Elkinton 2018).

Much of the research on spongy moth management comes from the 1970s through the 1990s and assessed the efficacy of foliar-applied products (e.g., Nielsen et al. 1988; Nielsen and Dunlap 1991; Smitley and Davis 1996, 1997). Many extension services in the United States mention that emamectin benzoate and acephate products, applied systemically, are registered for the management of spongy moth (e.g., Liesch and Williamson 2022; Dill et al. 2023). Aside from acephate, which is a relatively older active ingredient, there are surprisingly few published studies on the efficacy of various systemic insecticides. We could not find published data on the efficacy of emamectin benzoate, but collective, anecdotal industry experience indicates that this insecticide is effective in managing spongy moth and other defoliating insects. As for acephate, both Webb et al. (1988) and Fleischer et al. (1989) reported high levels of efficacy of acephate with implant-type devices (e.g., ACECAPS®, Creative Sales, Inc., Fremont, NE, USA). Goyer (1973) reported spongy moth LC_{50} values on acephate-infused artificial diet of 15 ppm to 25 ppm while Moldenke et al. (1997) reported spongy moth LC_{50} acephate values on white alder (*Alnus rhombifolia*) and Douglas fir (*Pseudotsuga menziesii*) treated trees as 27 ppm and 20 ppm, respectively. Acephate can also be applied to the rhizosphere of trees as a soil injection or soil drench, absorbed by roots and translocated to the canopy where it provides protection. Some insecticides, such as acetamiprid, can be applied as sprays to the trunk of trees (known as "bark sprays" within the industry), where they are absorbed into vascular tissues and transported systemically. These bark sprays can be an attractive option for practitioners because they require low volumes of mixed product, can be executed quickly with little training, and concerns such as drift can largely be avoided. Interestingly, using paper disk bioassays, Feng et al. (2018) reported that acetamiprid can cause spongy moth larval mortality, though the LC_{50} value that these authors report was relatively high (221 $\mu g/cm^2$). Nevertheless, a bark spray option for the management of spongy moth would be a welcome option for the arboriculture industry.

A common management recommendation made by arborists amid a spongy moth outbreak, or defoliation by any pest, is nitrogen (N) fertilization in conjunction with insecticide application (authors' personal observation). The logic of such a recommendation likely stems from the idea that N lost to defoliation will be replaced in the system. It remains unclear as to whether carbon (C) or nutrient availability limits reflush postdefoliation in trees, as some studies suggest carbon to limit reflush (Kays and Canham 1991; Landhäusser and Lieffers 2002) while others have found N to limit recovery (Purvis 2024). Ultimately, the limiting factor(s) are likely to be situationally and species specific (Purvis 2024), turning the applied question into whether a generalized recommendation for N fertilization is acceptable or should be reconsidered.

From a pest management perspective, the impact of N fertilization on the efficacy of insecticide treatment is another consideration. It is widely known and accepted that N fertilization will likely benefit piercing-sucking pests such as aphids, but variation exists within the literature for other herbivorous feeding guilds (Kytö et al. 1996; Herms 2002). Fertilization was found to alter the mortality of hemlock woolly adelgid (*Adelges tsugae*) when exposed to several insecticides, and this appeared to be related to increased N content of hemlock (*Tsuga canadensis*) tissues (McClure 1992). Specifically for spongy moth, Giertych et al. (2005) found that N fertilization of pedunculate oak (*Q. robur*) seedlings, with added ammonium (NH_4), enhanced performance (i.e., development, pupal mass, and survival) and food utilization of larvae, likely due to N and/or phosphorous quantity, and possibly quality, within foliage. With any systemic insecticide, larvae would need to feed and cause damage to the foliage/crown to be controlled, necessitating an interaction between the nutritional quality of foliage and the insecticide, and these interactions are not well understood, particularly for spongy moth and mature trees.

The purpose of this study was to provide relative efficacy data for acephate, emamectin benzoate, and acetamiprid for the prevention of defoliation by spongy moth, utilizing an existing outbreak among a grove of northern red (*Q. rubra*) and white (*Q. alba*) oaks. We further sought to evaluate how N supplementation influenced the ability of a systemic insecticide (emamectin benzoate and acetamiprid, only) to provide protection against defoliation (i.e., an

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interactive effect). We hypothesize that all systemic insecticide treatments will provide efficacy against defoliation by spongy moth relative to untreated controls, and that efficacy will be impacted by application method or timing. Lastly, we hypothesize that N supplementation may increase foliar N levels and therefore could affect the efficacy of systemic products at the visual/aesthetic level of defoliation.

MATERIALS AND METHODS

Site Description

Privately owned property used as a playground, park, and picnic area located adjacent to forested public parks (Cook County Forest Preserve) in the Chicago, IL, USA metropolitan area experiencing heavy spongy moth pressure was identified during the late summer of 2023. Site managers reported no observations of spongy moth at any time during their tenure prior to 2023, when they reported heavy defoliation and spongy moth presence. The stand of trees within the park space is oak dominated with a mixture of northern red and white oak, with only a few individual shagbark hickory (*Carya ovata*), silver maple (*Acer saccharinum*), and black cherry (*Prunus serotina*) trees located within the stand. Observations during the late summer and fall of 2023 confirmed extremely high spongy moth pressure, as numerous fresh spongy moth egg masses were observed on most trees throughout the stand. Oak trees used for this study averaged 27.6 in ± 0.7 in (70.1 cm ± 1.8 cm) in diameter at breast height (DBH; approximately 1.3 m above the soil surface), and there were no significant differences in tree DBH between treatments (ANOVA; $F_{6,53} = 1.219$, $P = 0.311$). Trees had not been treated with insecticides or pruned within the past 5 years and were surrounded by turf which is fertilized biennially with an unknown fertilizer.

