Flatheaded and roundheaded borer management and phenology in nursery systems

A Thesis

Submitted to

The School of Graduate and Professional Studies

Department of Environmental Science

Tennessee State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

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May 2024

Keywords: Aegomorphus, artificial diet, Chrysobothris, herbicide

Committee Page

To the Graduate School:

We are submitting a thesis by Aubree Morrison entitled, *Flatheaded and Roundheaded Borer Management and Phenology in Nursery Systems.* We recommend that it be accepted in partial fulfillment of the requirements for the degree, Master of Science in Environmental Sciences with a concentration in Plant Science.

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Dedication

I would like to dedicate this thesis to my loving husband, Zach Morrison. I wouldn't be where I am today without you. You have provided endless love and support throughout my academics. You have stood by my side throughout all my adventures whether it was bats or beetles.

To my wonderful parents, Don, and Sandee Weitzel. You have always been my biggest cheerleader in life and without you I wouldn't be where I am today. You have always pushed me and challenged me in academics, and I can't thank you enough for always believing in me.

Finally, I would also like to dedicate this thesis to my beautiful daughter, Laramie. You can do ANYTHING you put your mind to even if it feels like the world is against you.

I love you all.

Acknowledgments

With this thesis I would like to acknowledge the hard work of the wonderful people that make up the Entomology and Chemical Ecology laboratories.

Nadeer Youssef

Shae King

Paul O'Neal

Garrett Roper

Josh Basham

Without you this would never have been possible. You guys are the best!

Abstract

Flatheaded borers (Coleoptera: Buprestidae) and longhorn beetles (Coleoptera: Cerambycidae) are common pests in nursery production systems. The thesis objective was to examine characteristics of a pest buprestid [flatheaded appletree borer, *Chrysobothris femorata* (Olivier)] and cerambycid [tupelo borer, *Aegomorphus morrisi* (Uhler)]. The experiments included borer phenology, and development of an artificial diet to facilitate beetle rearing. Stress factors like mechanical damage and herbicide-stressed-foliage were evaluated for effects on beetle tree attacks and trap captures. Both beetles were successfully reared from artificial diet with older instars; however, flatheaded borer larvae fed minimally compared to longhorn beetle larvae. In the field, adult flatheaded borers were fully developed at ~746 growing degree days (GDD) (base 10°C [50°F]) based on spring tree dissections. Among different mechanical stress treatments of large red maples, a wedge removed from the trunk had more attacks than girdled or felled trees. Based on the data, higher attacks may be due to the tree still being partially alive and declining more slowly when attacked versus completely dead. When looking at the attractiveness of herbicide-stressed vegetation, vegetation sprayed throughout the summer months did not affect the number of flatheaded borers caught on pole traps. This study also evaluated different lures commonly used to attract a variety of longhorn beetles for capture of tupelo borer; however, the tupelo borer was not trapped using fuscumol or fuscumol acetate. With the data collected, better management strategies and practices to reduce flatheaded borer and longhorn beetle attacks within a nursery system can be developed.

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Chapter 1: Introduction

In Tennessee, deciduous shade, and flowering tree production account for over 50% of the total annual nursery sales within the state. Many of these trees are susceptible to attacks by buprestid *Chrysobothris femorata* complex species and cerambycid species. Both beetle families are wood-boring beetles, and their larvae feed on the inner bark (phloem), cambium, and xylem of healthy and stressed host trees. The larvae can cause permanent damage to the vascular system of trees, which can result in tree death or create aesthetically unappealing damage to the trunk. Borer damage results in fewer sales, and an overall negative financial impact on nursery production.

Managing these borers can oftentimes be difficult. Current managers often use insecticides for reliable and rapid control. However, overreliance on chemical management by nursery grower communities using limited active ingredients and minimal rotations practices could lead to borer insecticide resistance development in the future, as well as possible non-target pollinator effects and long-term impacts to the environment.

New management techniques are currently being explored for borers; however, before research on management can be done more information on these beetle lifecycles, suitability for artificial rearing, and host preferences must be examined. The purpose of this study was to determine flatheaded borer phenology, evaluate host tree and trap preferences for flatheaded and roundheaded borers, and develop an artificial diet for both wood-boring pests.

Chapter 2: Review of Literature

Flatheaded Appletree Borer

Taxonomy and Identification

The flatheaded appletree borer (FAB), *Chrysobothris femorata* (Olivier) (Coleoptera: Buprestidae), is a species now recognized to be one member of a species complex (Wellso and Manley, 2007). Wood borers in this species complex are all small-bodied (i.e., usually 0.25 to 2.25 in [6 to 64 mm]; USDA, 2011), have short moniliform antennae, bullet-shaped elytra and some metallic areas on the wings, abdomen, legs, and head (Figure 1A). Many species in the complex are difficult to identify morphologically, which usually involves microscopic examination of minute differences in the reproductive structures. Some females of the species cannot be identified conclusively by morphology, whereas male genitalia are diagnostic for identification purposes on many species. The larval head is small, and the next thorax segments (pro-, meso-, and meta-thorax) are much broader than the following abdominal segments and usually have a hardened plate on the top and bottom, giving the appearance of a flattened head (i.e., basis for family common name of the larval stage) (USDA, 2011) (Figure 1B). Larvae cannot be identified to species level at this time without molecular procedures or rearing to the adult stage. Hansen (2010) indicated molecular procedures could have potential for determining species of larvae or in cases where species can be confused because of their similar outward appearance or when external morphological characters have yet to be described. Molecular procedures also have demonstrated potential for adult species identification (Hansen, 2010).

Life Cycle of Flatheaded Appletree Borer

For beetles in the *C. femorata* species complex, completion of the life cycle from egg to adult typically takes about 1 yr. Adults emerge from May to June in Tennessee and female beetles select locations to oviposit on the bark surface, often preferring bark cracks or damaged locations (Brooks, 1919; Burke, 1919; Fenton, 1942). Female beetles also prefer to lay eggs on the sunny-southwestern-side of the tree (Oliver et al., 2010) and often at the graft union on grafted trees (LeBude and Adkins, 2014). Eggs hatch in about 7 d, and the larvae begin tunneling through the bottom of the egg directly into the tree (Potter et al., 1988). The larvae feed under the bark until they create pupal chambers deeper in the wood for overwintering. Once the pupal chamber is completed and plugged with frass, the larvae remain inactive (based on laboratory observations [Morrison, pers. comm.]) until they begin pupation. After the pupation process is completed, the adult will exit the pupal chamber and leave a D-shaped exit hole on the bark surface.

Host Plant Selection and Nature of Flatheaded Appletree Borer Damage

North America alone is home to nearly 800 species of buprestids, which utilize a wide variety of hosts, including herbaceous perennial plants to hardwood trees (Nelson et al., 2008). Deciduous shade and flowering tree production in Tennessee accounted for 54% of total annual nursery sales and $78 million in gross sales during 2006 (USDA, 2007). Many of these economically important nursery trees are susceptible to attacks by *C. femorata* and other *Chrysobothris* species. While most *C. femorata* complex species are polyphagous, studies have been conducted to specifically quantify the percentage of red maple trees (*Acer rubrum* L.)

produced in nursery fields that are attacked by these borers. In Tennessee, infestations rates as high as 38% were recorded for one red maple cultivar within a non-treated control treatment of an insecticide trial (Oliver et al., 2010). Other studies also found high infestation rates among some cultivars of red maple tree crops (Seagraves et al., 2012). *Chrysobothris femorata* is reportedly able to attack healthy trees, but trees stressed by other environmental conditions like drought, flooding, disease, physical damage, etc. are still preferred (Fenton, 1942; Potter et al., 1988).

Flatheaded Appletree Borer Damage

The most severe damage to trees is caused by the larval stage, which feeds beneath the outer bark and makes irregular tunnels partially packed with sawdust-like frass (Potter et al., 1988). The larval tunneling in the inner bark (phloem) and beneath the phloem damages the cambium, which affects the ability of the tree to produce vascular tissues needed to circulate water and nutrients (Figure 2). The tunneling activity can kill the bark tissues resulting in sunken and discolored areas on the bark surface (Figure 2A). A single larva is capable of girdling and killing a young tree within one season. In nursery production systems, unprotected red maples may sustain almost 50% crop losses because of larval borer injury (Oliver et al., 2010; Potter et al., 1988).

Flatheaded Appletree Borer Management

Managers most often turn to insecticides for reliable and rapid control of flatheaded borers (Hansen et al., 2009; Potter et al., 1988). The application of a systemic neonicotinoid in the spring following transplant is the current standard for flatheaded borer insecticide management. The application of imidacloprid provides up to 3-yr of protection, while annual applications of more water soluble and shorter-residual neonicotinoids, such as dinotefuran, are also effective for about 1-yr (Oliver et al., 2010). Although recognized for having low mammalian acute toxicity, neonicotinoid products like imidacloprid have been under more regulatory scrutiny due to potential non-target pollinator effects and long residual activity in the environment. In addition, overreliance on chemical management by nursery grower communities using limited active ingredients and minimal rotations practices could lead to flatheaded insecticide resistance development in the future.

Several alternatives to modern insecticides have been studied, like cover crops to reduce trunk visibility and access by adult borers, and larval biological control agents like nematodes, predators, and parasitoids. One study found that cover crop use was as effective at preventing borer attacks as the standard imidacloprid soil drench (Addesso, 2020). Although cover crops may function as a natural camouflage to make the trees less favorable for female oviposition, cover crops also negatively affected the growth of the tree via competition for nutrients and water. Therefore, cover crops may or may not be ideal for nursery production systems and more research needs to be conducted on the best use of cover crops. Entomopathogenic nematodes have also been successfully used for management of beetle and moth borers (Martinez de Altube et al., 2008). The nematode *Steinernmema carpocapsae* (Fil.) reduced emergence of one economically important buprestid species by 70–90 % (Martinez de Altube et al., 2008). The primary issue with nematodes relates to application and formulation issues for the dry trunk environment. Nematodes cannot be applied on days with low humidity, as it results in death before they are able to reach the larval host inside the tree. Other *C. femorata* controls include birds like woodpeckers and predatory and parasitic insects. Woodpeckers take a large toll on *C. femorata* populations (Brooks, 1919; Loerch and Cameron, 1983); however, for nursery production, birds are not a viable management option due to the trunk damage they cause from extracting the borer larva from the tree. Trunk damage from woodpeckers also may trigger additional stress and open new entry ways for future borer attacks and plant pathogens. Another natural pest management for these beetles is the use of natural insect predators or parasitoids that feed upon buprestid larvae. For example, ants can follow the path of sub-surface galleries and extract the immature buprestids from beneath the bark (Brooks, 1919). There also are at least four different wasp families (i.e., Ichneumonidae, Chalicidae, Eupelmidae, and Braconidae) that will parasitize *C. femorata* larvae. Fenton (1942) estimated parasitization rates of 7-58% on *C. femorata* during a 3-yr drought period. Host plant vigor and reduction in tree stress would be additional management options to reduce tree attractiveness to flatheaded borers in general.

Tupelo Borer

Taxonomy and Identification

Tupelo borer, *Aegomorphus morrisi* (Uhler) (Coleoptera: Cerambycidae), is a member of the longhorn beetle family. Adult beetles are large ~2 to 2.5 cm (~0.8 to 1 in) long with robust and flat bodies. The adult beetles have long antennae, which are equal to or slightly longer than the body length (hence the common name for the family of longhorn beetles). Although beetle coloration may vary, tupelo borer will always have a distinctive ‘M’ – shaped black marking on their lower outer wing (elytra). They also may have alternating light and dark color patterns on the antennae and legs (Figure 3A). Larvae have short dark mandibles and large spiracles that run along the sides of their large cream-colored abdomen, which also is covered in coarse to velvety setae (Figure 3B). Unlike flatheaded borers, the thorax segments of roundheaded borers like tupelo borer are about the same width as the rest of the abdomen (hence the common larval name of roundheaded borers).

Lifecycle of Tupelo Borer

Adult tupelo borers emerge in mid-June (Craighead, 1923). Females deposit eggs on the lower trunks of small living host trees, typically saplings ~7.6 to 12.7 cm (~3 to 5 in) in trunk diameter. The larvae feed in the phloem and cambium but bore deeper into the sapwood and heartwood to create a pupation chamber. Galleries extend ~2.5 to 5 cm (~1 to 2 in) inward and ~7.6 to 12.7 cm (~3 to 5 in) upward, before turning back toward the bark surface. The new adults emerge through a round ~2 cm exit hole. The life cycle of this borer is estimated to be 2 yr or longer.

Tupelo Borer Range

Although tupelo borer is endemic to North America, the beetle has been reported only from a few widely scattered areas in the eastern United States, including Arkansas, Florida, Mississippi, Missouri, Pennsylvania, South Carolina (Solomon, 1995) and recently Tennessee (Morrison et al., 2022). It also has been documented in eastern Canada.

