

The Potential of Chemical and Biological Management Options for Controlling Jumping Worms (*Amyntas* spp.) in Container Nursery Production

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ABSTRACT. Jumping worm species belonging to the genus *Amyntas* (Kinberg) threaten biodiversity and soil health significantly across temperate ecosystems. One inadvertent method of invasive jumping worm spread is through container-grown nursery stock. In nursery production, jumping worms modify substrate characteristics such as water holding capacity and nutrient availability by consuming and redepositing organic matter, resulting in negative effects to plant quality and appearance. There are currently no products listed for controlling jumping worms in the United States, leading to challenges in managing their spread. With increasing regulation on the transport of jumping worms by state agencies, plant producers may face unrealistic or labor-intensive management options. We hypothesized that control methods not yet listed for jumping worms in the United States have the potential to suppress jumping worm populations effectively in container-grown crops. Therefore, we studied chemical and biological controls touted as potential options for controlling jumping worms in nursery containers by measuring their effects on jumping worm mortality. In addition to an untreated control, we evaluated BotaniGard® 22WP, T-Bird® 4.5L (thiophanate-methyl fungicide), Root Cleaner® (sodium lauryl sulfate and soybean oil), Cedarcide® (cedarwood oil), Conserve® SC (spinosad), Castaway® 3-0-1 Tea Seed Meal Fertilizer, Slug Magic™ (iron phosphate), and Sevin® (zeta-cypermethrin). The results of our work suggest differential efficacy among treatments and highlight viable options with the potential for application in horticultural production. Specifically, T-Bird® 4.5L (thiophanate-methyl fungicide) and Sevin® (zeta-cypermethrin) demonstrated at least 80% mortality in two trials, whereas all remaining products yielded no effect or less than 12% mortality. Identifying effective control methods benefits the scientific community and the horticultural industry by providing a foundation for future research activities centered on jumping worm management and by supporting the goal of limiting their spread through horticultural products.

Jumping worms, annelids of the *Amyntas* genus, are among the leading causes of plant and animal biodiversity loss across temperate ecosystems in the United States (Ziter et al. 2021). Originating in east-central Asia, they have been translocated unintentionally to and around the United States through horticultural materials, including containerized plants and substrates such as compost, potting media, mulch, field soil, and turf (Bellitürk 2015; Redmond et al. 2016).

Jumping worms have earned their name because they thrash around in serpentine-like locomotion. Among earthworms, they are uniquely capable of such movement because they have setae that encircle their entire body, allowing

them to grip and twist in all directions. As ecosystem engineers, jumping worms alter the soil structure of temperate forest ecosystems, leading to erosion and changes in nitrogen and phosphorus, as well as sudden increases and subsequent losses in organic nutrients (Laushman et al. 2018). As the soil structure changes with the invasion of jumping worms, temperate ecosystems experience poor seed germination and plant growth, as well as loss of plant and animal biodiversity, including salamanders, birds, and frogs (Bethke and Midgley 2020; Loss and Blair 2011; Loss et al. 2012; Ziemba et al. 2015, 2016). Jumping worms consume organic matter such as roots, modify substrate structure and

chemistry, and contribute to excessive nutrient leaching (Frellich et al. 2019; Görres et al. 2019; Schult et al. 2016). The extent of jumping worm damage to plants and potting media in containers has not been widely documented. However, based on firsthand observations at the University of Minnesota Horticultural Research Center, jumping worms appear to consume organic matter and redeposit it as castings, altering the texture of the potting substrate significantly (Fig. 1). These modifications have a direct effect on the health of the plant grown in the containers, likely as a result of changes in the water holding capacity and leaching of nutrients. These observations align with the documented effects jumping worms have on soils in natural settings.

It can be challenging to detect these pests because of their ability to survive harsh climatic conditions during their cocoon stage (Schult et al. 2016). The cocoons are hard to detect because of their small size (diameter, 2–4.5 mm) (Nouri-Aiin and Görres 2019). Jumping worms reproduce primarily through parthenogenesis—meaning, new populations have the potential to arise from one undetected individual (Chang et al. 2021). It has long been believed that jumping worms fully reproduce parthenogenetically; however, their genetic diversity seems to suggest there may have been sexual reproduction in the not-so-distant past (Nouri-Aiin et al. 2022). Jumping worms can exist in different morphs, ranging from hermaphroditic to fully parthenogenetic (Gates 1956).