Insecticide and N Supplementation Treatments

A total of 59 Northern red and white oak trees were included in this study, which were all oak trees available at the site, and were randomly assigned to one of the treatments described below using a random number generator. Of these, 12 oak trees were injected with 4% emamectin benzoate (Mectinite®; Rainbow Ecoscience, Minnetonka, MN, USA) on 2023 October 20 immediately prior to senescence (fall color change occurred approximately one week later), half of which were later supplemented with fertilizer (see below). Oak trees were either treated at a rate of 5 mL product/in (1.97 mL/cm) DBH (12-in to 35-in DBH size class)(30.48 cm to 88.9 cm) or at 10 mL product/in (3.94 mL/cm) DBH (35 in + size class)(88.9 cm +) using a Q-Connect (Rainbow Ecoscience, Minnetonka, MN) injection device. One injection site for every 2 in (5 cm) in diameter was used to inject emamectin benzoate, and injection sites were drilled on root flares with a standard battery-powered drill and high-helix (15/64 in)(6 mm) drill bit. This autumn emamectin benzoate treatment occurred at 4,867 growing degree days (GDD) as calculated by the simplified "GMPHEN" model for spongy moth development (Sheehan 1992) using the closest weather station available on uspest.org (98% adult emergence occurs at 3,250 GDD). The weather conditions the day before treatments were 55 °F to 60 °F (12.8 °C to 15.6 °C) with mostly cloudy conditions and light afternoon precipitation, and the weather conditions at the time of treatments were approximately 54 °F to 56 °F (12.2 °C to 13.3 °C) and overcast with no precipitation.

On 2024 April 18 (418 GDD), 6 oak trees were trunk injected with 97.4% acephate (Lepitect Infusible™; Rainbow Ecoscience, Minnetonka, MN, USA), and 6 oak trees were trunk injected with emamectin benzoate using a Q-Connect injection device. Spongy moth caterpillars were confirmed to be active at this time (2% egg hatch occurs at 350 GDD). Acephate was injected into the root flares of these trees by diluting product in water at a rate of 300 mg/mL and injecting 5 mL/in (1.97 mL/cm) DBH of mixed solution (one injection site per 2 in [5 cm] DBH) using a Q-Connect injection device. The emamectin benzoate trees were treated as described above. The weather conditions the day before the treatments were temperatures of 55 °F to 68 °F (12.7 °C to 20 °C) with cloudy conditions and occasional, light precipitation; the conditions at the time of these treatments were 54 °F to 57 °F (12.2 °C to 13.9 °C) and overcast with no precipitation.

On 2024 April 25 (451 GDD; after 2% egg hatch but before peak 1st instar which occurs at 596 GDD), 3 additional insecticide treatments were completed. A treatment of 97.4% acephate (Lepitect™; Rainbow Ecoscience) was applied via soil injection at low (5.7 g/in [2.24 g/cm] DBH)(6 trees) and high (11.3 g/in [4.45 g/cm] DBH)(5 trees) rates. For the low rate,

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acephate was mixed with water at a rate of 10 oz (283.5 g) product in 12.5 gallons (47.32 L) water and 1 qt/in (0.37 L/cm) DBH injected 6 in (15.24 cm) below the soil line around the root flare using a PSI-2 Precision Soil Injector (Altec Industries Inc., Birmingham, AL, USA). For the high rate, acephate was mixed at the same rate as for the low soil acephate treatment, but 2 qt/in (0.75 L/cm) DBH were applied instead of 1. Another 12 trees, 6 of which had received fertilizer (see below), were treated with a bark application of 8.5% acetamiprid (Tristar® 8.5 SL; Nufarm, Alsip, IL, USA). One gallon (3.79 L) of application solution was generated by mixing 105 fl oz (3.11 L) water, 20 fl oz (591.47 mL) acetamiprid, and 3 fl oz (88.72 mL) Pentrabark® (Quest Products Corp., Linwood, KS, USA). The mixed solution was applied at an approximate rate of 3 fl oz/in (34.9 mL/cm) DBH. Applications were made with a FlowZone® Typhoon 3 Electric Backpack Sprayer (Wessol LLC, Charlotte, NC, USA) from the soil line to approximately 6 ft (1.83 m) above the soil line. Finally, 12 random trees within the stand were also selected as untreated controls, 6 of which were treated with fertilizer (see below). The weather conditions the day before these treatments were temperatures of 36 °F to 46 °F (2.2 °C to 7.8 °C) with cloudy conditions and no precipitation, and the weather conditions at the time of these treatments were 48 °F to 57 °F (8.9 °C to 13.9 °C) with overcast conditions and no precipitation.