Host Plant Selection and Nature of Tupelo Borer Damage

Tupelo borer typically occurs in living saplings of the water tupelo (*Nyssa aquatica* L.) and black gum (*Nyssa sylvatica* Marshall) trees that are ~7.6 to 12.7 cm (~3 to 5 in) in trunk diameter (Lugger, 1884; Craighead, 1923). Although undocumented in the literature, tupelo borer is probably able to attack other *Nyssa* species (Morrison et al., 2022). Larval feeding causes small to large areas of loosened bark, that sometimes are filled with coarse excrement (i.e., frass) that can protrude from bark openings (Figure 4). If the bark is removed, a large irregular cavity ~ 5 to 10.2 cm (2 to 3 in) in diameter is visible, which generally is packed with fibrous frass. If an infested tree is split, the larval entrance and feeding cavities under the bark can be observed. Depending on the age of the wound, the gallery may vary in size with a circle-shaped exit hole present in the bark if the adult has emerged. Bark scars resulting from previously healed attacks will consist of large patchy scars with a small round scar directly above. Tupelo borer attacks have been documented on sapling trees at heights from slightly above ground level to about 1.8 m (6 ft). Populations are assumed to be small and widely scattered; thus, overall damage in nurseries and landscape plantings have been reported as minor in the past. However, two nurseries in middle Tennessee were documented during the summer of 2021 with extensive black gum tree losses (> 90%) (Morrison et al., 2022).

Tupelo Borer Management

Although the available literature indicates tupelo borer can be managed with sprays or injections of insecticides into galleries, no insecticide active ingredients were specified (Solomon, 1995). Insecticide injections would be impractical for nurseries due to trunk damage on small saplings, as well as the large numbers of trees requiring a time-consuming treatment process like injection. Successful management of tupelo borer likely is minimal or reduced once larvae have entered the tree, at least with surface trunk sprays of non-systemic insecticides. Some systemic insecticides (e.g., neonicotinoids like dinotefuran, imidacloprid, or thiamethoxam or anthranilic diamides like chlorantraniliprole or cyclaniliprole) may be useful if applied before larval infestations or damage begins. Full trunk sprays of non-systemic contact insecticides like bifenthrin (e.g., Talstar, OnyxPro), lambda-cyhalothrin (e.g., Scimitar), permethrin (e.g., Astro, Perm-Up 3.2EC), chlorpyrifos (e.g., Dursban), etc. also may provide control during the adult flight period if timed appropriately. Nursery trees already infested should be removed and burned or deep-buried to reduce new tree infestations. More research is needed to determine optimal products, rates, and timings and create management protocols for this borer species.

Chapter 3: Methodology

Flatheaded Borer Larval Winter Development

Red maple (*Acer rubrum* L.) tree nursery blocks were surveyed for evidence of flatheaded borer damage (i.e., broken, or cracking bark, visible frass, or sunken bark on trunks or branches). Trees with flatheaded borer damage were flagged and their location mapped using a handheld sub-meter global positioning unit (GPS) (Hemisphere GPS Crescent A100 Model and version 6.8/2.6K connected via Bluetooth to a Nomad Data Collector [Tripod Data Systems, Inc., Corvallis, OR] running SOLO Forest for Windows CE version 4.0.7 and receiving Wide Area Augmentation System [WAAS] corrected signal). Every 2 wk from December to April, four trees with flatheaded borer damage were randomly selected. Tree trunks and roots were removed from the field by digging the roots from the ground with a shovel. In the laboratory, the top of the tree was removed, and the trunks were split in half using handheld loppers. Flatheaded borer larvae that were found inside the tree trunks were carefully extracted from the tree tissues (Figure 5). Individual larvae were then placed on an artificial diet for subsequent rearing to the adult stage (see Section: ***Artificial Diet for Flatheaded Borers and Tupelo Borers***). Larvae that died before reaching the adult stage were preserved in molecular grade ethanol (Fisher Scientific, Pittsburgh, PA; CAS 64-17-5) for possible future molecular taxonomic assessments. At the nursery tree harvest location, external air temperature and relative humidity were recorded hourly using a Model 450 Watchdog Weather logger (Spectrum Technologies, Inc., Aurora, IL). At the end of each month, air temperature weather data were downloaded for growing degree day calculation and analysis comparison with the developmental state of larvae or other stages like pupae and adults at the time of field collection.

Adult Flatheaded Borer Field Emergence Timing – Spring 2021

Additional red maple trees with evidence of flatheaded borer damage in middle Tennessee nursery blocks were caged over the injured trunk areas to estimate adult emergence date in relation to growing degree days accumulated in the field. Aluminum cages were constructed out of 1.2mm (0.047in) window screen. Cages were 31cm length and 16cm wide. 8cm black foam pipe insulation was used to prevent the screen cages from causing physical damage. Cages were attached to trees using zip ties, fastened around the top and bottom of the cage across the pipe insulation. A total of 100 aluminum insect screen cages (Figure 6) were deployed from the beginning of April to the end of June 2021. Traps were checked every other day until the first adult beetle was caught, and then daily until no more beetles were captured. Date of capture was recorded, as well as tree location with a GPS unit. All adult beetles collected were identified to species if possible (Wellso and Manley, 2007). Daily maximum and minimum air temperatures were obtained from Watchdog Model 450 weather loggers.

Adult Flatheaded Borer Field Emergence Timing – Spring 2022

Due to difficulties in collecting adult borers during spring 2021 using the aluminum insect cages, a different method for rearing adult borers from trees was tested during spring 2022. To obtain borer infested trees for the spring 2022, trees with noticeable damage by flatheaded borer larvae and were harvested by chainsaw into 30-cm (12-in long) pieces in April 2022 (Figure 7A). Tree pieces were placed in a handmade fabric bag. The bags were assembled by taking a 3.1 by 3.1 m (10 ft by 10 ft) piece of white sheer fabric and folding in half. Two sides of the sheet were then hot-glued together, and the top was zip-tied shut once tree pieces were placed inside. Bags were left outside on a plastic rack under a carport to keep a constant outside temperature and reduce weather effects on the bags (Figure 7B). Each bag was checked daily for adult beetles. Daily maximum and minimum air temperature and temperature within the bags was obtained from Watchdog Model 450 weather loggers.

Calculating Degree Days

Daily heat units accumulated were calculated using the average of the daily maximum and minimum temperature subtracted from a base temperature of 10°C (50°F). Heat units for each date above zero were totaled to determine growing degree day accumulated s for each field tree harvest date.

Herbicide-Stressed Foliage – Effects on Flatheaded Borer Sticky Trap Captures

Corrugated purple plastic prism traps (1.5-m tall with 7.6 cm wide sides [59.1 to 3.0 in]) were deployed along a forested edge at a middle Tennessee nursery. Traps were covered in Pestick™ glue (Hummert International, Earth City, MO). Treatment plots were arranged in a randomized complete block design (RCBD) with four replicates and were spaced 10 m (32.8 ft) apart. Each 3 by 3 m (9.8 by 9.8 ft) treatment plot had three sticky traps spaced 1-m (3.3 ft) apart in an equilateral-triangle-like pattern in the plot center. An industry recommended late winter pre-emergent herbicide treatment consisting of indaziflam (Marengo® , Bayer Environmental Science, Research Triangle Park, NC [mixed at a rate of 1.1 ml product / liter or 0.14 fl oz product / gal using an estimated basis of 950 ml product / Ha or 13 fl oz product / acre]) and a spray pattern indicator (Signal™ Green, Precision Laboratories, Kenosha, WI [mixed at 5.2 ml product / liter or 0.67 fl oz product / gal) was applied on 15 Feb. 2022 (Fig 8C, 9) (Yeager et al. 2007). In addition, since pre-emergent herbicides do not control vegetation that has already germinated from seed, post-emergent glyphosate (Gly Star® 5 Extra, Albaugh LLC, Ankeny, Iowa [mixed at a 4% solution of 15.6 ml product / liter or 2.0 fl oz product / gal]) was added to the Marengo tank mix, which is a common nursery production practice (Yeager et al. 2007). Other post-emergent herbicide treatments were applied on 13 May 2022, 14 June 2022, and 20 July 2022 and consisted of either glyphosate (same rate and product as above) (Fig 8D) or Scythe® Herbicide (Gowan Co., LLC, Yuma, AZ; 7% solution mixed as 72.9 ml product / liter [9.33 fl oz product / gal]), which contains pelargonic acid (57%) and related fatty acids (3%) for control of perennial herbaceous and late-stage annuals) (Figure 8A). The additional May, June, and July treatments also had Signal Green spray indicator mixed as previously described. One trap plot was only mowed on the same treatment dates of 13 May 2022, 14 June 2022, and 20 July 2022 (Figure 8B). During months when treatments were not being applied, plots were left untouched. The traps (depicted in each plot in Figure 8) were checked once per week for 4 wk, and all buprestid beetles were removed, cleaned in Histo-Clear™ (National Diagnostics, Atlanta, GA) and 70% ethanol (diluted from 200 proof ethanol, Fisher product #BP2818-4), and pinned and labeled for subsequent identification.

Herbicide-Stressed Foliage - Effects on Flatheaded Borer Attacks on Potted Red Maples

Field plots (6 by 6 m [19.7 by 19.7 ft]) consisting mostly of grass and some broadleaf weeds (Figure 10) at the Otis L. Floyd Nursery Research Center and adjacent to a mixed deciduous hardwood forest were sprayed with glyphosate and Signal Green dye (see previous rates) during 2022 on 30 May, 29 June, and 27 July. Nine number 3 containers (~ 3-gal [11.4 liter]) with 'October Glory' red maple trees (Herd Farms Nursery, Belvidere, TN) were moved into the herbicide-sprayed or non-herbicide-sprayed treatment areas and left for 4-wk (with watering as needed) (Figure 11). Trees were returned to the container yard at the end of treatment 4-wk exposure period, and the next group were moved from the container yard to the June and/or July sites. A third group of maple trees were left in the container yard during the entire summer (i.e., non-field treatment exposed control group). The container yard was isolated from forested areas and was assumed to be a low flatheaded borer active area (Figure 12). Treatments were arranged in a RCBD with four replicates and at least 10 m (32.8 ft) between herbicide and non-herbicide plots. Trees were examined for presence of larval buprestids in December 2022 by peeling the bark back to reveal frass and larval galleries. Larvae recovered were placed on diet for rearing to the adult stage to confirm the species. Larvae that died were preserved in molecular grade ethanol for possible future molecular taxonomic assessment.

Comparing Three Different Stress Treatments on Large Red Maple Trees

A large in-field block of red maple trees was purposely stressed by girdling, notching (wedging), or felling the trees. To girdle trees, bark and cambium were removed with a gridling knife to create a ~1.27 cm (0.5 in) wide band cut all the way around the circumference of the tree trunk at 15.2 cm (6 in) above the ground (Figure 13C). To notch the trees, a large chunk of tree tissue was removed on the southwest side by using a chainsaw to cut to a depth equivalent to the trunk radius of the tree parallel to the ground. The next cut was a 45-degree angle to connect the previous cut, to create a wedge shape 15.2 cm (6 in) above the ground (Figure 13A). To fell the trees, the tree was cut all through with a chain saw at a height of 15.2 cm (6 in) (Figure 13B). All stress treatments were initiated in mid-May 2021 and again in mid-May 2022 (with different trees). Three trees (one from each treatment) were brought into the laboratory weekly for dissection beginning in September through January to remove flatheaded borer larvae. Tree bark was peeled with a knife to expose any mining damage in the inner bark, cambium, or wood. Data recorded included harvest date and presence of borer frass. Trees with significant larval tunneling damage and larvae already in pupal chambers were held in rearing containers to collect the emerging adults in the spring. Adults were sexed and identified to species, if possible, to determine which beetles were associated with the different stress-inducing damage treatments.

Artificial Diet for Flatheaded Borers and Tupelo Borers

An artificial diet described by Gindin (2009) for two *Capnodis* spp. (Coleoptera: Buprestidae) was used for diet studies with flatheaded borer larvae (presumed to be mostly *Chrysobothris spp.*) extracted from red maple nursery trees and tupelo borer larvae extracted from tupelo trees (Table 1). To prepare diets, hosts trees (i.e., red maple) were used to create the cortex needed for the diet recipe. Host tree bark or heartwood was peeled and dried in a drying oven on 30º C for ~12 h to remove all moisture. The tree cortex was then placed in a Whiley Mill to create a coarse cortex material, and then placed in a kitchen blender to create a finer cortex if needed. The cortex was stored in an airtight container in a walk-in cooler to preserve freshness.

Sucrose, wesson salt mix, agar, brewer’s yeast, and cortex from host tree were mixed in a beaker and autoclaved on setting liquid 1 (15 minutes at 121℃). Contents were removed from autoclave and are set to cool to 60 - 70 ℃. Casein, sorbic acid, vaderzant mix, methyl paraben and cellulose were mixed in slowly and were continually stirred. Diet was then placed on a cookie sheet with wax paper underneath it. Diet was left out on a laboratory table with a sheet of wax paper placed on top to prevent debris from falling into it for ~3 h. to let the cellulose harden and then placed in a dyer at 30 ℃ for ~12 h. Dried diet was removed from dryer, crumbled, and placed in containers. If too dry to crumble, DI water was added to the diet to increase a crumbly texture.