Enforced management by state authorities seemingly cannot move forward without labeled chemical products at the ready that can serve as effective control tools for these invasive pests in the horticulture industry. As a result of limited research and few resources, it is unclear which activities and management options are available for growers to respond to an infestation of jumping worms. Meanwhile, the presence of jumping worms in an operation may affect their reputation negatively in the industry and with consumers. Until effective management options are available, jumping worms will continue to spread into adjacent forests and degrade temperate ecosystems in the United States, often with the green industry blamed as a predominant vector.



Fig. 1. The effect of a jumping worm (*Amyntas* spp.) infestation on potting media in a nursery container located at the Horticulture Research Center of the University of Minnesota Landscape Arboretum. Depicted are castings and their effect on the overall substrate texture as a result of the jumping worms consuming the organic material within the container.

We hypothesize that control methods not yet listed for jumping worms in the United States have the potential to

suppress adult jumping worm populations effectively in container-grown plants. These methods were chosen based on previous observations of earthworm and other soft-bodied organism population declines in home gardens, golf courses, and airfields resulting from the use of saponin-rich tea seed cake pellets, a by-product of tea tree seed oil, *Camellia oleifera* (C. Abel) (Potter 2010; Seamans et al. 2015). Other vermicides have been used previously on soft-bodied organisms, but are no longer registered because of environmental concerns—specifically, ozone-depleting properties in chemicals such as methyl bromide (Methyl Bromide Technical Options Committee 2018; Redmond et al. 2016). The objective of our study was to evaluate various chemical and biological control methods that can potentially control jumping worms of the *Amyntas* genus in container-grown horticultural commodities.

Materials and methods

Experimental design, facilities, and crop culture

Two experiments were conducted to evaluate the effectiveness of products not yet labeled for use on jumping worms in the United States, with an

emphasis on their suitability for application in nursery production. Suitability of applications was based on product availability to nursery growers, potential in causing mortality of jumping worms, and ease of treatment adoption into nursery production systems.

EXPERIMENT 1. In Spring 2024, bare root whips (~18 inches tall) of sugar maple (*Acer saccharum* Marshall) were purchased from Cold Stream Farms (Free Soil, MI, USA) and planted singly into 1-gal (#1) containers that measured 7.5 inches in diameter and 7 inches tall, composed of black, high-density polyethylene (Nursery Supplies®, Chamsburg, PA, USA). The containers were filled with Gertens® Container Mix (40% pine fines, 30% compost, 20% peatmoss, and 10% topsoil; Inver Grove Heights, MN, USA). To prevent worms from escaping or foreign worms from entering, each container was surrounded with a 23.5- × 23.5-inch TOPTIE® polyester mesh zippered bag, which was zip-tied shut to ensure zipper stability.

Plants were assigned randomly to one of the following eight treatments: BotaniGard® 22WP [US Environmental Protection Agency (EPA) registration no. 82074-2; Certis USA LLC, Columbia, MD, USA], T-Bird® 4.5L (thiophanate-methyl fungicide; US EPA registration no. 70506-251; United Phosphorus, Inc., King of Prussia, PA, USA), Root Cleaner® (sodium lauryl sulfate and soybean oil; Central Coast Garden Products, Salinas, CA, USA), Cedarcide® (cedarwood oil; Chemical Abstracts Service no. 687-47-8; Cedarcide Industries, Inc., Spring, TX, USA), Conserve® SC (spinosad; US EPA registration no. 62719-291; Corteva Agriscience LLC, Indianapolis, IN, USA), Castaway® 3-0-1 Tea Seed Meal Fertilizer (The Andersons, Inc., Maumee, OH, USA), Slug Magic™ (iron phosphate; Bonide Products LLC, Oriskany, NY, USA), Sevin® (zeta-cypermethrin; TechPac, LLC, Atlanta, GA, USA), and an untreated control of water at rates of 1 oz/gal, 0.2 fl oz/gal, 1 fl oz/gal, 0.2 fl oz/gal, 0.06 fl oz/gal, 0.1 oz/1-gal container, 0.5 oz/1-gal container, and 2.8 fl oz/gal, respectively (Table 1). Treatment rates were calculated using the product label rate, when available. Not all products included in the evaluation had a label