We deployed treatments so that there were 4 insecticide treatments with 6 replicates each (except for the soil-injected acephate at the high-rate treatment which had 5 replicates). Three of these treatments had twelve replicates in total, as the additional six trees received fertilizer (trial summary is presented in Table 1). Prior to budbreak and 2% egg hatch, on 2024 March 29 (229 GDD), a total of 18 trees (6 control trees; 6 trees treated in the fall with emamectin benzoate; and 6 trees slated for treatment with acetamiprid) received an application of Bartlett Boost® NK (20-0-6; N:P:K)(The F.A. Bartlett Tree Expert Company, Stamford, CT, USA) liquid fertilizer containing 45% N as slow-release urea and a proprietary mix of other nutrients including sulfur, copper, iron, manganese, and zinc. We mixed 5 gallons (18.93 L) of Bartlett Boost® NK with 100 gallons (378.54 L) water, and 25 gallons were applied to each tree in sequential rings within 10 ft (3.05 m) of the trunk approximately 6 in (15.24 cm) under the surface using the same type of soil probe as described above. This ultimately resulted in the supplementation of each treated tree with 2.5 lbs (1.13 kg) of N, 1.125 lbs (0.51 kg) of which was applied as slow-release N. The amount of fertilizer applied was not scaled to the size of the specific tree or intended to be prescriptive (i.e., correct deficiencies); rather, our aim was to reflect a reactionary response of a tree manager to defoliation from the previous year (i.e., to "replace N lost to defoliation"). Therefore, this fertilizer treatment is better described as "N supplementation" (henceforth referred to as "N supplementation"). The weather conditions the day before these applications were 29 °F to 50 °F (–1.7 °C to 10.0 °C) and partly cloudy with no precipitation, and the weather conditions at the time of these applications were 45 °F to 50 °F (7.2 °C to 10.0 °C) with mostly cloudy conditions and no precipitation.

Insecticide Efficacy Evaluation

Crown defoliation was visually estimated on 2024 June 14 (1,596 GDD) after peak 4th instar, which occurred on 2024 June 3 at 1,284 GDD. Three researchers (all of which are ISA Certified Arborists®) visually estimated the percent crown remaining for each tree with binoculars, blind to treatment and independent from each other, from the ground to the nearest 10% for each of the four cardinal directions. Each cardinal direction of a tree was inspected for a minimum of 5 seconds, and these 4 ratings were then averaged for a total rating of the tree crown. The 3 ratings estimated by the 3 researchers were averaged for the final % crown remaining estimate. A 100% crown remaining rating represented a full crown without gaps or bare twigs, with even distribution throughout, where a 0% crown remaining rating would signify a crown completely lacking foliage.

Foliar Nitrogen

Tissue harvesting for foliar N occurred on the same day as pesticide efficacy evaluations using a bucket truck on the most sun-exposed side of the crown roughly midway up the crown. The cardinal direction of the harvest branch was recorded. Foliage was placed into brown paper bags (roughly filling the bag) and immediately shipped to Waypoint Analytical (Memphis, TN, USA) for analysis.

Statistics

All statistical analyses were performed in R (R Core Team 2023) and RStudio v4.5.0 (Posit Team 2023).

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Table 1. Layout of pesticide efficacy and N supplementation trial as described in Materials and Methods, including the trade name and active ingredient of insecticides used. All combinations contained 6 biological replicates (i.e., trees), except for soil-injected acephate at the high rate (which had 5 replicates), and the number of northern red (*Quercus rubra*) and white (*Q. alba*) oaks within each treatment are indicated. "Application date" refers to the date of the insecticide treatments, specifically. All GDD values are reported as GMPHEN GDD units, and DBH is approximately 1.3 m above the soil surface. Nitrogen supplementation with Boost® NK (20-0-6) occurred on 2024 March 29 (229 GDD). Mectinite® was used for emamectin benzoate treatments; Lepitect Infusible™ for acephate root flare injections; Lepitect™ for acephate soil injections; and Tristar® 8.5 SL for acetamiprid bark sprays. N (nitrogen); GDD (growing degree day); DBH (diameter at breast height).

Active ingredient (trade name)	*Q. rubra*: *Q. alba*	N supplementation	Application date (GDD)	Application method	Rates (mixed product; application)
N/A	1:5	1.13-kg N tree^{-1}	N/A	N/A	N/A
N/A	2:4	None	N/A	N/A	N/A
Emamectin benzoate (Mectinite®)	2:4	1.13-kg N tree^{-1}	2023 Oct 20 (4,867)	Root flare injection	neat; 5- or 10-mL/inch DBH (1.97- or 3.94-mL/cm DBH)
Emamectin benzoate (Mectinite®)	3:3	None	2023 Oct 20 (4,867)	Root flare injection	neat; 5- or 10-mL/inch DBH (1.97- or 3.94-mL/cm DBH)
Emamectin benzoate (Mectinite®)	1:5	None	2024 Apr 18 (418)	Root flare injection	neat; 5- or 10-mL/inch DBH (1.97- or 3.94-mL/cm DBH)
Acephate (Lepitect Infusible™)	1:5	None	2024 Apr 18 (418)	Root flare injection	300 mg/mL; 5 mL/inch DBH (1.97 mL/cm DBH)
Acephate (Lepitect™)	3:3	None	2024 Apr 25 (451)	Soil injection	6 g/L; 0.95 L/inch DBH (0.37 L/cm DBH)
Acephate (Lepitect™)	3:2	None	2024 Apr 25 (451)	Soil injection	6 g/L; 0.95 L/inch DBH (0.37 L/cm DBH)
Acetamiprid (Tristar® 8.5 SL)	1:5	1.13-kg N tree^{-1}	2024 Apr 25 (451)	Bark spray	156.1 mL/L; 88.72 mL/inch DBH (34.9 mL/cm DBH)
Acetamiprid (Tristar® 8.5 SL)	1:5	None	2024 Apr 25 (451)	Bark spray	156.1 mL/L; 88.72 mL/inch DBH (34.9 mL/cm DBH)

To determine the impact of N supplementation and treatment application on foliar N levels, percent foliar N was modeled as a function of insecticide treated (yes/no; fixed effect); N supplementation (yes/no; fixed effect); percent canopy remaining (fixed effect); and tree species (random intercept) using a mixed-effect linear regression with the *lme4* package (Bates et al. 2015). Only treatments that included at least one N-supplemented tree were used in this analysis. An ANOVA was performed using the *car* package (Fox and Weisberg 2019) to test for treatment effects.