Diet was placed in small plastic petri dishes, 40-dram plastic snap cap vials (United States Plastic Corp, Lima, OH) or 7-dram glass shell vials (Fisher brand) depending on larval size with lids containing six holes to facilitate air exchange and reduce mold growth (Figure 14). Each container received one larva placed in the center of the diet (Figure 14). All flatheaded borer larvae reared to adult stage were identified to species if possible, using morphological characters (Wellso and Manley, 2007), and adults or any larvae that died during rearing were placed in molecular grade ethanol. Larvae and undetermined adults were preserved in molecular grade ethanol for possible future molecular species identifications. Diet in larval containers was replaced about every 2 wk.

Tupelo Borer Trapping with Different Lure Types

Traps likely to collect cerambycids (Hughes et al., 2016; Mitchell et al., 2011) were deployed along mixed deciduous forested edges within ~100 m (109.4 yd) of black gum nursery blocks with extensive tupelo borer damage. The trees in the nursery block were about 5-year-old with ~7.6 to 12.7 cm (3 to 5 inch) diameter trunks. Traps consisting of black corrugated plastic cross vein traps (7.62 cm wide vanes by 60.96 cm tall [3 in wide by 24 in tall]) with kill basins (filled with 20ml of Splash RV & Marine Antifreeze (FMP 130 Corporate Center Curve, Eagan MN) drowning solution) were baited with fuscumol, fuscumol acetate, ethanol, fuscumol in a black gum tree bolt, fuscumol acetate in a black gum tree bolt, or ethanol in a black gum tree bolt (Figure 15). These lures (i.e., fuscumol acetate and fuscumol) were selected based on reports of their attractiveness to other cerambycid beetles in the same subfamily as tupelo borer (i.e., Lamiinae) (Mitchell et al., 2011). Tree bolts were made by cutting a 12.7 cm [5 in] branch from a black gum forest tree and drilling a 9 cm deep by 9 mm (3.5 in deep by 0.35 in) diameter hole and then filling with one of the previously described liquid lure treatments. Hollowed- and filled-bolt baits were corked with a silicone stopper to reduce evaporation of the lure components (except through the wood). Each treatment was spaced 10 m (10.9 yd) apart, and the treatment position was rotated after each sample collection date (i.e., approximately every 2d). Sample collection consisted of pouring the kill basin contents through a paint funnel to filter out unnecessary liquid. Basins were reattached and 50 ml (1.7 fl oz) of antifreeze killing solution (Splash RV & Marine Antifreeze) was replaced. Paint funnels with trap contents were placed in labeled bags and stored in a freezer until they could be sorted and identified. All roundheaded borers captured (and other borers of interest) were identified to species if possible and stored in 70% ethanol in a 10-dram glass vial.

Data Analysis

Generalized linear models with both negative binomial and Poisson distributions were ran for all tests that required statistical anaysis. The model distributions were compared using the

Aikeke information critereon (AIC). The model with a lower AIC score indicates a better fit of the data to that distribution and was therefore selected. When a contrast of varaible means was needed, a Tukey’s honestly significant difference test (Tukey HSD) was used. All statistics were ran using R statistical analytics (R Core Team, 2021).

Chapter 4: Findings

Flatheaded Borer Larval Development During Winter

2021

Twenty-eight trees that were dissected had 32 larvae, 5 pupae, and 4 adults. Thirty larvae were found in the pupal chambers, and two were found on the surface. The larvae recovered in January had an average thoracic plate width of 4.52 ± 0.250 mm, February larvae had an average of 4.23 ± 0.123 mm, and March had an average of 4.29 ± 0.145 mm. From January to March, larval thorax plate width did not show apparent indications of growth. Consequently, larval growth and molting to new larval instars likely ceased from January through March. Larvae held on diet also appeared to remain quiescent until the correct amount of GDD was reached to begin pupation. One pupa was found near the trunk surface and four were found in the pupal chambers, while all adults (n = 4) were found in pupal chambers. Larvae were found from 20 Jan. until 3 Mar. Pupae were first found on 30 Mar. 2021 at 316 GDD. Adults were first found on 6 May at 746 GDD. Adults were still found within their pupal chamber, and no exit holes were shown, which indicates adults were not ready to leave the trees at the time of dissection.

2022

Thirty-two trees that were dissected had live or dead larvae, empty pupal chambers, or parasitoids present. Eleven larvae were already dead upon dissection and seven were alive, and one was found near the trunk surface, while the remaining six were in pupal chambers. Nine pupal chambers were found empty, and five had parasitoids in the chamber. Five pupae were found in pupal chambers beginning on 11 Apr. at 368 GDD. No adults were found during 2022 dissections.

Adult Flatheaded Borers Field Emergence Timing

2021

During 2021, 11 adult *C. femorata* were caught from 13 May to 6 June. The first beetle was trapped on 19 May at 942 GDD. Six beetles were caught on 20 May at 966 GGD and four were caught on 24 May at 1,060 GGD.

2022

During 2022, no adult beetles were caught in the fabric bags. Based on 2021 results, flatheaded appletree borer adults begin to emerge from pupal chambers at ~942 GDD and continue to emerge until at least 1,060 GDD. However, without adult emergence data from 2022 or other years, the average 2021 GDD has not been confirmed across multiple years. This study would need to be repeated several more times to confirm 2021 observations on adult beetle emergence. The range in adult emergence time might be explained by gender differences in beetles (not quantified), host suitability for development, external factors like shading of the trunk or position of the larvae in the trunk relative to heat sources like sunlight.

Herbicide-Stressed Foliage – Effects on Flatheaded Borer Sticky Trap Captures

In the herbicide stress test, 144 adult flatheaded borers were caught from May–August 2022, spanning three different herbicide treatment times of early, mid-, and late-summer. The early-summer treatment caught the most beetles (n=124), followed by mid-summer (n=18) and late-summer (n=2). Wood boring beetles trapped included genus *Agrilus* (n=59), *Acmaeodera* (n=6), *Dicerca* (n=2), and *Chrysobothris* (n=83) with a total of 14 species among these genera. The primary target *Chrysobothris* genus had 58% of the total beetles caught during this study.

In the early-summer treatment timing, adult buprestids were captured on the industry recommended treatment (i.e., February post- and pre-emergent herbicide providing minimal vegetation during the summer nursery-plant growing period) (n=52), Mowed treatment (n=29), Gly Star 5 Extra treatment (n=27), and Scythe treatment (n=16) (Table 2). Thirteen species of wood boring beetles were caught in the early-summer treatment timing with eight being the target *Chrysobothris* genus. Sixty-five *Chrysobothris* beetles were caught making up 52% of the total beetles captured for early summer treatment timing. The emerald ash borer (*Agrilus planipennis* Fairmaire) (EAB) was trapped more than any other beetle species (n=49). When looking across the treatments, more total EAB were captured on traps in the recommended treatment (n=21) than the other treatments including Mowed (n=14), Gly Star 5 Extra (n=9), and Scythe (n=5), respectively. While EAB was not the target buprestid of the study, the trap capture information provides additional data on production practices that might increase the catch rate of other pest wood borers like EAB.

Among the species in the target *Chrysobothris* genus, *Chrysobothris quadriimpressa* (Olivier) was the most frequently trapped (n=38). The recommended treatment caught more total *C. quadriimpressa* (n=15) than the Mowed (n=7), Gly Star 5 Extra (n=11), or Scythe (n=5), respectively. The early-summer timing was the only timing with trap captures from the genus *Dicerca*. A negative binomial general linear model did not detect significant differences among the four treatment types during the early-summer treatment timing (χ^2=3.2, df=3, P>0.05).

A total of 18 buprestids were trapped during the mid-summer treatment period. Buprestids were captured in the recommended treatment (n=8), Scythe treatment (n=6), Gly Star 5 Extra treatment (n=3), and mowed treatment (n=1) (Table 2). The mid-summer treatment timing caught seven different species, four (55%) of which were in our target genus *Chrysobothris*. The EAB and *Chrysobothris adelpha* Harold were the most frequently captured. For EAB, a total of two, one, and one specimen were trapped in the recommended, Scythe, and Gly Star 5 Extra treatments, respectively. For *C. adelpha*, the recommended and Scythe treatments each had two specimens trapped, respectively. A negative binomial general linear model indicated that there was a significant lower number in the mowed treatment type (χ^2=5.766, df=3, P=0.0265).

The late-summer treatment timing traps had the fewest beetle captures among test timings with only one *C. quadriimpressa* and one *Chrysobothris viridiceps* Melsheimer trapped (Table 4). The *C. quadriimpressa* and *C. viridiceps* specimens were captured on Scythe and recommended treatments, respectively. The beetle captures during the late-summer treatment timing were too low for statistical analysis. The late-summer timing had no other buprestid genera captured than the target *Chrysobothris* genus.

Based on test results, the recommended glyphosate (i.e., Gly Star 5 Extra) treatment during February might be attractive to newly emerging *Chrysobothris* beetles, as well as freshly mowed areas. The test plots in the recommended treatment also had bare ground, which may have enhanced tree or trap visibility and host location by adult beetles. Previous studies have suggested that cover crops aid in wood boring beetle deterrence. The vegetation-deterrence-effect may be the explanation for results in this study as well, with the herbicide-dying foliage during early-, mid- and later-summer timings still camouflaging the traps or trees from the beetles.

Herbicide-Stressed Foliage - Effects on Flatheaded Borer Attacks on Potted Red Maples

Trees in this test had an average trunk diameter of 16.63 mm (0.65 in). Trees were dissected for borer assessment and a total of 32 trees out of 216 were attacked (15% of the total). Trees placed in herbicide-treated, or non-treated (control) plots had 14 and 13 total attacks, respectively (Table 3 & 4). The total number of attacked trees in the treated compared to the control were the same for May (n=3 and 3) and June (n=6 and 6), but totals varied by one beetle attack in July (n=4 and 5), respectively. The container pad had a total of five trees attacked during the study. Since trees were attacked on the container pad, it is difficult to draw conclusions on whether the control and herbicide trees received attacks in the field or while residing on the container pad. If this test were repeated, to avoid attacks on the control trees (container pad), a method to better isolate the control trees from wood boring beetles would be an improvement. Examples of enhanced tree isolation methods could include a closed in greenhouse, netted tent, or something similar by design. Since both the container pad "control site" and field treatment locations had borer activity, there is no way to draw conclusions about treatments from this test other than borers were attracted to the test maple trees. Whether that was due to drought stress, the treatment, or location is unknown. A total of 44 larvae were dissected from the attacked trees, which was an average of 1.5 larvae per tree. The largest number of larvae removed from a single tree was five.

Comparing Three Different Stress Treatments on Large Red Maple Trees

One hundred twenty trees were dissected during 2021 and 2022 to determine flatheaded borer infestation status. In 2021, eight out of 60 trees had visible surface symptoms of flatheaded borer infestation (i.e., frass present) (Table 5). In 2022, more trees had visible symptoms of infestation with 29 out of 60 trees having borer-related frass present. In 2021, more notched trees had frass present. While in 2022, more felled trees had frass present. None of the girdle-treated trees had symptoms of infestation (i.e., frass) in either year. A zero-inflated negative binomial regression was performed on total frass counts and found that notched trees were significantly different from girdled and felled (χ^2=48.59, df=2, P=0.009).

The study indicates trees that are girdled were not attacked by flatheaded borer, while notched and felled trees were attacked at a percentage of 40% and 52.5%, respectively. The frass present in the notched trees was mostly flatheaded borer, which indicates this beetle group may be more attracted to trees that are slowly dying, and the associated volatiles they emit. It appeared the trees that were felled may be more attractive to longhorn beetles based on the frass observed, but most of the trees were damaged so much it was difficult to make observations on frass type. Future studies should focus more on frass and larval dissections to determine treatment preferences of flatheaded borer and longhorn beetles.

Artificial Diets for Flatheaded Borers and Tupelo Borers

Both tupelo borer and *Chrysobothris* spp. were successfully reared on artificial diet media described in Table 1. However, no visible signs of feeding (e.g., frass) were present for flatheaded borer larvae placed on diet, while tupelo borer larvae did have evidence of active feeding (i.e., tunneling in the diet and excrement). Likewise, the flatheaded borer larvae also never exhibited any larval molts from the time they were dissected from trees and placed on the diet until they pupated. Consequently, it is presumed that the winter and late spring harvested flatheaded borer larvae had reached their final instar and were no longer molting. In contrast, tupelo borer larvae collected in June had up to ~3 molts after post-diet placement. All tupelo borer larvae were collected during the summer and were placed in a refrigerator at 4°C for 3 mo to simulate winter conditions.