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Table 1. Treatment information of biological and chemical products and compounds used to evaluate their effect on the mortality of adult jumping worms (*Amyntas* spp.) when applied to container-grown nursery crops cultivated using bark and peat-based substrates.¹

Treatment	Category	Rate	Dose
BotaniGard® 22WP, <i>Beauveria bassiana</i>	Biological	1.0 oz/gal, 7.0 g·L ⁻¹	400-mL soil drench
Castaway® Tea Seed Meal Fertilizer*	Fertilizer	1 oz/container, 2.7 g/container	Top-dress
Cedarcide®, cedarwood oil	Essential oil with surfactant	0.2 fl oz/gal, 1.5 mL·L ⁻¹	400-mL soil drench
Conserve® SC, spinosad	Insecticide	0.06 fl oz/gal, 0.5 mL·L ⁻¹	400-mL soil drench
Root Cleaner®, sodium lauryl sulfate and soybean oil	Insecticide	1.0 fl oz/gal, 8.9 mL·L ⁻¹	400-mL soil drench
Sevin®, zeta-cypermethrin	Insecticide	2.8 fl oz/gal, 20.7 mL·L ⁻¹	400-mL soil drench
Slug Magic™, pulverized iron phosphate and spinosad	Insecticide	0.5 oz/#1 container, 14.2 g/#1 container	Top-dress
T-Bird® 4.5L*, thiophanate-methyl	Fungicide	0.2 fl oz/gal, 1.5 mL·L ⁻¹	400-mL soil drench

¹Treatments followed by an asterisk (*) were used in Expts. 1 and 2, whereas all others were only evaluated in Expt. 1.

recommendation for use as a drench. As a result of discrepancies in application rates and uses on product labels, some treatment rates were estimated using container volume and approximate substrate surface area. Ten replicates (containers) represented each of the eight treatments (Table 1), with every container inoculated with six randomly selected, healthy adult jumping worms at the onset of the study (N = 90). Earthworm mortality (measured as a count) was used as the response variable.

Jumping worms were collected from the top 6 inches of the soil profile by hand in a nearby (~2 miles from the experiment site) sugar maple forest infested predominantly with jumping worms, located in Chaska, MN, USA, where castings were present. Collectors agitated the organic litter layer by hand, exposing the jumping worms and causing their thrashing behavior, making them easily identifiable in the field. The identity of jumping worms was confirmed using an illustrated identification field key from Chang et al. (2016), by evaluating the perichaetine arrangement of jumping worm setae. The morphological and behavioral traits of the earthworms collected aligned with species belonging to the genus *Amyntas*—specifically, affinity with *Amyntas tokioensis*, the only jumping worm species described previously as occurring onsite. Jumping worms were collected at least 2 d before experimentation and were kept in a 10-gal glass container filled with moistened peat, sphagnum, bark, sand, and maple leaves. The jumping worms collected and used were ≥ 3 inches in length, developed a white clitellum band, and

exhibited vigorous thrashing movements. At the time of treatment initiation, six random, individual worms were each inspected visually to confirm correct species identification before placing them in the substrate of the nursery containers and tightly zipping the mesh bags closed.

After preparing nursery containers and inoculating them with worm specimens, treatment compounds were applied at random, and containers were placed in the gravel nursery using a completely randomized design. Granular treatments measured in grams were applied as a dry top-dress, whereas liquids were applied as a drench. Each container was given a 1.69-cup drench of the treatment once at the start of the trial (Table 1). The control and granular treatments were given 1.69 cups of water for standardization. Treatments were left in trial for 4 weeks (28 d) from 11 Jul to 9 Aug 2024. During that time, temperature, precipitation, and relative humidity > 90% were logged daily by the Network for Environmental Weather Applications (NEWA). The mean temperature was 73 °F, with a range of 64 to 81 °F. The mean precipitation each day was 0.161 inch. Each day had a mean relative humidity > 90% for 6.6 h, with a range of 0 to 22 h. The University of Minnesota HRC station is located at the University of Minnesota Horticultural Research Center in Chaska, MN, USA.