Mixed-effects ordered beta regressions (*ordbetareg* package in R)(Kubinec 2025) were used to determine the potential for N supplementation to influence the efficacy of insecticides in the subset of treatments that were supplemented with N or not and to evaluate insecticide efficacy with the larger dataset. These analyses were performed because our response variable (percentage canopy remaining) is continuous and proportional and include values of "0" and/or "1" (Kubinec 2025). For mixed-effects ordered beta regressions, *P*-values are not calculated as part of the model, and there is no way to extract or derive a calculated *P*-value for individual factors (i.e., insecticide treatments, N supplementation, tree species). However, significance at the $\alpha = 0.05$ level can be inferred by assessing the calculated confidence intervals: a factor with a confidence interval that includes "0" is considered not significant, while a factor with a confidence interval that does not include "0" can be considered significant (Kubinec 2025). Therefore, significance for these factors is reported as "$P > 0.05$" (i.e., considered not significant) or "$P < 0.05$" (i.e., considered to be significant).

To determine the potential for N supplementation to influence the efficacy of insecticide treatments, the

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model was fit using only the control, fall emamectin benzoate root flare injection, and spring acetamiprid bark spray trees. Ratings were modeled as a function of treatment (fixed effect); N supplementation (yes/no; fixed effect); and tree species (random intercept). To determine the efficacy of insecticides to limit canopy defoliation for all insecticide treatments, the same mixed-effects ordered beta regression model was fit using all replicates from all treatments. The percent canopy remaining ratings were modeled as a function of treatment (fixed effect); N supplementation (yes/no; fixed effect); and tree species (random intercept). Despite N supplementation having no impact on insecticide efficacy (see Results), we elected to retain this variable in this model because Akaike Information Criterion analysis (AIC) of models with and without this variable did reveal some information lost if it was removed. Lastly, to determine differences between these treatments, post hoc pairwise comparisons (Tukey HSD) were performed using the *emmeans* package (Lenth and Piaskowski 2026).

RESULTS

Impact of N Supplementation and Insecticide Treatment on Foliar N Levels and Insecticide Efficacy

For treatments that both received and didn't receive N supplementation (i.e., untreated controls, fall emamectin benzoate root flare injections, and spring acetamiprid bark sprays), the mixed-effect linear regression model indicated N supplementation ($X^2 = 1.07$, df = 1, $P = 0.30$), insecticide treatment ($X^2 = 2.62$, df = 1, $P = 0.11$), percent canopy remaining ($X^2 = 2.43$, df = 1, $P = 0.12$), or species ($X^2 = 0.00$, df = 1, $P = 1.00$) had no impact on percent N levels in leaves. The mean (± one standard error) percent foliar N of these trees was 1.79% ± 0.6%.

The ordered beta regression model used to determine if N supplementation influenced insecticide efficacy (including only untreated control, fall emamectin benzoate root flare injection, and spring acetamiprid bark spray trees) indicated that tree species ($b = 1.74$; 95% CI = 0.44 to 4.56; $P < 0.05$) had a significant effect of percent canopy remaining ratings, and the fall emamectin benzoate root flare injections had significantly higher ratings than controls ($b = 2.33$; 95% CI = 1.61 to 3.03; $P < 0.05$), while spring acetamiprid bark sprays did not ($b = -0.22$; 95% CI = −0.91-0.48; $P > 0.05$). Ultimately however, N supplementation had no impact on percent crown remaining rating ($b = –0.41$; 95% CI = –0.98 to 0.14; $P > 0.05$) for the two insecticide treatments when paired with N supplementation.

Efficacy of Insecticides

The full ordered beta regression model used to determine insecticide efficacy indicated that the percentage of crown remaining was significantly impacted by oak species ($b = 1.64$; 95% CI = –0.43 to 4.09; $P < 0.05$), with red oaks having a greater percentage of canopy remaining (81.10% ± 4.71%) compared to that of white oaks (46.70% ± 5.42%)(Figure 1). Regarding individual insecticides, all treatments, with the exception of acetamiprid ($P > 0.05$), had percent crown remaining ratings that were significantly higher than untreated controls ($P < 0.05$ for all)(Table 2). Post hoc mean separation indicated that the 5 insecticide treatments that had percent canopy remaining ratings that were significantly higher than controls (i.e., all but acetamiprid) were not statistically different from each other save for the acephate root flare injection compared to the acephate soil injection at the low rate (Table 2).

DISCUSSION

We found emamectin benzoate and acephate to be effective insecticides at limiting defoliation during a spongy moth outbreak. While not statistically different, the timing of emamectin benzoate application is likely still an important consideration. The average percentage of the canopy remaining on spring emamectin benzoate treated trees was lower and more variable than the trees treated in the fall. Any reduction in average defoliation following a fall root flare injection, rather than one in the spring, would be positive for infested hosts and may be more pronounced on certain hosts or under great pest density. Though we cannot definitively conclude so, we suspect this was likely due to the time required for translocation throughout the tree crown, as this process can take weeks for emamectin benzoate (Liang et al. 2024). The presence of insecticide within leaf tissue at larvicidal levels at bud break is even more critical for spongy moth, as caterpillar emergence occurs right before or during spring oak bud break (Sheehan 1992). These systemic insecticides must not only be ingested, but the amount of ingested material required