Twenty-two *Chrysobothris* larvae were placed on the diet in March 2021. Following the larval stage (Figure 16A), the pupae progressed through various periods of melonization (Figure 16B-F). The larvae had an average thoracic plate width of 5.19 mm (0.2 in). There were visible signs that larvae were moving diet around and creating small chambers for possible resting sites. Larvae did not have apparent issues like entrapment when moving through the diet. At one point, there were issues with slime mold forming in the diet. To address this issue, diet was changed regularly, and the diet stock was oven dried further to remove excess moisture. The larvae integument became leatherier and more shriveled in appearance near the time of pupation. The first pupa was found on 8 Apr. 2021 (Figure 16). Of the 22 larvae that were placed on diet, 10 successfully pupated, and five of those made it to adulthood. Some adult flatheaded borers had signs of deformities from the final molt or did not survive the pupation process due to a failed molting process. It is likely the larvae or pupae did not have an adequately hard surface on both sides to remove the exuviae, which would be typical in a natural pupation chamber within a tree trunk. Once beetles reached adulthood and had hardened elytra, adult beetles still exhibited a sluggish behavior that lasted ~7 d (typically around 5 to 10 May 2021). Beetles in their normal environments may be using this inactive period to physically adjust to adulthood and to begin chewing their exit hole. Since there was no exit hole to chew in the diet and lab-setting, the beetles remained quiescent until they reached what would be a presumed “ready to emerge” state in a natural non-diet setting.

On July 2021, 24 black gum trees were cut down from a nursery in middle Tennessee that had noticeable borer damage to the truck. These trees had an average trunk diameter of 4.1 cm (1.6 in). There were no trees with exit holes present at the time of dissection. Twenty trees had entry holes present. The maximum number of entry holes into the heartwood found within one tree was four. The average size of the entry holes was 12.17 mm (0.48 in). Thirty-six larvae were dissected from the trees with an average thoracic plate width of 5.21 mm (0.21 in). On the tupelo borer diet (Table 1), larvae showed visible signs of feeding in the artificial diet with frass being present and pathways chewed through the diet. Larvae even made chewing marks on the sides of the plastic petri dishes. Larval molting was observed during the period these larvae were on diet. Diet was changed a total of 5 times from July 2021 to May 2022. From February through May, beetles were left in a refrigerator at 4°C to imitate outside winter conditions. The last diet change occurred on 1 Feb. 2022, and thoracic plates were measured a final time. From larval collection during June 2021, the larval thoracic plate grew an average of 0.95 mm (min./max. range of 5.48 to 6.06 mm [0.04 in with range of 0.22 to 0.24 in]). Once larvae began the pupation process, no further diet changes or handling were done to reduce the risk of injuring the beetles. Pupae were sprayed with deionized water to keep them from drying out. The first pupa was observed on 4

Apr. 2022, and the first adult completed molting on 2 June 2022 (Figure 17). It was observed that once the elytra of the beetle were fully hardened, beetles remained quiescent for approximately a week before movement occurred. Among larvae placed on diet, 72% (n=26) successfully pupated and became adult beetles. Some adult tupelo beetles showed signs of deformities after the final molt. Like flatheaded borers, deformities were likely the result of not having an adequately hard surface on both sides to facilitate exuviae removal as would be available in a natural pupation chamber within a tree trunk.

With this study, the artificial diet formulation worked well for rearing tupelo borer larvae to adulthood. However, to better determine whether flatheaded borer larvae would feed on the diet, eggs or smaller instars would need to be collected, since it appears the larvae collected in late winter and early spring do not feed. Due to their small size and minimal trunk damage, younger flatheaded borer larvae will continue to be difficult to locate in the field and remove from host trees without injury for diet feeding studies. In contrast to flatheaded borers, longhorn beetles were successfully reared on the diet and showed visible signs of feeding. When working with longhorn beetles, it is important to monitor the container and diet condition. There were issues with larval longhorn beetles chewing through plastic petri dishes or plastic vials and escaping. Glass vials worked better for containing tupelo borer larvae. When working with a larger beetle such as a tupelo beetle, it was important to give larvae sufficient space to move vertically as larvae normally would do in a trunk of a tree. After larvae were moved to glass vials with more vertical space, they appeared to consumer more diet and to reach the next stadia quicker than in flat petri dishes, although direct vial versus petri dish comparisons were not made. While using borer diets (Table 1) to rear both flatheaded borer and longhorn beetles was generally successful, beetles did not always molt correctly. Finding a substance that larvae could bore down into that has the same density and roughness of wood may resolve this problem; however, these diet changes would also modify the character of the diet requiring more monitoring and study. It is possible that transferring pre-pupae into a different set of containers with a harder substrate prior to pupation would aid in increasing adult emergence success. A benefit of these diets could be future studies to observe borer development and phenology at various temperatures to better understand emergence periods, damaging larval stages, or basic biology.

Tupelo Borer Trapping with Different Lure Types

Seventy-one longhorn beetles were caught from 19 June through 22 July 2022 (Table 8). Unfortunately, the target *A. morrsi* species was not collected in any trap treatment. When comparing weekly catch rate of other cerambycids, the period of 19 June through 23 June 2022 had the highest trap capture of longhorn beetles (n=16). Among months, June had the highest overall capture rate (n=38; average=9.5) (Table 8). Fuscumol acetate had the numerically highest catch rate (n=20) when compared to other treatments (Table 8). Sixteen different species of longhorn beetles were caught from 19 June through 22 July 2022 (Table 8). *Elaphidion mucronatum* (Say) caught across all lure treatments and in the highest total number (n=24). The second highest trap capture was *Aegomorphus modestus* (Gyllenhal in Schoenherr) (n=11), and this species was only caught in fuscumol acetate or fuscumol treatments.

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A negative binomial general linear model comparing trap numbers and month timings determined that months were significantly different (χ^2=29.9, df=9, P=0.008). A June contrast did not detect significant differences (P>0.05) among trap treatments. However, Fuscumol acetate had significantly more cerambycid trap captures than the ethanol treatment (P=0.021). Ethanol and fuscumol with bolt, as well as fuscumol and fuscumol acetate only lure treatments, were not statistically different (P=0.069). A larger sample size may have improved discernment of statistical differences.

The *A. modestus* species was in the target genus for tupelo borer, so either tupelo borer is not attracted to the same lures, the wrong types of traps were used, or the area where traps were deployed did not have active tupelo borer populations. Because some of the trees at the site had been removed for diet rearing studies, the localized population may have been reduced. Trap placement at ground level may also have been incorrect for this species. It was also speculated that tupelo borer would either be near the deciduous forest or flying from the nursery infested trees to the forest, but because it is reported to attack smaller trees (Solomon 1995), it is possible traps should have been placed near the nursery trees and not the adjacent forest. Lastly, adult borers observed in the nursery appeared to be somewhat inactive, and if the biology habit is to fly to a host tree and then remain relatively sessile, a trap may not be the best approach for monitoring adult activity.

Chapter 5: Conclusion

Flatheaded Borer Larval Development During Winter

The growing degree day (GDD) values developed during this thesis research can be used to estimate the time insects, such as flatheaded borers, will emerge from overwintering chambers. Because GDD calculations use heat units accumulated, it can be used to predict emergence at other latitudes or areas with different temperature patterns. Based on nursery tree dissection results, pupation occurred between 316 to 368 GDD, and adult eclosion occurred at ~746 GDD. Due to low numbers of flatheaded borers recovered in the second year, this study had less multi-season confirmation of GDD estimates for flatheaded borers, so there may be some GDD variability in larval, pupal, and adult development data. Weather, predation, parasitoids, or insecticide treatments are possible reasons for empty chambers or dead larvae found in 2022. The grower had indicated the site was untreated with insecticides, but it is possible the site might have been treated by another farm assistant without grower knowledge. The trees selected for harvest in 2022 had recognizable flatheaded borer damage, so borer larvae had been alive long enough to cause visible trunk damage. The high visible trunk damage in the nursery tree block was a reason for using the 2022 trees in this study, but unfortunately, there was no way to know in advance that these trees had high larval mortality, which resulted in less data for GDD estimates. Since we had so few numbers in 2022, more years of flatheaded borer dissection work would improve GDD prediction estimates for borer development. However, the

2021 data did provide GDD estimates for flatheaded borers and will aid future studies that might investigate borer growth and development.

Adult Flatheaded Borers Field Emergence Timing

Like the development rate dissection studies, the spring emergence time of adult flatheaded borers also was limited to 1-yr of field data due to the inability to find locations with active beetle damage in 2022. This study needs to be replicated several more times to draw more robust conclusions. Another issue encountered during this study was the metal cages, which were difficult to re-attach after daily checks and made it difficult to know if beetles were escaping. A different method with fabric bags was attempted in 2022 but was unsuccessful. It is unknown whether emergence failures of flatheaded borers were due to the bag design, or if there were no viable larvae in the harvested logs. If the test were repeated, a better approach would be mixing the two designs together by harvesting trees from a trap crop of red maples in January and leaving them in a container in outside conditions. The improved approach would allow closer monitoring of the containers, while still ensuring they are enclosed completely to reduce adult beetle escape from the traps.

Herbicide-Stressed Foliage – Effects on Flatheaded Borer Sticky Trap Captures

The herbicide-stressed foliage test hypothesized that borers would orient more towards areas with high vegetation stress, which in this case was created by use of artificially-induced-damage with herbicides or mowing. During the active periods of adult beetle flight (May to July), mowing or herbicide treatment with a systemic post-emergent herbicide (Gly Star 5 Extra) or contact post-emergent (Scythe) did not dramatically increase trap capture totals relative to non-treated plots. A possible explanation for the inability to find differences between ‘damaged’ and ‘non-damaged’ plots could be that borers are not attracted to the stress volatiles from damaged plants or from the types of vegetation that were treated (i.e., grass and broadleaf weeds). Secondly, the use of traps to measure beetle response to vegetation damaged plots may not have been an optimal approach since traps measure both insect activity and relative population size. Adult flatheaded borers have an attraction to violet colors (Perkovich et al., 2022; 2023), but the reason for the attraction is unknown; thus, there may be asynchrony between borer color attraction purpose and borer response to plant stress-related volatiles. In other words, traps may not be the best method to measure borer response to plant stress damage volatiles. Interestingly, the nursery-recommended weed management program of a pre- (e.g., Marengo) and post- (e.g., Gly Star 5 Extra) emergent herbicide during late winter (Yeager et al. 2007), like the February timing in this study, had the more beetle captures on traps than the other test treatments. The February-timed herbicide treatment was originally added to the study as a both the recommended grower weed management method and to serve as the ‘standard control’. Based on our hypothesis, it was assumed that herbicide damage to vegetation in February and the subsequent foliage death and drying, would release all stress-related plant volatiles well in advance of the adult borer flight season (i.e., thus, this treatment would be non-attractive to borers). In contrast to our hypothesized expectations, the February-timed herbicide spray had more trap captures than other treatments. During the period with the highest beetle trap activity (i.e., May timing), the mowed treatment had the next highest total beetle captures. Interestingly, the February recommended herbicide treatment and mowed treatment both created conditions for high trap visibility (i.e., vegetation was dead and mostly flattened to the ground in the February herbicide treatment or immediately lowered by cutting in the mowed treatment). In contrast, May, June, and July applied pre- and post-emergent herbicide treatments did not remove vegetation height, but just caused a rapid (i.e., Scythe) or gradual (i.e., Gly Star) death of the vegetation. The mowed treatment was initially selected because it was expected to release a rapid pulse of plant stress volatiles, which would cease after the clipped grass desiccated or the cut vegetation sealed the cut damage wounds. Thus, the mowed and Scythe treatments were probably the most similar in terms of rapid pulses of plant stress volatiles, although their mechanism of damage (i.e., cutting versus foliar burning) were different. Unfortunately, one treatment missing from this study was a treatment that received no treatment at all. A non-treated treatment would have had vegetation with similar height to the herbicide treatments, which would have possibly answered the question of whether higher beetle captures in February herbicide and mowed treatments were just due to greater trap visibility or some other factor associated with these treatments. Future studies should evaluate plant damage and non-damage plots with similar trap visibility conditions. However, the herbicide and non-herbicide damaged plots with red maple trees (see next section) may address this question, since that study moved trees in and out of herbicide treated and non-treated plots with similar vegetation heights yet found no major differences in attack rates between trees in those plots. Thus, the results of a separate study using potted maple trees in this thesis project supports that plant stress volatiles (at least from grass and broadleaf damaged weeds) may not be that attractive to flatheaded borers; and likewise, that the higher trap captures in some treatments of this test may have been due to greater trap visibility and not damage-associated treatments. This study corresponds to other studies that suggest that cover crops are beneficial as a wood boring beetle deterrent possibly due to camouflage or blocking effect of nursery tree trunks by the surrounding vegetation or alteration of the environment (Dawadi et al., 2019; Addesso et al., 2020; Gonzalez et al., 2023). A similar camouflage effect may have occurred with the reduction of trap captures in this study in the treatments with higher vegetation heights (i.e., the May, June, and July post-emergent herbicide treatments). This study provides vital information on ways to change the culture of nursery production and reduce the number of crops being damaged by wood boring beetles.