The experiment was conducted in an outdoor gravel nursery at the University of Minnesota Horticultural Research Center in Chaska, MN, USA (lat. 44.86°N, long -93.63°W; elevation, 1029 ft above sea level). The

particle size of the landscape gravel under the containers was ~0.5 inch in diameter, and sprinkler-type overhead irrigation was used at least once daily as needed to ensure it never dried completely.

At the conclusion of the trial, living jumping worms in each container and mesh bag combination were counted by hand by unpotting each plant, breaking apart the root ball, and sifting through the substrate. The number of living jumping worms was subtracted from six to give the mortality rate of each container per treatment. Jumping worm mortality rates were calculated using Abbott's formula for determining natural causes of mortality from disturbances in handling and transport (Abbott 1987):

$$\text{Corrected mortality} = \frac{\% \text{ Test mortality} - \% \text{ Control mortality}}{100 - \% \text{ Control mortality}} \quad [1]$$

Eq. [1] was used to calculate the corrected mortality rate of treatments used to manage jumping worms in nursery containers. This accounts for the natural mortality rate of organisms from the control group (Abbott 1987).

EXPERIMENT 2. In Spring 2024, bare root whips (~18 inches tall) of white oak (*Quercus alba* L.) were purchased from Cold Stream Farms (Free Soil, MI, USA). Whips were planted singly into 1-gal (#1) containers measuring 7.5 inches in diameter and 7 inches tall, composed of black, high-density polyethylene. The containers were filled with Gertens® Container Mix: 40% pine fines, 30% compost, 20% peatmoss, and 10% topsoil. To prevent jumping worms from escaping, or

foreign earthworms from entering, each container was surrounded in a 23.5- $\times$ 23.5-inch) TOPTIE[®] polyester mesh zippered bag and was zip-tied shut to ensure zipper stability.

Plants ($n = 11$) were assigned randomly to one of the following five treatments: T-Bird[®] 4.5L (thiophanate-methyl fungicide; United Phosphorus, Inc.), Castaway[®] 3-0-1 Tea Seed Meal Fertilizer (The Andersons, Inc.), Slug Magic[™] (iron phosphate; Bonide Products, LLC), Sevin[®] (zeta-Cypermethrin; TechPac, LLC), and an untreated control of water at rates of 0.2 fl oz/gal, 0.1 oz/1-gal container, 0.5 oz/1-gal container, 2.8 fl oz/gal, and 1.69 cups of pure water, respectively (Table 1). Eleven replicates (containers) represented each of the five treatments (Table 1), with every container inoculated with six healthy jumping worms at the onset of the study. Collection and inoculation methodologies, nursery setting, supplemental irrigation schema, as well as data collection approach were identical to those used in Expt. 1. Jumping worm mortality (measured as a count) was used as the response variable.

For treatment implementation, each container was given a 1.69-cup drench of the treatment once at the start of the trial. Treatments were left in trial for 2 weeks (14 d) from 15 Aug to 29 Aug 2024. During that time, temperature, precipitation, and relative humidity $> 90\%$ were logged daily by the University of Minnesota HRC weather station within the NEWA system. The mean temperature was 73 °F, with a range of 66 to 82 °F. The mean precipitation each day was 0.3 inch. Each day had a mean relative humidity $> 90\%$ for 4.1 h, with a range of 0 to 13 h.

STATISTICAL ANALYSIS. Statistical analysis began by verifying the assumptions of normality and homogeneity of variances. Normality was assessed using the Shapiro-Wilk test, whereas Bartlett's test was used to evaluate the homogeneity of variances across groups. When the assumptions were met, a one-way analysis of variance (ANOVA) was conducted to determine whether there were statistically significant differences in mortality rates among the treatments, followed by Tukey's test to assess pairwise comparisons. If the assumptions of normality and homogeneity

were not met, the Kruskal-Wallis test was performed to determine statistically significant differences in mortality rates among the treatments, followed by Dunn's test with a Bonferroni adjustment for pairwise comparisons. A significance level of 95% ($\alpha = 0.05$) was applied. Jumping worm mortality rates were calculated using Abbott's formula (Eq. [1]) for natural causes of mortality (Abbott 1987). Analysis was performed using RStudio 2024.12.0+467.