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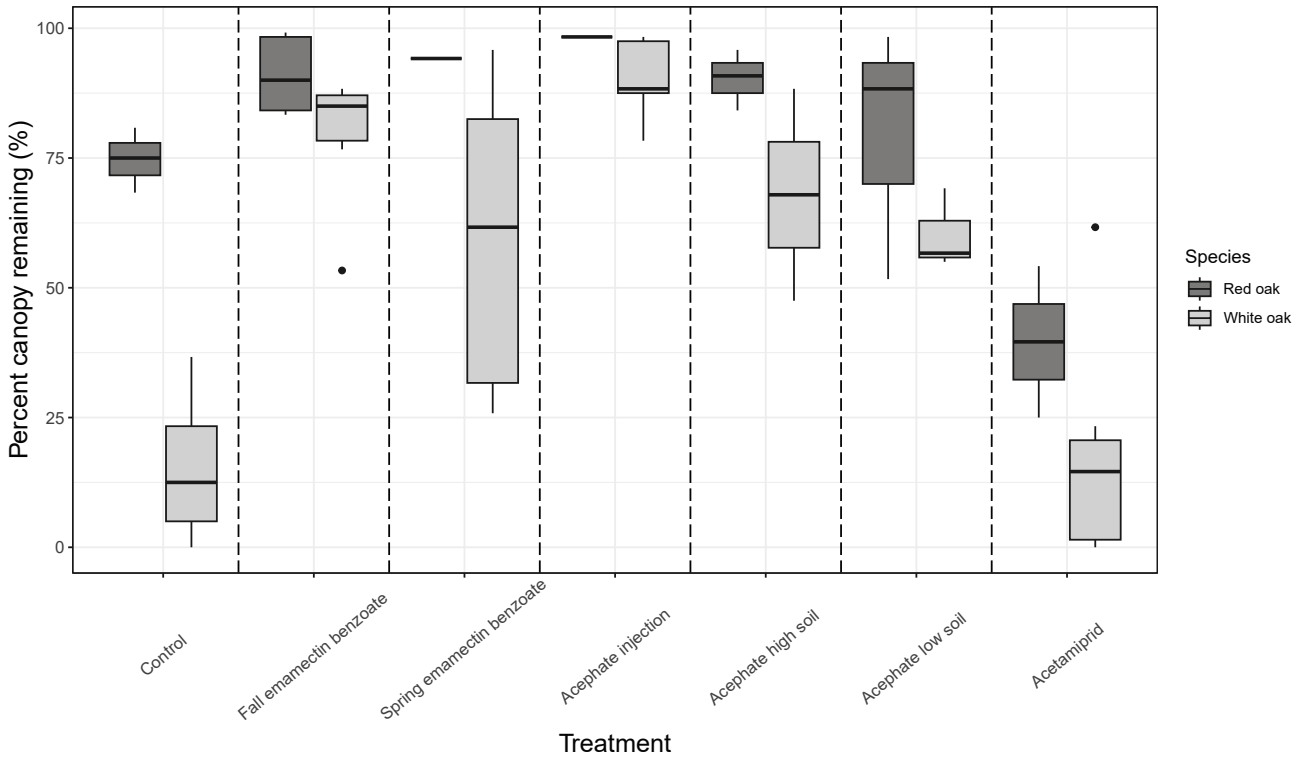

Figure 1. Boxplot of percent canopy remaining by insecticide treatment, split between red oaks (dark gray) and white oaks (light gray), illustrating the differences between species in percent canopy remaining ratings. Boxes denote the interquartile range containing the middle 50% of values, and the solid horizontal line within boxes denotes the median value. Lower and upper whiskers denote the minimum and maximum values, respectively, and dots represent values beyond 1.5× the interquartile range from the lower and upper limits of the interquartile range. It should be noted that fertilized and unfertilized trees within the control, fall emamectin benzoate, and acetamiprid treatments are not differentiated in this plot due to the insignificant effect of fertilization on insecticide efficacy in those treatments. Also, only a median value is presented (as solid horizontal lines) for spring emamectin benzoate and acephate injection because there was only a single red oak tree as part of those treatments.

Table 2. Efficacy and results of mixed-effects ordered beta regression fit utilizing all treatments. Rating is the mean ± one standard error (Mean ± 1SE) percent crown remaining rating. The ordered beta regression coefficient is represented by *b*. *P*-values are the interpretation from the ordered beta regression 95% CI (i.e., *P* > 0.05 if zero is included in range, and *P* < 0.05 if zero is not included in range); values in bold are considered significant. Different letters with the *P*-value indicate statistical differences via post hoc mean separation. Lowest rating and highest rating represent the individual replicate within each treatment that had the lowest and highest percent crown defoliation rating, respectively. SE (standard error); CI (confidence interval).