Herbicide-Stressed Foliage - Effects on Flatheaded Borer Attacks on Containerized Red Maples

Like the herbicide-stressed foliage test with purple sticky traps, the herbicide-stressed foliage test with potted red maples had a similar hypothesis that damaged plant foliage would increase borer attack rates on nearby nursery trees. Because flatheaded borer attack rates were similar on container maple trees exposed for 1-mo intervals during May, June, or July to field sites with or without a post-emergent herbicide (Gly Star 5 Extra) treatment, there was no apparent increase in tree attacks resulting from the vegetation damage herbicide treatment. Thus, the observed results of this study did not support our hypothesis that adjacent plant-associated stress would increase borer attacks on nearby nursery trees under the conditions of this study. A third group of trees in this study were left on the container pad for the duration of the May, June, and July treatment exposures. The container-pad-only group was intended to provide a measure of any attacks that occurred among the May, June, and July exposure tree groups when they were on the container pad. Unfortunately, the non-moved tree group on the container pad also had flatheaded borer tree attacks, which complicates the assessment of treatment effects for tree groups moved in and out of herbicide or non-herbicide treatment plots. If this test were repeated, an improved approach would be to put all trees in an enclosed environment such as a greenhouse when plant groups were not being moved to experimental field treatment sites. Otherwise, there is no way to know if the trees moved to the field in June and then brought back in July were really attacked in the field, or if they were attacked once they were returned to the container pad. The assumption that the container pad was sufficiently isolated to avoid flatheaded borer attacks was incorrect based on non-moved control trees that were attacked in the container yard. During this test, it was challenging to keep the containerized maples in an upright position while on the container pad. The trees were ~ 1.82 m (~6 ft) tall, so they often fell over with a slight wind. Trees that fell over did not receive uniform watering, potentially creating further stress-related factors that attracted beetles. Future tests also would need to ensure a better irrigation system for all trees in the study both in non-experimental holding areas and when deployed at experimental treatment locations. Large tree size is important for borer studies because smaller trees (< 1.9 cm [< 0.75 in]) (Anthony Witcher, pers. comm.) are less likely to be attacked; thus, tree size will continue to create an issue for maintaining adequate irrigation and preventing wind-throw of trees. Aside from the issues with trees during their constant or sporadic intervals on the container pad, a positive outcome of this study was that trees field deployed into vegetation patches treated with or without post-emergent herbicides still had similar levels of borer attack. Although these trees may have experienced additional stresses on the container yard, they should have had similar levels of stress for the duration of the study with the only differences being exposure to borers during field deployment. Thus, the study still provides support for rejection of our hypothesis that placement of nursery trees near sites with high vegetation stress will result in trees experiencing differential borer attack levels. The study should be repeated using a beetle-free control area, trees with better stabilization from falling over, and improved irrigation to confirm the conclusions that plant associated stress treatments are not enhancing borer attacks. Validation of the rejection of our hypothesis is important because some nursery producers do treat weeds and adjacent vegetation near nursery blocks during periods when adult borers are active. Thus, producers need to know whether late season post-emergent treatments are safe to use near their nursery crops or if they enhance the risk of attacks. However, at the present, this study supports that adjacent post-emergent herbicide damage treatments do not increase producer risk of borer attack.

Comparing Three Different Stress Treatments on Large Red Maple Trees

Unlike the herbicide-damaged vegetation studies that were used to evaluate effects on borer trap activity or tree attacks on potted plants when located near these stress treatment sites, this study evaluated the hypothesis that stress treatments applied directly to the nursery trees would increase borer attacks on the tree. Based on the results, girdling a tree did not increase flatheaded borer attacks, so this type of stress damage may not have been sufficient to increase the attraction of flatheaded borers. The girdled trees still appeared very healthy even though they had some aesthetic damage to the trunk. In contrast, flatheaded borer attacks increased on trees receiving either a notched (wedge removed) or felled tree treatment in both 2021 and 2022. These treatments caused more damage to the tree trunk, and it is likely the stress signal attracted more flatheaded borer adults. In 2021, notched trees had more tree trunks with wood-borer frass present. The notched-trunk-trees, although severely damaged, remained alive and may have continuously produced stress volatiles resulting in more borer oviposition and larval attacks. However, during 2022 the felled trees had more trees with wood-borer frass present. The higher borer incidence in the 2022 felled tree treatment might be due to the amount of longhorn damage present and the challenges with identifying and separating flatheaded borers damage from longhorn damage using frass. Longhorn beetles typically prefer trees that are fully dead, so future studies should examine more carefully which beetle species is responsible for the frass being observed. In conclusion, notched and felled trees had more visible damage from flatheaded borers and longhorn beetles based on frass evidence, while girdling trees showed no indications of increasing flatheaded borer or longhorn beetle attacks. The results for notched and felled trees supported our hypothesis that direct damage to nursery trees can increase wood borer attacks and there was also evidence that the type of damage and severity was another factor in tree attractiveness to borers.

Artificial Diets for Flatheaded Borers and Tupelo Borers

The purpose of the flatheaded borer and tupelo borer diet studies was to develop a diet could be used to rear these borer groups in the laboratory, thus allowing observations on development stages and rate and other biological factors like numbers of instars. The diets were formulated from ground host-materials (cortex) and several other common diet ingredients published in a different larval buprestid rearing study (Gindin, 2009). In this study, the flatheaded borers that were held on diet were collected during winter (January) to late spring (April) from trees with obvious borer damage. It was expected flatheaded borer larvae collected during this period would be older instars. At tree dissection, some of the beetle larvae were already in pupal chambers, and these larvae apparently did not feed on the flatheaded borer diet. However, an unexpected finding from this study was that larvae not in pupal chambers also were not apparently feeding. Thus, one conclusion from this study is that flatheaded borer larvae are mostly non-feeding from January until adult emergence in the late spring. It is likely these larvae have reached their final instar by January, since this study also did not observe any molting activity among the larvae collected from January to April. These older flatheaded borer larvae were mostly quiescent in the tree or their overwintering chambers, and due to their poikilothermic development process, likely remaining inactive until GGD was sufficient to begin the pupation process. Since these older larvae were essentially non-feeding, in the future, if younger larvae or eggs can be collected, the diet could be more thoroughly evaluated for its potential as a food source to rear flatheaded borers.

Unlike flatheaded borers, all tupelo borer larvae placed on the experimental diet showed indications of continued growth based on larval molting. Tupelo borer larvae also appeared to be feeding through the diet, as well as even causing chewing marks on the plastic holding containers. The tupelo borer larvae were much more active in comparison to the larvae of the flatheaded borers. Tupelo borer larvae would tunnel and bore downward into the diet to create chambers. It was necessary to move tupelo borer larvae into glass containers to prevent them from chewing and escaping the plastic petri dishes or plastic vials. With 26 of the 36 larvae being reared to adulthood, the diet was successful for rearing this species of longhorn beetle.

For both borers in the diet containers, the study did allow observations of development processes that would not be available in a natural setting (see Figures 16 and 17). Some of the beetles in both families had wing deformities, so the diet environment was not as conducive for completion of adult eclosion. It was speculated that the absence of rigid substrate beside the pupae, as would occur in a natural tree-trunk setting, may have hindered the completion of the final molt from pupa to adult.

Tupelo Borer Trapping with Different Lure Types

The hypothesis of this study was that commonly used longhorn lures or host material (i.e., black gum) of *Aegomorphus morrisi* would increase trap captures of this beetle. A better monitoring trap is needed for this wood-boring beetle species because it has caused extensive damage to black gum nursery trees in the middle Tennessee area. While no *A. morrisi* were caught among lure treatments used with traps, the study did have similar results to previous literature that supported *Aegomorphus modestus* being caught in traps with lures of fuscumol acetate or fuscumol. Since *A. modestus* is in the same genus as *A. morrisi*, it was expected both species might respond to the fuscumol-related lures. Unfortunately, it is not clear from the study whether *A. morrisi* was not attracted to the trap lure types or was just not in the vicinity of the trap treatments. If the test was repeated, an improved approach to increase the likelihood of capturing *A. morrisi* might include running different trap types at different heights. In this study, traps were placed at ground level on metal trap rods about 1-m (3.3 ft) above the ground. However, *A* *morrisi* may be more active in upper tree canopy regions compared to *A. modestus* that was captured in the lower canopy traps; thus, traps in this study may have been deployed in the wrong site. Likewise, since the traps were close to a block of tupelo trees that previously had tupelo borer damage, it is possible the adult tupelo borers were more attracted to the trees than the traps with different lures. This type of trap study could be important in determining the flight patterns of tupelo borer and how they enter nursery fields. While no *A. morrisi* were caught in study traps, valuable information was obtained on a variety of other longhorn beetle species. Based on capture data, *Elaphidion mucronatum* did not prefer any of the longhorn beetle pheromones evaluated. *Aegomorphus modestus* was only caught in fuscumol acetate and fuscumol lure traps, suggesting they are attracted to these lures and are not attracted to ethanol. More information on trap type, placement and lures will be vital for future targeted trapping efforts of tupelo borer.

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Table 1

Ingredients used in experimental flatheaded borer and tupelo borer artificial diets using methods described in Gindin (2009) for developing a flatheaded borer diet.

Ingredient	Amount used (g)	
	Flat Headed Borer	Tupelo Borer
Sucrose	8.00	8.00
Wesson Salt Mix	2.00	2.00
Agar	6.00	6.00
Brewer Yeast	15.00	15.00
Cortex of Host Plant	15.00	30.00
Casein	8.80	8.80
Sorbic Acid	0.50	0.50
Vanderzant Mix	2.40	2.40
Methyl Paraben	0.32	0.32
Cellulose	74.00	74.00

Table 2. *Total beetle species captured on purple sticky traps in plots with different vegetation stress treatment.*

Timing and Species[a]	Treatments[b]				Total
	Gly Star	**Mowed**	**Scythe**	**Recommended**	
Early Summer					
Agrilus bilineatus (Weber)	1	0	1	3	5
Agrilus lecontei Saunders	1	0	0	0	1
Agrilus planipennis Fairmaire	9	14	5	21	49
Acmaeodera tubulus (Fabricius)	0	1	0	1	2
Dicerca obscura (Fabricius)	0	1	0	1	2
Chrysobothris adelpha Harold	0	0	0	3	3
Chrysobothris cribraria Mannerheim	0	0	1	1	2
Chrysobothris femorata (Olivier)	1	2	1	2	6
Chrysobothris quadriimpressa Gory & Laporte	11	7	5	15	38
Chrysobothris rugosiceps Melsheimer	1	0	1	0	2
Chrysobothris sexsignata Say	1	1	1	4	7
Chrysobothris shawnee Wellso & Manley	2	2	1	1	6
Chrysobothris viridiceps Melsheimer	0	1	0	0	1
Early Summer Total	**27**	**29**	**16**	**52**	**124**
Mid-Summer					
Agrilus planipennis Faimaire	1	0	1	2	4
Acmaeodera pulchella (Herbst)	1	0	2	0	3
Acmaeodera tubulus (Fabricius)	0	1	0	0	1
Chrysobothris adelpha Harold	0	0	2	2	4
Chrysobothris femorata (Olivier)	0	0	0	2	2
Chrysobothris quadriimpressa Gory & Laporte	0	0	1	2	3
Chrysobothris rugosiceps Melsheimer	1	0	0	0	1
Mid-Summer Total	**3**	**1**	**6**	**8**	**18**
Late Summer					
Chrysobothris quadriimpressa Gory & Laporte	0	0	1	0	1
Chrysobothris viridiceps Melsheimer	0	0	0	1	1
Late Summer Total	**0**	**0**	**1**	**1**	**2**
Grant Total	**30**	**30**	**23**	**61**	**144**

[a] Early Summer = May – June, Mid-Summer = June – July, Late Summer = July – August

[b] Three traps were deployed in a plot that had been treated with either Gly Star 5 Extra (glyphosate, 53.8%), Mowed, Scythe (pelargonic acid [57%] and related fatty acids [3%]), or the “Recommended” glyphosate (Gly Star 5 Extra, 53.8%) and indaziflam (Marengo® at ~950 ml product / Ha [13 fl oz product / acre]) during three different timings throughout summer 2022. Traps were checked weekly, and beetles were brought back to the lab for identification.

Table 3

Total numbers of trees that showed signs of flatheaded borer damage among trees exposed to herbicide or non-herbicide treated vegetation patches at three different month timings as well as attacks on trees that were not moved from the container pad holding area.

Month[a]	Treatment[b]	Total Number of Attacked Trees[c]
May	Control	3
	Herbicide	3
Total		**6**
June	Control	6
	Herbicide	6
Total		**12**
July	Control	4
	Herbicide	5
Total		**9**
	Container Pad	5
Grand Total		**32**

[a] May = trees exposed to treatments at field sites from May 1 to 31 and then moved back to container pad, June = trees exposed to treatments at field sites from June 1 to 30 and then moved back to container pad, July = trees exposed to treatments at field sites from July 1 to 31 and then moved back to container pad, and Container Pad = trees left on container pad from May 1 to July 31
[b] Each treatment had 4 replicates. Control and Herbicide treated trees were placed in plots 6 m by 6 m. Control trees were placed in plots with no herbicide damage to vegetation and Herbicide trees were placed in plots treated with Gly Star 5 Extra (15.6 ml product / liter [4% solution]). Container pad trees were not moved from the container pad.
[c]32 out of 216 showed signs of flathead borer damage.