Results

In Expt. 1, Bartlett's test and the Shapiro-Wilk test revealed that the ANOVA assumptions of homogeneity of variances and normality were not met ($P < 0.001$). The Kruskal-Wallis test revealed that differences occurred in mortality rates among the treatments ($P < 0.001$). This indicates that at least one treatment group differed in its distribution compared with the others. The Dunn's test for pairwise comparisons revealed that Sevin[®] (zeta-cypermethrin; TechPac, LLC) and T-Bird[®] 4.5L (thiophanate-methyl fungicide; United Phosphorus, Inc.) were different from each other and from all other treatments, resulting in corrected mortality rates of 80.9% and 87.6%, respectively (Fig. 2). Root Cleaner[®] (sodium lauryl sulfate and soybean oil; United Phosphorus, Inc.) resulted in a corrected mortality rate of 5.8%, but was not different from the remaining treatments. Treatments with a corrected mortality rate of 0%, including BotaniGard[®] 22WP (Certis USA LLC), Cedarcide[®] (cedarwood oil; Cedarcide Industries, Inc.), Conserve[®] SC (spinosad; Corteva Agriscience LLC), Castaway[®] 3-0-1 Tea Seed Meal Fertilizer, and Slug Magic[™] (iron phosphate) were also not different from each other.

BotaniGard[®] 22WP, T-Bird[®] 4.5L (thiophanate-methyl fungicide; Certis USA LLC), Root Cleaner[®] (sodium lauryl sulfate and soybean oil), Cedarcide[®] (cedarwood oil; Cedarcide Industries, Inc.), Conserve[®] SC (spinosad; Corteva Agriscience LLC), Castaway[®] 3-0-1 Tea Seed Meal Fertilizer, Slug Magic[™] (iron phosphate), Sevin[®] (zeta-cypermethrin; TechPac, LLC), and an untreated control of water resulted in unadjusted mortality rates of $11.6\% \pm 4.3\%$, $100\% \pm 0\%$,

$18.3\% \pm 7.6\%$, $10.0\% \pm 3.6\%$, $10.0\% \pm 5.6\%$, $3.3\% \pm 2.2\%$, $5.0\% \pm 3.5\%$, $93\% \pm 2.7\%$, and $12.5\% \pm 5.2\%$, respectively.

For Expt. 2, Bartlett's test and the Shapiro-Wilk test revealed that the ANOVA assumptions of homogeneity of variances and normality were met with $P = 0.0354$ and $P = 0.5031$, respectively. The ANOVA revealed significant differences among the treatments ($P < 0.001$). Tukey's test revealed that Sevin[®] (zeta-cypermethrin; TechPac, LLC) and T-Bird[®] 4.5L (thiophanate-methyl fungicide; United Phosphorus, Inc.) resulted in similar control efficacy, yielding corrected mortality rates of 81.1% and 82.6%, respectively, but the results for both were different from Castaway[®] 3-0-1 Tea Seed Meal Fertilizer, which only incurred a corrected mortality rate of 11.4% (Fig. 3).

Castaway[®] 3-0-1 Tea Seed Meal Fertilizer, Sevin[®] (zeta-cypermethrin), T-Bird[®] 4.5L (thiophanate-methyl fungicide; TechPac, LLC), and an untreated control resulted in unadjusted mortality rates of $19.7\% \pm 4.9\%$, $89.4\% \pm 6.4\%$, $91\% \pm 7.6\%$, and $10.6\% \pm 5.2\%$, respectively.