Treatment	Rating (mean ± 1SE)	*b*	95% CI	*P*-value	Lowest rating	Highest rating
Control	29.7 ± 8.5	–0.28	–2.42 - 1.97	> 0.05[c]	0.00	80.83
Fall emamectin benzoate root flare injection	84.4 ± 3.4	**2.30**	**1.59 - 3.01**	**< 0.05[ab]**	53.33	99.17
Spring emamectin benzoate root flare injection	65.3 ± 12.6	**1.60**	**0.73 - 2.45**	**< 0.05[ab]**	25.83	95.83
Acephate root flare injection	91.4 ± 3.3	**2.89**	**1.92 - 3.83**	**< 0.05[a]**	78.33	98.33
Acephate soil injection – high rate	81.3 ± 8.7	**1.64**	**0.74 - 2.61**	**< 0.05[ab]**	47.50	95.83
Acephate soil injection – low rate	69.9 ± 7.9	**1.37**	**0.52 - 2.26**	**< 0.05[b]**	51.67	98.33
Acetamiprid bark spray	20.0 ± 5.8	–0.23	–0.97 - 0.49	> 0.05[c]	0.00	61.67

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to be fatal increases with larval size (Lyu and Lee 2019). Therefore, more foliage must be consumed later in the season after larvae have grown, leading to intensifying defoliation. The fact that fall-injected emamectin benzoate was already in the vascular tissues by the onset of spring likely reduced the time required for translocation, such that more of the product was in the foliage earlier, ultimately providing protection sooner after egg hatch. Indeed, Cosler et al. (2018) found substantially greater levels of emamectin benzoate in spring leaves of apple (*Malus* sp.) trees injected the previous fall than trees injected earlier that spring. It is not to say that spring emamectin benzoate injections were ineffective in our study, per se, as some trees remained almost completely undefoliated, but there was substantial variation within this treatment.

Unlike emamectin benzoate, acephate is highly soluble in water, is rapidly translocated throughout the crown, and has substantially shorter residual activity which all necessitates that application occur at the onset of pest activity (Doccola and Wild 2012). The root flare injected as well as the soil-applied acephate at both rates were all effective at reducing defoliation compared to untreated controls in accordance with our hypothesis. Though there was a slight difference in when the acephate applications were made (root flare injections on 2024 April 18 at 418 GDD and soil applications made on 2024 April 25 at 451 GDD), neonatal larvae were in the process of hatching this entire time, and temperatures remained somewhat cool (30 °F to 60 °F; –1 °C to 15.5 °C), limiting larval activity. Administering acephate to soils and relying on root uptake likely slows the process of translocation and results in the loss of some amount of product to run off and/or soil microbial metabolism due to its high soil mobility (Yen et al. 2000) and short soil half-life (approximately 12 hours)(Doccola and Wild 2012). Notably, there is a very real tradeoff for practitioners when it comes to root flare injections vs. soil applications. Root flare injections require specialized equipment and training (increasing time and monetary costs), and the injections themselves necessitate injury to the tree, but they virtually eliminate the risk of chemical trespass or environmental exposure, as the product is completely contained in the injection equipment or in the tree. Alternatively, soil applications may not require specialized equipment, entail less technical training (reducing time and monetary costs), and no wounding to the tree occurs. However, unconfined product introduced into the environment can be undesirable in many situations.

We hypothesized that acetamiprid may be able to provide some level of protection from spongy moth defoliation, but this was not the case, as the crown ratings of the acetamiprid-treated trees tended to be worse than those of control trees. This could be due to the relatively greater amounts of acetamiprid required for spongy moth larval mortality (Feng et al. 2018) and/or translocation dynamics. This is unfortunate for practitioners, as a bark spray option could allow for a more targeted approach in the landscape while mitigating concerns about root uptake, soil and water dynamics, and chemical trespass.

We additionally saw no effect of N supplementation on insecticide efficacy or foliar N levels, which was not necessarily in accordance with our hypothesis. It could still be that N fertilization could result in benefits to larvae if increases in foliar N were realized. Consensus within the industry suggests that in the absence of a deficiency, mature trees generally do not respond to N fertilization (Smiley et al. 2020), and there was no visual evidence of N deficiency in any of the experimental trees. It could be that fertilization effects on insecticide efficacy are more likely to be realized on younger, more actively growing trees that typically respond to N fertilization (Werner and Jull 2013). We are unable to speak to the limitations for the production of new foliage following defoliation events, as we did not quantify carbohydrates. However, from an insecticide efficacy perspective, there was no effect of N supplementation in this study. This issue does require further study and future work should aim to further elucidate N supplementation effects for mature trees in these defoliation scenarios.

Ultimately, we found that root flare injections of emamectin benzoate, applied either the previous fall or at bud break in the spring, and acephate, applied root flare injected or soil injected at bud break in the spring, are effective at reducing crown defoliation from spongy moth, and that depending on the situation and the expectations of the tree owner, any of these 5 treatments could be an option. Bark sprays of acetamiprid, unfortunately, do not provide protection against defoliation. These general findings could also be extrapolated to the management of other early-season defoliators such as eastern tent caterpillar (*Malacosoma*

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americanum)(Herms 2003) in North America and oak processionary moth (*Thaumetopoea processionea*) in Europe (Halbig et al. 2024), where insecticide presence at insecticidal levels in the foliage is critical early in the season. The impact of N supplementation in conjunction with insecticide application as a management tactic warrants further investigation, as carbohydrate reserves could be impacted by N additions, and there is still potential for this to impact insecticide efficacy, perhaps in younger trees that are more actively growing.

CONCLUSIONS

Root flare injections of emamectin benzoate either in the previous fall prior to senescence or in spring at egg hatch/bud burst; acephate injected into root flares at egg hatch/bud burst; or acephate applied to soil in spring at egg hatch/bud burst all provide protection to mature oaks from defoliation by spongy moth during outbreaks. However, bark sprays of acetamiprid do not appear to provide any level of protection that is differentiable from no treatment. Furthermore, of the insecticide treatments that were evaluated in combination with N supplementation, we found no evidence that N additions to soil will impact insecticide efficacy. This information will help practitioners make more informed decisions and recommendations for the protection of trees during spongy moth outbreaks.