Table 4

Total numbers of trees that showed signs of flatheaded borer damage for the three treatment types that included container pad, control, and herbicide.

Treatment[a]	Total Number of Attacked Trees
Container	5
Control	13
Herbicide	14
Total Number of Trees	**216**

[a] Each treatment had 4 replicates. Control and Herbicide treated trees were placed in plots 6 m by 6 m. Control trees were placed in plots with no herbicide damage to vegetation and Herbicide trees were placed in plots treated with Gly Star 5 Extra (15.6 ml product / liter [4% solution]). Container pad trees were not moved from the container pad.

Table 5

Total numbers of trees with borer damage (indicated by frass) for three tree trunk stress inducing treatments applied to large red maple trees in 2021 and 2022.

Treatments – 2021[a]	Total Trees with Frass Present	Total Trees Dissected
Girdled	0	20
Notched	6	20
Felled	2	20
Treatments – 2022[a]		
Girdled	0	20
Notched	10	20
Felled	19	20

[a] *Girdling occurred by using a girdling knife, notched occurred by cutting a wedge out of the tree trunk, and felled occurred by cutting the tree down 15.2 cm (6 in) above the soil line. Trees were dissected to document frass presence.*

Table 6

Total numbers of cerambycid beetles trapped by lure treatment for June and July of 2022

		Total Cerambycid Captures by Trap Lure Treatment[a]				
Month	**Week**	**Fuscumol**	**Fuscumol Acetate**	**Ethanol**	**Fuscumol with Bolt**	**Ethanol with Bolt**
June	1	0	1	1	1	3
	2	2	2	5	3	4
	3	2	2	3	1	5
	4	1	1	0	1	0
July	1	2	5	0	3	0
	2	0	0	0	2	4
	3	0	2	1	2	0
	4	0	5	0	5	0
	5	0	2	0	0	0
Total:		**7**	**20**	**10**	**18**	**16**

[a] Each treatment had 4 replicates arranged in a randomized complete block design. Fuscumol and fuscumol acetate were commercial lures. Ethanol was a blank lure. Bolts were made from black tupelo branches ~ 6 cm diameter hollowed with a 3 cm diameter hole in the middle to a depth of 9 cm and filled with either 75% ethanol or fuscumol. Each treatment was placed in a black vane trap ~ 60 cm tall with 8.89 cm wide trap vanes and a killing basin (Figure 15).

Table 7

Total numbers of cerambycid beetles trapped by week in June and July of 2022.

Month	Week	Total[a]	Average
June	1	6	1.20
	2	16	1.45
	3	13	1.62
	4	3	1.00
July	1	10	1.42
	2	6	1.20
	3	5	1.25
	4	10	2.00
	5	2	1.00
Total:		**71**	

[a] *Totals are the combined vane trap (see Figure 15) caught from five treatments each with 4 replicates.*

Table 8

Species of cerambycid beetles trapped by lure treatment for June and July 2022

Species	Treatment[a]					
	Fuscumol	Fuscumol Acetate	Ethanol	Fuscumol with Bolt	Ethanol with Bolt	Total
Aegomorphus modestus (Gyllenhal)	2	9	0	0	0	**11**
Anelaphus villosus (Fabricius)	0	0	1	0	0	**1**
Eburia quadrigeminata (Say)	0	0	0	1	0	**1**
Ecyrus dasycerus (Say)	1	0	0	0	1	**2**
Elaphidion mucronatum (Say)	2	2	4	8	8	**24**
Eupogonius pauper LeConte	0	0	0	0	1	**1**
Lepturges angulatus (LeConte)	0	4	0	1	0	**5**
Liopinus alpha (Say)	0	0	0	1	0	**1**
Neoclytus acuminatus (Fabricius)	0	0	0	0	1	**1**
Obrium maculatum (Olivier)	1	1	0	3	0	**5**
Orthosoma brunneum (Forster)	0	1	1	0	0	**2**
Prionus imbricornis (Linnaeus)	0	0	2	1	0	**3**
Strangalia luteicornis (Fabricius)	1	1	1	1	4	**8**
Styloleptus biustus (LeConte)	0	0	0	1	0	**1**
Urographis faciatus (DeGeer)	0	1	0	0	0	**1**
Xylotrechus colonus (Fabricius)	0	1	1	1	1	**4**
Total	**7**	**20**	**10**	**18**	**16**	**71**

[a] Each treatment had 4 replicates arranged in a randomized complete block design. Fuscumol and fuscumol acetate were commercial. Ethanol was a blank. Bolts were made from black branches ~ 6 cm diameter hollowed with a 3 cm diameter hole in the middle to a depth of 9 cm and filled with either 75% ethanol or fuscumol. Each treatment was placed in a black vane trap ~ 60 cm tall with 8.89 cm wide trap vanes and a killing basin (Figure 15).

Figure 1

A flatheaded borer A) adult reared from and B) a larva dissected from a tree harvested from a middle Tennessee nursery. (Photos taken by Aubree Morrison)

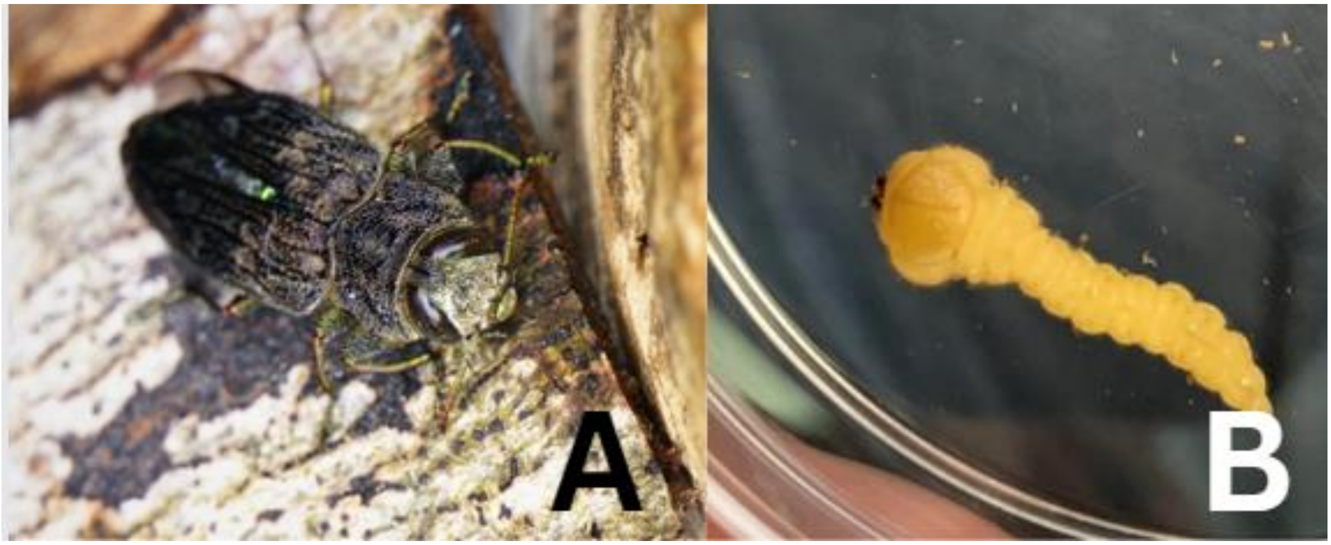


Figure 2

Flatheaded borer damage on a red maple (Acer rubrum L.*) tree trunk with A) visible damage on the surface of the trunk without the bark removed and, B) the bark removed exposing the frass in the serpentine feeding gallery. The ~2-year-old red maple trees were culled from in-field production rows at a middle Tennessee nursery. (Photos taken by Aubree Morrison)*

Figure 3

Tupelo borer (Aegomorphus morrisi (Uhler)*) A) adult and B) larva that were recovered from infested tupelo (Nyssa sylvatica* Marshall*) trees harvested from field production rows in a middle Tennessee nursery. Adults were observed walking on a tupelo tree branch and larvae were dissected from galleries beneath splitting bark evident on ~3-year-old trees. (Photos taken by Aubree Morrison)*

Figure. 4.

Tupelo borer signs of damage with cracked bark and coarse frass protruding out the exit hole. The tupelo trees came from a middle Tennessee nursery. (Photos taken by Aubree Morrison)

Figure 5

Flatheaded borer larvae visible inside its pupal chamber following trunk splitting and before removal for measuring and placement on artificial diet for rearing to the adult stage. (Photos taken by Aubree Morrison)

Figure 6

*Tree cages made from aluminum insect screen to determine emergence timing of adult flatheaded borer species between April and June 2021 on red maple trees at a Middle Tennessee nurs*ery. *(Photos taken by Aubree Morrison)*

Figure 7

Photos of A) flatheaded borer attacked trees that were felled and cut into 30-cm long pieces and B) pieces of trees that were placed in sheer cloth bags and left under a carport on a plastic shelving unit for adult emergence. (Photos taken by Aubree Morrison)

Figure 8

Photos of flatheaded borer purple sticky prism trap plots treated with A) Scythe herbicide (formulated as pelargonic acid [57%] and related fatty acids [3%]) mixed at 72.9 ml / liter (7% solution) B) mowed vegetation, C) standard post-emergent herbicide Gly Star 5 Extra (formulated as glyphosate 53.8%) mixed at 15.6 ml product / liter (4% solution), and pre-emergent herbicide Marengo (indaziflam; mixed at 1.1 ml product / liter during February timing, and D) Gly Star 5 Extra and Marengo treatments applied on May, June, or July timings

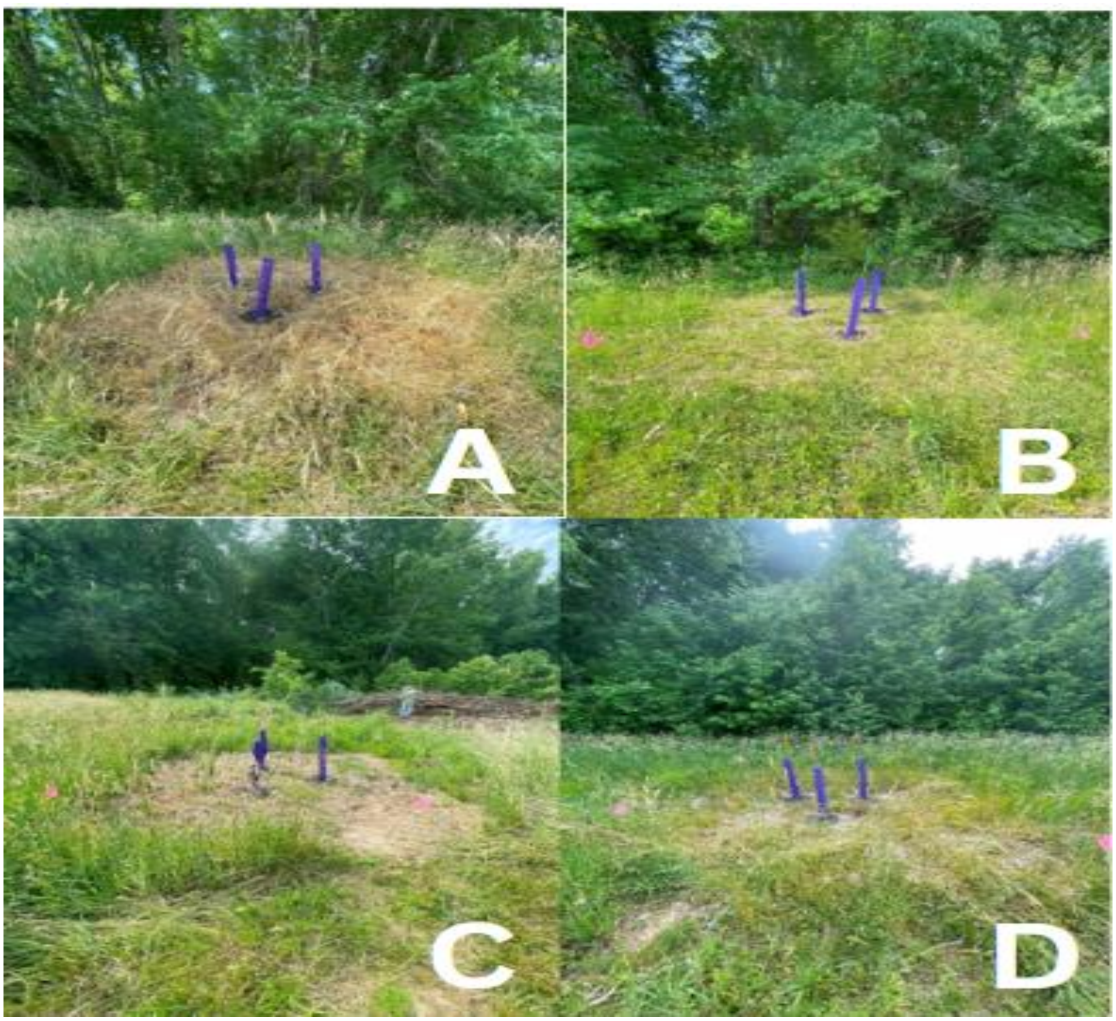


Figure 9

Photo of glyphosate (Gly Star 5 Extra, Albaugh LLC, Ankeny, Iowa [15.6 ml product / liter [4% solution]) and indaziflam (Marengo® at 1.1 ml product / liter; Bayer Environmental Science, Research Triangle Park, NC) treatment applied to a study block during February 2021.