Discussion

Efficacy of pest management options varies significantly across nursery pests and settings (Parke and Grünwald 2012). The lack of jumping worm treatment options in the United States leads to challenges in managing their spread. This lack of jumping worm treatment options is caused by limited research and funding surrounding jumping worm control and has likely not received the attention it deserves because of the long-held idea that worms are beneficial for soil health (Simon et al. 2025). As jumping worms disperse across the United States through horticultural materials, their ecological impacts increase rapidly. Proactive management (decisions made before the pest becomes a problem) is more cost-effective and efficient than reactive tactics (management decisions made after the pest has become problematic) when dealing with invasive pests. Venette et al. (2021) emphasizes the importance of early intervention strategies such as prevention efforts and rapid response. Our work highlights the efficacy of potential control treatments for use in the nursery when labels are updated, suggesting an impressive

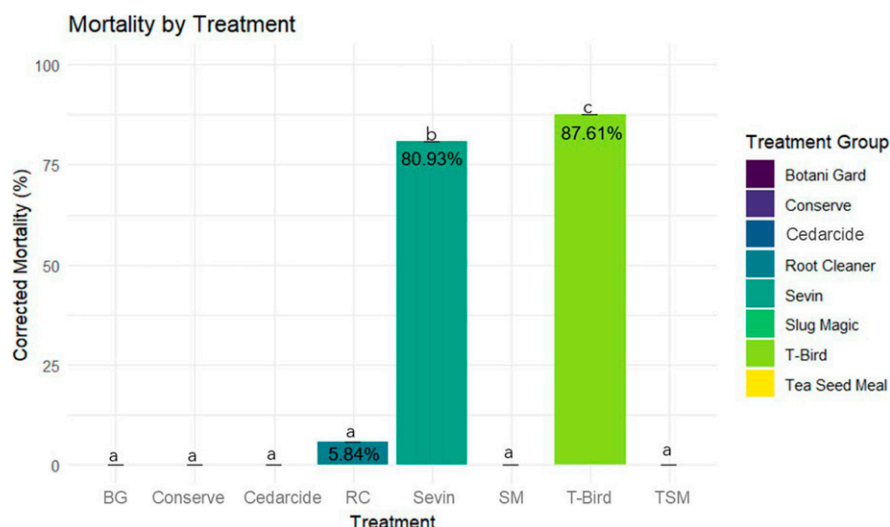


Fig. 2. Corrected mortality rates of jumping worms when treated with chemical and biological products thought to offer potential control of jumping worms in container-grown horticultural crops in Expt. 1. Jumping worm corrected mortality rates were calculated using Abbott's formula to account for natural causes of mortality from disturbances in handling and transport. Treatments sharing the same letter above the bar are not significantly different from each other according to Dunn's test ($P < 0.05$). Treatments presented without a mean percent-corrected mortality value represent no effect on the mortality of the jumping worms. BG = BotaniGard®; RC = root cleaner; TSM = tea seed meal.

potential for application in horticultural production.

The threshold at which management products are found to be effective varies by situation (Parke and Grünwald 2012). The goal for effectiveness should be a product that causes a high enough mortality of the pest to elicit population control, while not causing detrimental environmental effects. The results of

both experiments demonstrate that Sevin® (zeta-cypermethrin) and T-Bird® 4.5L (thiophanate-methyl fungicide) consistently exhibit high mortality rates, indicating their effectiveness as reliable control treatments for adult jumping worms. Although the experiments were evaluated on different timelines, both resulted in a mortality of at least 80.0%. Zeta-cypermethrin is a