LITERATURE CITED

Bates D, Mächler M, Bolker B, Walker S. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*. 67(1):1-48. https://doi.org/10.18637/jss.v067.i01

Beninger CW, Abou-Zaid MM. 1997. Flavonol glycosides from four pine species that inhibit early instar gypsy moth (Lepidoptera: Lymantriidae) development. *Biochemical Systematics and Ecology*. 25(6):505-512. https://doi.org/10.1016/S0305-1978(97)00034-3

Chase KD, Frank B, Diss-Torrance A, Rigsby CM. 2023. Pre-egg hatch efficacy of dormant applications against *Lymantria dispar* (Lepidoptera: Erebidae). *Journal of Economic Entomology*. 116(4):1243-1248. https://doi.org/10.1093/jee/toad123

Cosler CC, Vandervoort C, Wise JC. 2018. Insecticide dose and seasonal timing of trunk injection in apples influence efficacy and residues in nectar and plant parts. *Pest Management Science*. 75(5):1453-1463. https://doi.org/10.1002/ps.5268

Davidson CB, Gottschalk KW, Johnson JE. 1999. Tree mortality following defoliation by the European gypsy moth (*Lymantria dispar* L.) in the United States: A review. *Forest Science*. 45(1):74-84. https://doi.org/10.1093/forestscience/45.1.74

Davis MJ, Elkinton JS. 2018. Efficacy of two systemic insecticides with stem gall wasp, *Zapatella davisae* (Hymenoptera: Cynipidae) on black oak. *Journal of Economic Entomology*. 111(2):986-988. https://doi.org/10.1093/jee/tox358

Dill JF, Kirby CA, Armstrong CD. 2023. Spongy moth (*Lymantria dispar*): Pest management fact sheet #5024. Orono (ME, USA): The University of Maine Cooperative Extension. https://extension.umaine.edu/ipm/ipddl/publications/5024e

Doccola JJ, Wild PM. 2012. Tree injection as an alternative method of insecticide application. In: Soloneski S, Larramendy M, editors. *Insecticides—Basic and other applications*. London (United Kingdom): IntechOpen Limited. p. 61-78 https://doi.org/10.5772/29560

Feng Y, Chen J, Zhang A. 2018. Commercially available natural benzyl esters and their synthetic analogs exhibit different toxicities against insect pests. *Scientific Reports*. 8:7902. https://doi.org/10.1038/s41598-018-26242-6

Fleischer SJ, Delorme D, Ravlin FW, Stipes RJ. 1989. Implantation of acephate and injection of microbial insecticides into pin oaks for control of gypsy moth: Time and efficacy comparisons. *Journal of Arboriculture*. 15(7):153-158. https://doi.org/10.48044/jauf.1989.034

Fox J, Weisberg S. 2019. An R companion to applied regression. 3rd Ed. Thousand Oaks (CA, USA): Sage Publications. https://www.john-fox.ca/Companion

Giertych MJ, Bakowski M, Karolewski P, Zytkowiak R, Grzebyta J. 2005. Influence of mineral fertilization on food quality of oak leaves and utilization efficiency of food components by the gypsy moth. *Entomologia Experimentalis et Applicata*. 117(1):59-69. https://doi.org/10.1111/j.1570-7458.2005.00332.x

Goyer RA. 1973. Gypsy moth: Toxicity of five systemic insecticides to larvae reared on an artificial diet. *Journal of Economic Entomology*. 66(2):544-545. https://doi.org/10.1093/jee/66.2.544

Halbig P, Stelzer AS, Baier P, Pennerstorfer J, Delb H, Schopf A. 2024. PHENTHAUproc—An early warning and decision support system for hazard assessment and control of oak processionary moth (*Thaumetopoea processionea*). *Forest Ecology and Management*. 552:121525. https://doi.org/10.1016/j.foreco.2023.121525

Herms DA. 2002. Effects of fertilization on insect resistance of woody ornamental plants: Reassessing an entrenched paradigm. *Environmental Entomology*. 31(6):923-933. https://doi.org/10.1603/0046-225X-31.6.923

Herms DA. 2003. A biological calendar for predicting pest activity: Six years of plant and insect phenology in Secrest Arboretum. In: Chatfield JA, Boggs JF, Darper EA, Bennett PJ, editors. *Ornamental plants: Annual reports and research reviews 2002*. Special Circular 189. Wooster (OH, USA): The Ohio State University Extension. p. 40-49. https://docslib.org/doc/8452885/ornamental-plants-annual-reports-and-research-reviews-2002

Hilmers T, Leroy BML, Bae S, Hahn WA, Hochrein S, Jacobs M, Lemme H, Müller J, Schmied G, Weisser WW, Pretzsch H. 2023. Growth response of oaks to insect defoliation: Immediate and intermediate perspectives. *Forest Ecology and Management*. 549:121465. https://doi.org/10.1016/j.foreco.2023.121465

Kays JS, Canham CD. 1991. Effects of time and frequency of cutting on hardwood root reserve and sprout growth. *Forest*