Figure 10

Photo of a study block for containerized tree herbicide test 2022. Herbicides glyphosate (Gly Star 5 Extra, Albaugh LLC, Ankeny, Iowa, 15.6 ml product / liter [4% solution]) and indaziflam (Marengo® at 1.1 ml product / liter; Bayer Environmental Science, Research Triangle Park, NC) were applied before trees were moved into treatment blocks.

Figure 11

Photo of nine trees aligned in their field placement orientation in the study block for containerized tree herbicide test 2022. The spacing was 1 m between each container.

Figure 12

Photo of trees on container pad for containerized tree herbicide test 2022.

Figure 13

Induced stress treatments on large maple trees. A) Notched stress treatment occurred by cutting a wedge out of the trunk using a chainsaw. Trees stayed partially alive. B) Felled stress treatment occurred by cutting the tree down 15.2 cm (6 in) above the soil line. Trees fully died by using the felled method. C) Girdled stress treatment occurred by using a girdling knife to girdle the trunk. Trees stayed healthy with this treatment but had cosmetic trunk damage.

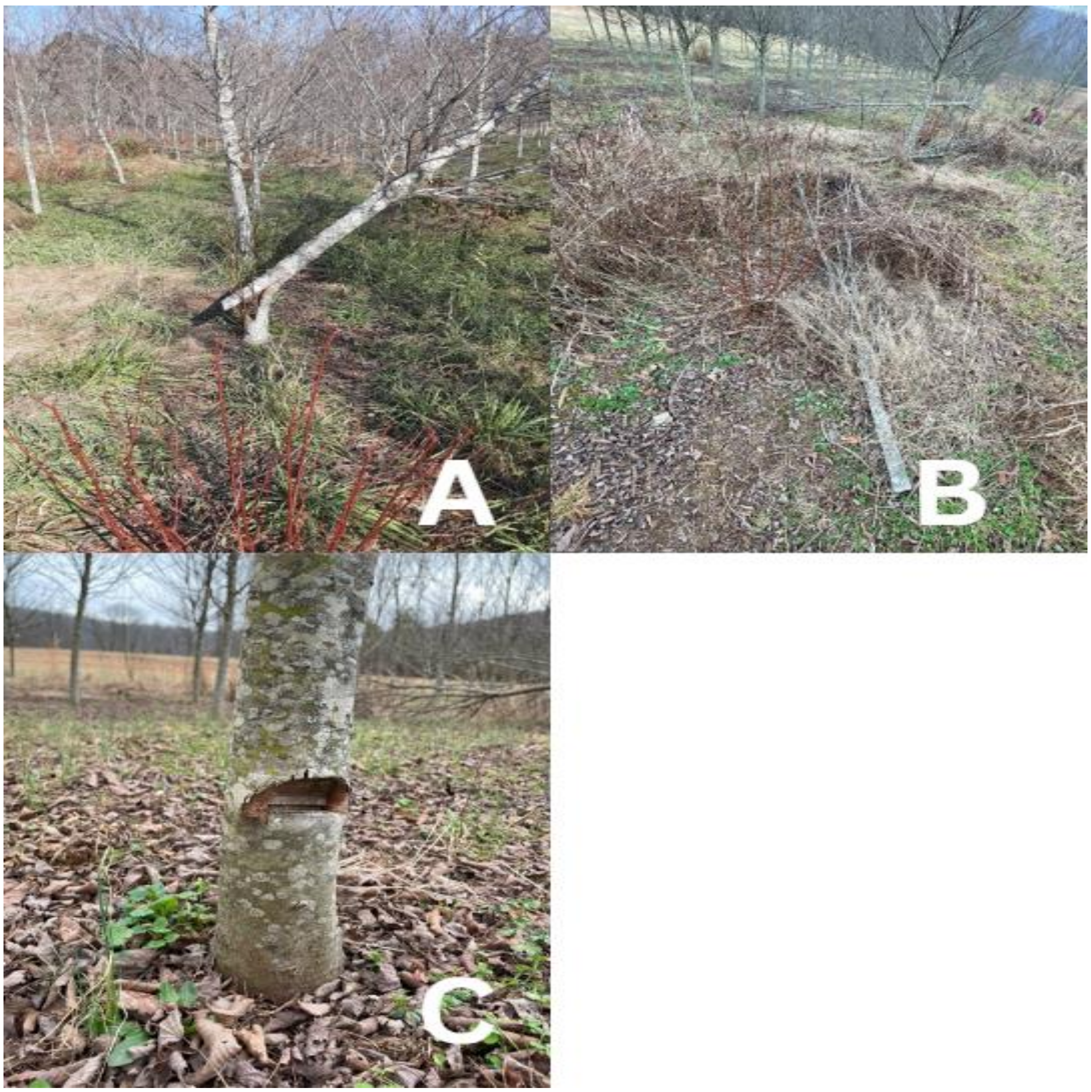


Figure 14

Images of containers with artifical diet housing developing flatheaded borer larvae and tupelo borer larvae. Holes were made in the lids to facilitate air exchange.

Figure 15

Black cross vein traps were used in a longhorn beetle trapping study evaluating different trap lures. Traps were suspended from a steel shepherd's hook and were checked every two days. Insects that were caught were found in the kill basin that was filled with an antifreeze drowning solution. Samples were filtered through a paint filter and brought back to the lab for identification.

Figure 16

The development process of a flatheaded borer larva to adult viewed through artificial diet rearing. A) flatheaded borer larva, B) flatheaded borer beginning pupation process, C) flatheaded borer pupa showing the eyes are the first to darken, D) flatheaded borer pupa showing the mandibles are next to darken, E) flatheaded borer pupa showing the legs and abdomen begin darkening, F) flatheaded borer pupa showing the head and abdomen darkened and G) flatheaded borer adult.

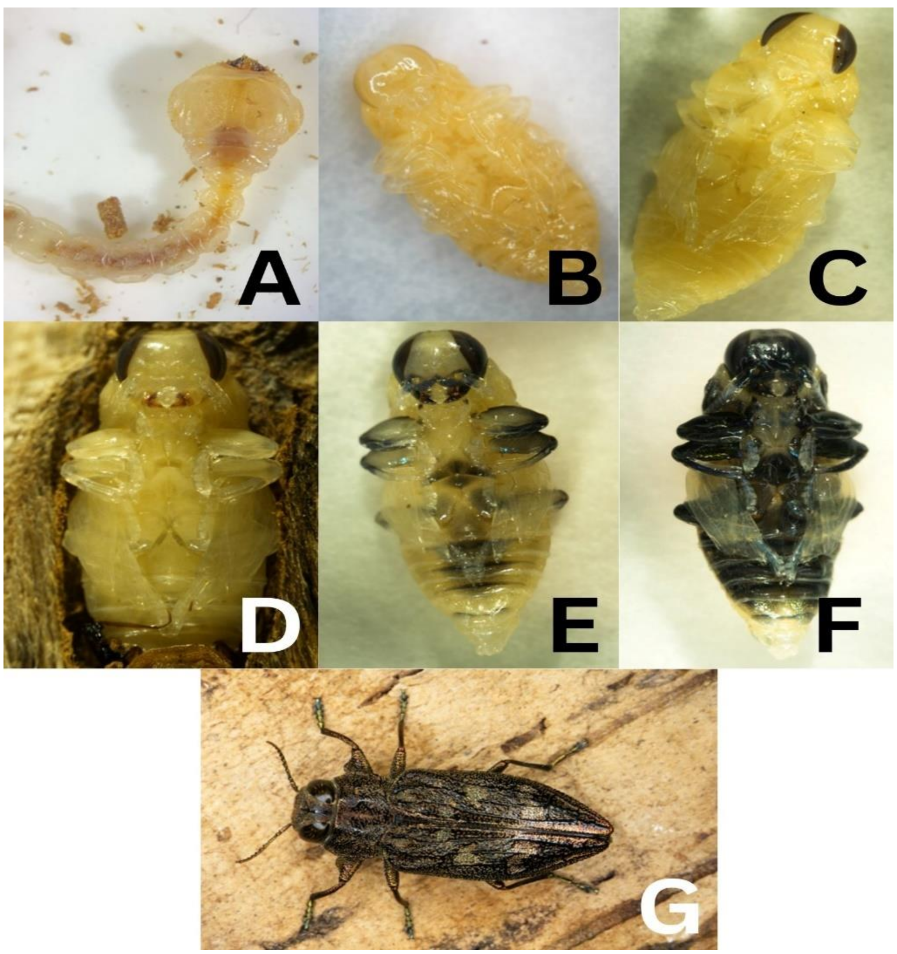
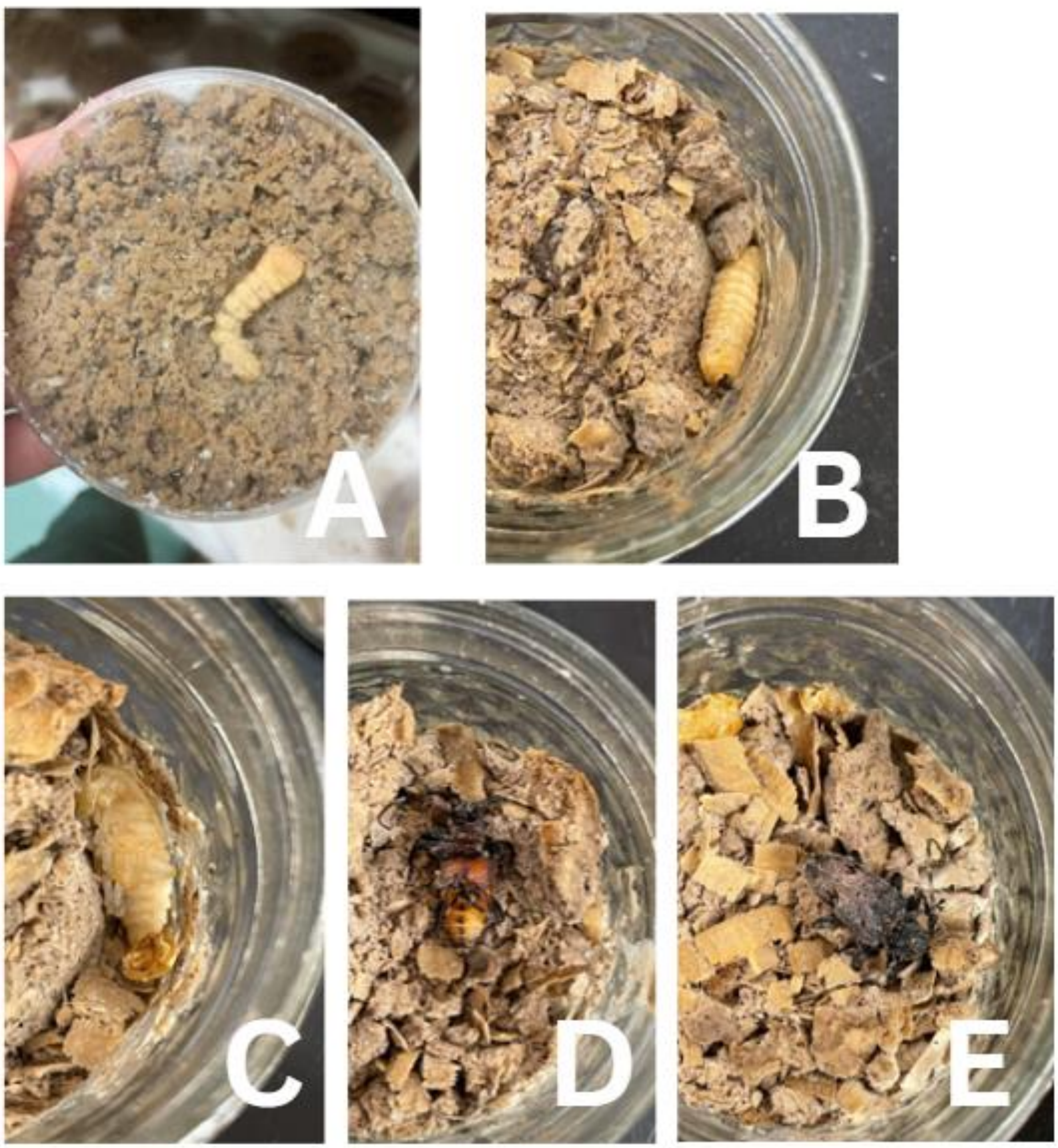


Figure 17

The development process of tupelo borer larva to adult viewed through artificial diet rearing. A) tupelo borer larva in artificial diet, B) tupelo borer larva beginning pupation process, C) tupelo borer pupa, D) tupelo borer pupa in inactive period, E) adult tupelo borer.