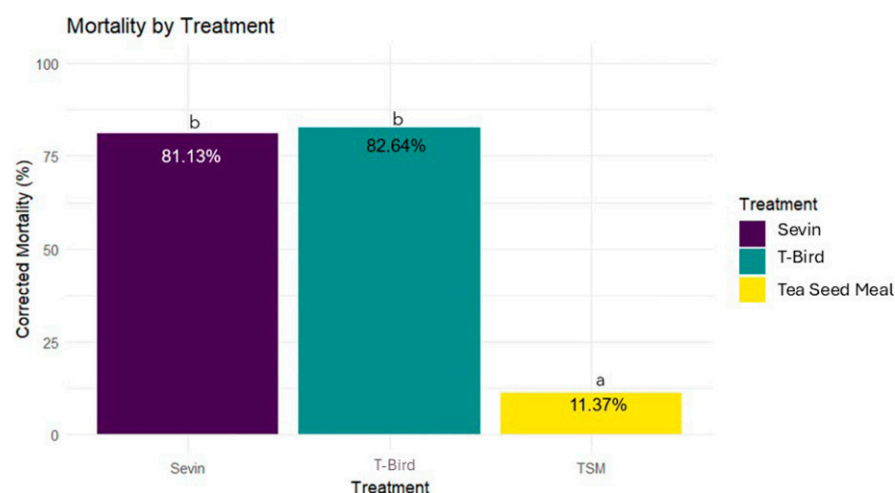


Fig. 3. Corrected mortality rates of jumping worms when treated with chemical products thought to offer potential control of jumping worms in container-grown horticultural crops in Expt. 2. Jumping worm corrected mortality rates were calculated using Abbott's formula to account for natural causes of mortality from disturbances in handling and transport. Treatments sharing the same letter above the bar are not significantly different from each other according to Tukey's honestly significant difference test ($P < 0.05$). TSM = tea seed meal.

synthetic pyrethroid used as a contact pesticide that controls the sodium channels of the central nervous system of target organisms, resulting in dehydration, paralysis, and death (Food and Agriculture Organization of the United Nations 2019). Thiophanate-methyl fungicide is a systemic fungicide used to manage plant disease in horticultural and agricultural crops (US Environmental Protection Agency 2004). We hypothesized that the compounds found in thiophanate-methyl agitate jumping worms enough to result in the degradation of the cuticle, resulting in death. The other treatments, such as BotaniGard® 22WP (Certis USA LLC), Cedarcide® (cedarwood oil; Cedarcide Industries, Inc.), Conserve® SC (spinosad; Corteva Agriscience LLC), Castaway® 3-0-1 Tea Seed Meal Fertilizer (The Andersons, Inc.), and Slug Magic™ (iron phosphate; Bonide Products LLC), were ineffective, which may be a result of treatment mechanisms, dosage, or specific pest characteristics. Not all treatments used in our study have application rates for containers, necessitating further research for optimal jumping worm control in this setting.

Our study is among the first investigations into the efficacy of various treatments against jumping worms, an emerging invasive pest in the United States. Nouri-Aiin and Görres (2021) found that *Beauveria bassiana* pellets reduced *Amyntas* hatchlings significantly but was far less effective on adults. With the still-larger adults used in our experiment, efficacy dropped to zero, confirming that *B. bassiana* impact declines steeply as worms mature. It is worth noting that Nouri-Aiin and Görres (2021) used an increased dose compared with our study, suggesting a rationale for the low mortality rates we observed. *Beauveria bassiana* has demonstrated the potential to be effective in causing jumping worm mortality at increased treatment rates Nouri-Aiin and Görres (2021). The lack of existing studies expanding to chemical options emphasizes the novelty and significance of these findings. Future studies should reevaluate the dosage, repeat applications, and modes of application of *B. bassiana* to determine which settings and concentrations may yield efficacy for different life stages of jumping worms.

The effectiveness of Sevin® (zeta-cypermethrin; TechPac, LLC) and T-Bird® 4.5L (thiophanate-methyl fungicide; United Phosphorus, Inc.) supports the need for further research and relabeling for commercial application for the control of jumping worms in the green industry in the United States. Identifying reliable control methods for jumping worms has the potential to reduce negative impacts and perceptions associated with the green industry.

The results of our study are limited to nondormant adult life stages of jumping worms, because it can be challenging to locate and identify dormant life stages of jumping worms as cocoons (McCay et al. 2020). Cocoons may require more extreme measures for management, given their increased survivability compared with adult worms. Many species of earthworms experience mortality at ~25 °C as juveniles and adults, with no mortality seen in cocoons because they have different sensitivities to high temperatures (Munnoli et al. 2010). Increased cocoon survivability may also be attributed to the composition of the cocoon, comprising polysaccharide compounds very similar to chitin (Avel 1959). Ikeda et al. (2015) found that soil temperatures of 32.2 °C reduce cocoon viability significantly in outdoor experimental beds, whereas vermiculture systems suggest some cocoons can withstand 35 °C (Munnoli et al. 2010). A study by Johnston and Herrick (2019) indicated that cocoon heat tolerance falls somewhere between 27.1 and 38.1 °C, depending on duration and intensity. In addition, our study did not evaluate nontarget effects of the chemicals studied to ensure a sustainable approach to jumping worm management. Further research is recommended to determine the concentration of products that kills 50% of the population and are found effective in causing jumping worm mortality.