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Science. 37(2):524-539. https://doi.org/10.1093/forestscience/37.2.524
Kubinec R. 2025. Ordbetareg: Ordered beta regression models with 'brms'. Version 0.8. https://CRAN.R-project.org/package=ordbetareg
Kytö M, Niemelä P, Larsson S. 1996. Insects on trees: Population and individual response to fertilization. *Oikos*. 75(2):148-159. https://doi.org/10.2307/3546238
Landhäusser SM, Lieffers VJ. 2002. Leaf area renewal, root retention and carbohydrate reserves in a clonal tree species following above-ground disturbance. *Journal of Ecology*. 90(4):658-665. https://doi.org/10.1046/j.1365-2745.2002.00699.x
Lenth RV, Piaskowski J. 2026. Emmeans: Estimated marginal means, aka least-squares means. Version 2.0.3. https://CRAN.R-project.org/package=emmeans
Liang Z, Zhou X, Li Y, Zhou M, Yang X, Zhang S, Wickham JD, Zhang QH, Zhang L. 2024. Distribution, residue dynamics, and insecticidal efficacy of trunk-injected emamectin benzoate in pecan trees. *Forests*. 15(3):535. https://doi.org/10.3390/f15030535
Liebhold A, Mastro V, Schaefer PW. 1989. Learning from the legacy of Leopold Trouvelot. *Bulletin of the Entomological Society of America*. 35(2):20-22. https://doi.org/10.1093/besa/35.2.20
Liebhold AM, MacDonald WL, Bergdahl D, Mastro VC. 1995. Invasion by exotic forest pests: A threat to forest ecosystems. *Forest Science*. 41(suppl_1):a0001-z0001. https://doi.org/10.1093/forestscience/41.s1.a0001
Liesch PJ, Williamson RC. 2022. Spongy moth. University of Wisconsin Garden Facts: XHT1063. Madison (WI, USA): UW-Madison Division of Extension. 2 p. https://hort.extension.wisc.edu/files/2022/04/Spongy_Moth_2022.pdf
Lyu D, Lee DW. 2019. Occurrence of gypsy moth, *Lymantria dispar* around pier in Korea and comparison of insecticide response depending on instar. *The Korean Journal of Pesticide Science*. 23(1):1-7. https://doi.org/10.7585/kjps.2019.23.1.1
McClure MS. 1992. Effects of implanted and injected pesticides and fertilizers on the survival of *Adelges tsugae* (Homoptera: Adelgidae) and on the growth of *Tsuga canadensis*. *Journal of Economic Entomology*. 85(2):468-472. https://doi.org/10.1093/jee/85.2.468
Mcmanus M, Csóka G. 2007. History and impact of gypsy moth in North America and comparison to the recent outbreaks in Europe. *Acta Silvatica Et Lignaria Hungarica.* 3(1):47-64. https://doi.org/10.37045/aslh-2007-0004
Moldenke AF, Berry RE, Miller JC, Wernz JG. 1997. Toxicity of acephate to larvae of gypsy moth as a function of host plant and bioassay method. *Entomologia Experimentalis et Applicata*. 84(2):157-163. https://doi.org/10.1046/j.1570-7458.1997.00210.x
Nielsen DG, Dunlap MJ. 1991. Birch, efficacy of selected insecticides against gypsy moth larvae, Wooster, Oh, 1989. *Insecticide and Acaricide Tests*. 16(1):267. https://doi.org/10.1093/iat/16.1.267
Nielsen DG, Dunlap MJ, Purrington FF. 1988. Evaluation of BT-pyrenone against gypsy moth larvae on red oak, Wooster, Ohio, 1986. *Insecticide and Acaricide Tests.* 13(1):379. https://doi.org/10.1093/iat/13.1.379
Posit Team. 2023. RStudio: Integrated Development Environment for R. Boston (MA, USA): Posit. https://posit.co/downloads
Purvis E. 2024. The effects of fertilization on defoliation recovery in river birch (*Betula nigra*) and northern red oak (*Quercus rubra*) [thesis]. Conway (AR, USA): University of Central Arkansas.
R Core Team. 2023. R: A language and environment for statistical computing. Vienna (Austria): R Foundation for Statistical Computing. https://www.R-project.org
Sheehan KA. 1992. User's guide for GMPHENL: A gypsy moth phenology model. Radnor (PA, USA): USDA Forest Service, Northeastern Forest Experiment Station. General Technical Report NE-158. 29 p. https://doi.org/10.2737/NE-GTR-158
Smiley ET, Lilly S, Werner L, Brantley B. 2020. Best management practices—Tree and shrub fertilization. 4th Ed. Atlanta (GA, USA): International Society of Arboriculture. 57 p.
Smitley DR, Davis TW. 1996. Control of gypsy moth on a Colorado blue spruce nursery, Ottawa Co., MI 1995. *Arthropod Management Tests*. 21(1):377-378. https://doi.org/10.1093/amt/21.1.377a
Smitley DR, Davis TW. 1997. Control of gypsy moth larvae on container grown crabapple, 1996. *Arthropod Management Tests*. 22(1):393. https://doi.org/10.1093/amt/22.1.393
Tatter TA, Dotson JA, Ruizzo MS, Steward VB. 1998. Translocation of imidacloprid in three tree species when trunk and soil-injected. *Journal of Arboriculture*. 24(1):54-56. https://doi.org/10.48044/jauf.1998.008
Webb RE, Reardon RC, Wieber AM, VK Boyd, Larew HG, Argauer RJ. 1988. Suppression of gypsy moth (Lepidoptera: Lymantriidae) populations on oak using implants or injections of acephate and methamidophos. *Journal of Economic Entomology*. 81(2):573-577. https://doi.org/10.1093/jee/81.2.573
Werner LP, Jull LG. 2013. Fertilizer nitrogen uptake and partitioning in young and mature common hackberry (*Celtis occidentalis*) trees. *Arboriculture & Urban Forestry*. 39(2):85-93. https://doi.org/10.48044/jauf.2013.012
Yen JH, Lin KH, Wang YS. 2000. Potential of the insecticides acephate and methamidophos to contaminate groundwater. *Ecotoxicology and Environmental Safety*. 45(1):79-86. https://doi.org/10.1006/eesa.1999.1846

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