Appendices

TSU- 22-106(B)-15c-61065

A newly identified longhorned beetle in Tennessee

TUPELO BORER

Aegomorphus morrisi (Uhler)

By Aubree Morrison, Dr. Jason Oliver, and Dr. Karla Addesso

The Tupelo borer, *Aegomorphus morrisi* (Uhler), is a member of the longhorned beetle family Cerambycidae (Coleoptera) and is native to North America. This beetle species has recently been found to cause external and internal trunk damage and death to black gum trees in three Tennessee nurseries. This discovery is the first documentation of the tupelo borer occurring in Tennessee.

Photo 3.
Adult Tupelo borer,
Aegomorphus morrisi (Uhler)

How to Identify

Adult Tupelo Borer Beetles

Adult beetles have large bodies (~0.8 to 1 inch long). The beetles have long antennae that are equal to or slightly longer than their total body length. Although beetle coloration may vary, the adult beetle will always have a distinctive M-shaped black marking on its lower, outer wing covering, or elytra **(Photo 3)**. Adult beetles also have an alternating dark and colored pattern that is evident on the antennae and legs.

Identifying Tupelo Borer Larva

Larvae of A. *morrisi* can be found beneath the bark of infested host trees. Larvae have short, dark mandibles. Their soft, cream-colored bodies are 1 to 2 inches long and have large spiracles that run down the length of their abdomen **(Photo 4)**. Larval bodies are covered in coarse to velvety hair-like structures called setae. The first several larval body segments (i.e., regions of their thorax) are the same width as the rest of the body, which has led to this larval characteristic contributing to the common name for the group, collectively called roundheaded borers. By way of comparison, flatheaded borers are another group of wood-boring beetle larvae that also may be found beneath the bark and within the sapwood of some nursery trees. Flatheaded borer larvae may grow up to about 1 inch long and have several enlarged body segments (i.e., thorax) behind the darkened mandibles on the head, which gives them their "flattened head" appearance **(Photo 5)**. At this time, tupelo borer larvae cannot be reliably identified to species on the basis of their morphological characteristics, therefore, adult beetles are needed for proper species identification

Photo 4.
Tupelo borer larva with the first several body segments, the thorax, equal in width as the rest of the body.

Photo 5.
For comparison, a flatheaded borer larva with the first several body segments, the thorax, enlarged relative to the rest of the body.

Tupelo Borer Biology

Adult beetles emerge in mid-June (Craighead 1923). Female beetles deposit eggs on the lower trunks of living black gum or water tupelo saplings (typically ~3 to 5 inches in trunk diameter) (Craighead 1923, Lugger 1884). The larvae feed in the phloem and cambium just below the bark, excavating a feeding gallery. The larvae then bore into the sapwood and heartwood, to create their pupation chambers. The new adults will emerge through a round dime-sized exit hole on the bark in late spring or early summer. The life cycle of this borer species is estimated to require 2 years or longer to transition from egg to adult. Additional monitoring efforts are underway that are expected to inform our understanding of the life cycle and larval behavior of A. *morrisi*.

Geographic Distribution of Tupelo Borer in North America

The tupelo borer, A. *morrisi*, has been reported only from a few widely scattered areas in the eastern United States: Arkansas, Alabama, Florida, Mississippi, Missouri, Pennsylvania, and South Carolina (Holt 2013, Solomon 1995). This species also has been documented in eastern Canada (Solomon 1995). A survey of longhorned beetles collected during more than 15 years of regional trapping efforts, as well as an examination of multiple university and museum collections, did not yield specimens of A. *morrisi* that were collected in TN (Klingeman et al. 2017). Since that report, adult tupelo borer and their larvae also have been collected from managed landscapes and nurseries in middle Tennessee.

Figure 1.
States reported by Solomon 1995 and Holt 2013 to have tupelo borer, *Aegomorphus morrisi* (highlighted in gray), and now Tennessee (highlighted in black).

Host Tree Distribution

Tupelo borer is reported to attack black gum **(Figure 2)** (*Nyssa sylvatica Marshall*; also called black gum or black tupelo) and water tupelo **(Figure 3)** (*Nyssa aquatica* L.) (Solomon 1995). Black gum has the widest U.S. distribution among *Nyssa* species and is a common forest and cultivated nursery tree. Black gum has vibrant red fall colors with various hues of orange, yellow, and purple. This tree species typically have few pest and disease issues, which makes it a favorable, low-maintenance landscape tree. All tupelo species vary from tolerant to very tolerant of wet conditions, also making them favored ornamental plants for wet landscape locations. Tupelo borers are also likely to attack other *Nyssa* species, including swamp tupelo **(Figure 4)**(*Nyssa biflora Walter*), and ogeechee tupelo **(Figure 5)**(*Nyssa ogeche Bartr. ex Marsh.*; also called bee-tupelo, ogeechee-lime, sour tupelo-gum, or white tupelo). To date, however, there are no literature reports about attacks on these tree species.

Figure 2.
Nyssa sylvatica Ma.
(black tupelo) range.

Figure 3.
Nyssa aquatica L.
(water tupelo) range.

Figure 4.
Nyssa biflora W.
(swamp tupelo) range.

Figure 5.
Nyssa ogeche B.
(ogeechee tupelo) range.

Photo 6. Tupelo borer damage

Tree Injury and Damage

Larval damage by A. *morrisi* results in feeding and gallery excavation-related damage that occurs leaving small to large areas of loosened bark. Sometimes coarse frass may be observed protruding from bark openings **(Photo 6)**. Removing the loose bark will often reveal a large irregular cavity (~2 to 3 inches in diameter) that is packed with fibrous frass. Splitting the wood of an infested tree may reveal the larval feeding gallery and pupation chamber beneath the bark. Depending on the age of the wound, the gallery may vary in size and have a circle-shaped exit hole if the adult already has emerged. Bark scars resulting from previously healed attacks will consist of rather large patchy scars with a small round scar directly above. Attacks have been documented on trunks from ~ 2 to 5 inches in diameter and at heights from ground level to about 6 feet high. The extent to which tupelo borer may become a widespread and established pest problem in nurseries and landscapes has yet to be determined. Only three Tennessee nurseries have reported severe damage, and these instances comprise the first report of this species in Tennessee.

Options for Managing Tupelo Borers in *Nyssa* Host Plants

Although the available literature (Solomon 1995) indicates that tupelo borer beetles can be managed with pesticide sprays or injections into galleries, no insecticide active ingredients have been specified. Trunk injections would be impractical for nurseries due to potential damage of the application method to the trunk, as well as because of the large number of tree specimens involved. Some systemic insecticides (e.g., imidacloprid) may be useful if applied before infestations begin. Trunk sprays of non-systemic insecticides like bifenthrin (e.g., Talstar, OnyxPro), lambda-cyhalothrin (e.g., Scimitar), permethrin (e.g., Perm-Up), chlorpyrifos (e.g., Dursban), etc., could provide control if applied to the full trunk during the adult flight period that begins about mid-June. However, management of the borer with trunk sprays may be minimal after the larva has entered the tree. Trees in nursery production blocks that are already infested no longer represent high-quality salable commercial stock. These infested trees should be culled, removed from the production area, and then chipped, burned, or deep-buried to reduce the threat of infestation of future nursery trees.

What other pest might be attacking my *Nyssa* trees?

Ambrosia Beetles:

The applewood stainer **(Photo 7)**, black twig borer **(Photo 8)**, and yellow-banded timber beetle **(Photo 9)** are all small ambrosia beetles (~1/16 to 1/8 inches [2-3 mm]). Their damage creates small circular entrance holes (shot holes) on the surface of the tree trunk **(Photo 10)** and small tunnels in the tree's interior wood, which are easily distinguishable from the extensive sub-surface tunneling damage caused by the tupelo borer.

Photo 7.
Applewood Stainer Beetle
Monarthrum mali [Fitch]

Photo 8.
Black Twig Borer
Xylosandrus compactus [Eichhoff]

Photo 9.
Yellow-Banded Timber Beetle
Monarthrum fasciatum [Say]

Photo 10
Ambrosia beetle damage of small circular entrance holes (shot holes) on the surface of the tree trunk

Clearwing Moths:

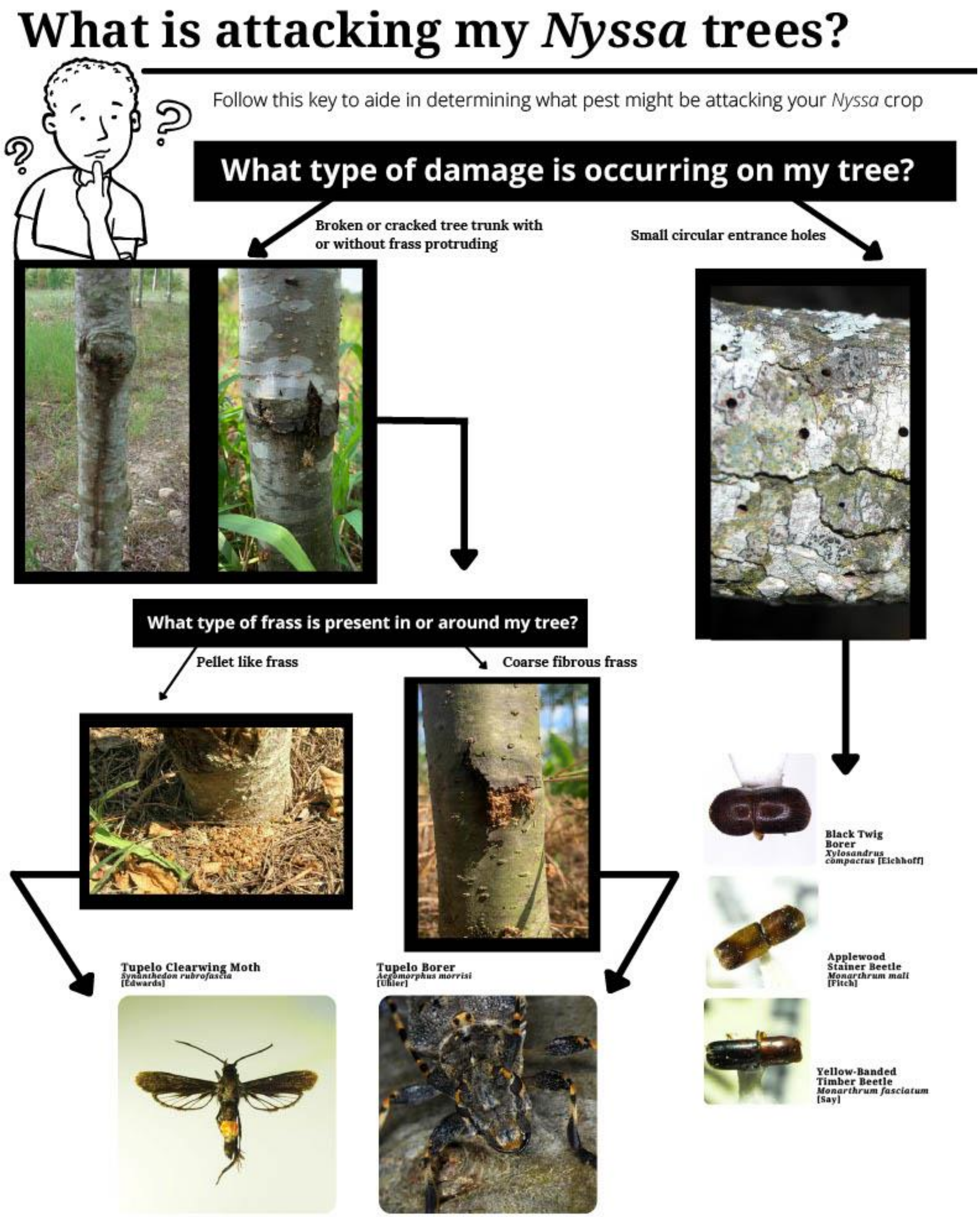
The tupelo clearwing moth **(Photo 11)** could cause sub-surface tunneling damage that could be confused with the tupelo borer. However, the excrement of clearwing borers is typically "pellet-like", and is distinct from the fibrous and string-like excrement of the tupelo borer. Clearwing borer larvae also may leave silk intermixed with the excrement. Clearwing borer larvae also have narrower and less robust bodies than the tupelo borer **(Photo 12)**, and the fleshy prolegs on the abdomen will have crochets on the tips **(Photo 13)**, which are visible with a hand lens. Only moth and butterfly larvae have crochets, so beetle larvae like the tupelo borer will not have crochets on the abdomen.

Photo 11
Tupelo Clearwing Moth
Synanthedon rubrofascia [Edwards]

Photo 13
Crochets found at the tips of the larvae's fleshy prolegs

Photo 12
Larvae of a tupelo clearwing moth with a narrower and less robust body than tupelo borer

BORER MANAGEMENT IN NURSERY



All photos were taken by Aubree Morrison & Jason Oliver

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Funding Support
Funding for this work was supported by Tennessee State University.

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