Active ingredients that have undergone comprehensive Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) registration, including mammalian toxicology, nontarget organism tests, and environmental fate studies, are promising candidates for supplemental labeling under FIFRA 2(ee) section 18, emergency exemption, to support earthworm research and management. Under FIFRA 2(ee),

reduced-rate or off-label soil applications for any crop or site already on the primary label, provided no explicit exhibition exists on the label, may be used. Although not required by FIFRA, a pesticide registrant can issue a 2(ee) recommendation bulletin and petition the US Environmental Protection Agency to add the pesticide to its section 3 label. However, because individual states may adopt more restrictive rules than FIFRA, such as additional data or jurisdiction, state acceptance of emergency exemptions varies. To streamline multi-state approvals and eliminate duplicate studies, formulators should prioritize active ingredients under FIFRA 25(b) exemption or unregulated in target jurisdictions (US Environmental Protection Agency 2000, 2025).

Future research should aim to achieve mortality rates (of adults and cocoons) as close to 100% as possible, potentially through increased dosage or applications. Organic nurseries rely on inputs and practices compliant with organic certifications, such as Organic Materials Review Institute-listed products, cultural controls, and botanical products such as *B. bassiana*. Cultural control methods should be evaluated in combination with chemical or biological treatments to enhance their effectiveness. Dörler et al. (2019) found that treatments for slugs in containers with earthworms added to evaluate nontarget effects were more effective with a less frequent watering regime, causing increased earthworm and slug mortality. In addition, it is important to explore the nontarget effects and mechanisms behind the effectiveness of treatments our trial found to cause increased jumping worm mortality. Identifying other products with similar modes of action with minimal effect on nontarget organisms should be a forefront goal of future research to ensure safe and sustainable use for broader applications. Future research should also explore the effects of jumping worm management with a wider array of nursery crops, including different species of woody plants, herbaceous perennials, and plants at different stages of production, such as shortly after germination or propagation. Jumping worm cocoons should also be explored to determine their threshold of chemical tolerance. Further investigation is warranted to understand the application and conditions under

which Castaway® 3-0-1 Tea Seed Meal Fertilizer (The Andersons, Inc.) and Root Cleaner® (sodium lauryl sulfate and soybean oil; Central Coast Garden Products) are consistently effective.

Conclusion

T-Bird® 4.5L (thiophanate-methyl fungicide; United Phosphorus, Inc.) and Sevin® (zeta-cypermethrin; TechPac, LLC) were the most effective treatments for managing jumping worms, achieving corrected mortality rates of 87.6% and 81.1%, respectively. Other tested products, including BotaniGard® 22WP (Certis USA LLC), Root Cleaner® (sodium lauryl sulfate and soybean oil; Central Coast Garden Products), Cedarcide® (cedarwood oil; Cedarcide Industries, Inc.), Conserve® SC (spinosad; Corteva Agriscience LLC), Castaway® 3-0-1 Tea Seed Meal Fertilizer (The Andersons, Inc.), and Slug Magic™ (iron phosphate; Bonide Products LLC), were ineffective in the form and dosage applied to the adult stage, with corrected mortality rates of 12% or less. Based on the product labels, none of these compounds are currently approved for use against jumping worms of the *Amyntas* genus in the United States and should not be used for this purpose without appropriate labeling. However, because of their demonstrated efficacy, additional work should be conducted to support further the relabeling of these products and their potential use in controlling jumping worms in container-grown nursery stock. Control products, as well as the collection and transport of earthworms in our study, were used under a Minnesota Department of Natural Resources prohibited invasive species research permit (no. 873). All potential leachate from the bottom of the containers was caught in a basin and disposed of post-treatment. The Minnesota Department of Agriculture did not issue an experimental use permit because the work took place on less than 10 acres of land and was for research purposes, and was therefore deemed exempt.

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