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Progression of Sugarberry (*Celtis laevigata*) Dieback and Mortality in the Southeastern United States

Emilee M. Poole, Michael D. Ulyshen, Scott Horn, Patrick Anderson, Chip Bates, and Chris Barnes

Emilee M. Poole (emp66194@uga.edu), Department of Entomology, University of Georgia, Athens, GA 30602, USA. Michael D. Ulyshen (michael.d.ulyshen@usda.gov) and Scott Horn (scott.horn@usda.gov), USDA Forest Service, Southern Research Station, Athens, GA 30602, USA. Patrick Anderson (panderson@treecarescience.com), Rainbow Treecare Scientific Advancements, Minnetonka, MN 55343, USA. Chip Bates (cbates@gfc.state.ga.us), Georgia Forestry Commission, Statesboro, GA 30641, USA. Chris Barnes (cbarnes@gfc.state.ga.us), Georgia Forestry Commission, Dry Branch, GA 31020, USA.

Abstract

The southeastern United States has been experiencing unexplained sugarberry (*Celtis laevigata*) mortality for over a decade, representing one of the most severe and widespread *Celtis* mortality episodes ever reported from North America. Here we describe external symptoms, progression of mortality, and the known geographic extent of the problem. More than half of all trees monitored at one site within the affected area died over five years of observation. Although many trees died within a year of first exhibiting symptoms (e.g., small yellow leaves, branch dieback, premature leaf fall), many others continued living for years after becoming symptomatic. A preliminary insecticide trial found no improvements in survivorship among trees treated with insecticides, emamectin benzoate and imidacloprid, relative to control trees. Our findings suggest the problem will likely continue and become more widespread in the coming years.

Study Implications: Sugarberry mortality in urban and forested environments is an ongoing problem that has the potential to spread throughout the southeastern United States and perhaps more widely, depending on the susceptibility of other native *Celtis* species. Many trees die within a year of first showing external symptoms, whereas others can live for many years after appearing symptomatic. Declining trees in rights-of-way and public spaces are presenting costly hazards to cities, and canopy gaps in natural areas are likely to facilitate the establishment and spread of invasive plants. Studies aimed at determining the cause of this problem are urgently needed.

Keywords: forest health, tree mortality, native species

Forests have experienced major changes in community composition over the past century as many tree species have been devastated by introduced pests and diseases. The number of dominant and codominant species affected raises questions concerning the cascading effects of reduced or eliminated individual taxa. For example, *Castanea* Mill. and *Ulmus* L. both suffered devastating mortality in North America and

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Europe from the pathogens causing chestnut blight (*Cryphonectria parasitica* Murr.) and Dutch elm disease (*Ophiostoma ulmi* Buism and *O. nova-ulmi* Moreau), respectively (Schlarbaum 1998). China has lost more than 10 million pines from red turpentine beetle (*Dendroctonus valens* LeConte), since its introduction in the 1990s (Li et al. 2020). Similarly, extensive losses of *Tsuga* from hemlock woolly adelgid (*Adelges tsugae* Annand) and *Fraxinus* L. from emerald ash borer (*Agrilus planipennis* Fairmaire) continue in North America. Although the movement of organisms through international commerce is responsible for many of these challenges, eruptions of native pest species can also cause major mortality events (Haavik et al. 2012). Moreover, climate change represents a growing threat to tree health throughout much of the world (Allen et al. 2010) and may further facilitate pest outbreaks (Gandhi and Herms 2010, Bao et al. 2020). Widespread mortality of individual tree species affects forest structure, species composition, competition with invasive plant species, and ecosystem processes. Disentangling the influences of biotic and abiotic factors in the development of these dieback or decline scenarios is becoming increasingly important (Cobb 2010, Sackett et al. 2011).

Because periodic tree mortality is not uncommon, more serious emerging problems can go unnoticed for many years. For example, it is thought that emerald ash borer arrived in North America as early as 1997 (Siegert et al. 2014), about five years before it was first detected. Since there is a much better chance of controlling such threats before the problem has become widespread, it is important to investigate unexplained tree mortality in its early stages. Documenting patterns of stressed and dying trees is an important step in understanding the severity and scope of a new problem (Siegert et al. 2014). As episodes of mortality commonly begin at a small scale and spread slowly, emerging forest health issues can easily go unnoticed for a long time (Larson et al. 2015, Gonzalez-Akre et al. 2016). Long-term monitoring allows a descriptive narrative as well as an opportunity to document small changes in tree health and mortality over time. Such studies provide a transcribed record of tree conditions and are pivotal in discerning between natural variation in tree health and indications of a larger problem. Patterns revealed from monitoring data can also be helpful in determining the cause(s) of mortality.

In this article, we report results from a long-term monitoring effort focused on unexplained *Celtis* mortality in the southeastern United States. Episodes of *Celtis* L. mortality or dieback are not uncommon, and numerous instances have been reported over the last 75 years in Europe and North America (Table S1). Although most events were brief and thought to be caused by physical damage, environmental stress, or temporary eruptions of native pest species, more protracted episodes of mortality have also been reported. In Europe, European hackberry (*C. australis* L.) decline has been reported since 1949, and several pathogens (phytoplasma and fungi), as well as their interactions with insect damage and drought, have been implicated in recent mortality events (Bertaccini et al. 1996, Linaldeddu et al. 2016). The worst episode of *Celtis* mortality reported previously from North America occurred in Louisiana between 1988 and 1990, where an estimated 3 million acres were affected. During the same time period, Mississippi reported similar symptoms (Solomon et al. 1997). A specific cause was not identified in that study, although a small nonnative psyllid (a sap-sucking insect) was suspected to play a role in the mortality.

The current episode of *Celtis* mortality underway in the southeastern United States is among the most severe ever to be reported in North America. Based on observations of dead and dying *C. laevigata* (hereafter sugarberry) from Columbia, South Carolina 34°1’48”N 81°0’0”W, in 2009 (A. Boone 2009, pers. commun.), this problem has been developing and expanding for at least 10 years (Figure 1). To our knowledge, mortality is currently limited to sugarberry, one of six *Celtis* species native to North America.

Sugarberry is a large tree common to riparian forests, reaching 24–30 meters and living for an average of 150 years (Tirmenstein 1990, Samuelson and Hogan 2003, Duncan and Duncan 2000). This species is typically considered an early colonizer of disturbed sites, and pure stands can occasionally be found (Ford and Van Auken 1982). The berries provide mast to numerous bird species, small game, and deer, and several butterfly species use it as a host plant. Although riparian areas are listed as historical habitats, sugarberry is now routinely found in urban areas where they serve as shade trees in parks, yards, streetscapes, fencerows, and more xeric sites. Although not widely used for timber, sugarberry is valued for pulp production (Tirmenstein 1990, Duncan and Duncan 2000). As mortality continues to expand into new areas, there is a great need for information on patterns of dieback and mortality as well as the geographic extent of the problem.

Herein, we describe the pattern of unexplained sugarberry dieback and mortality in the southeastern

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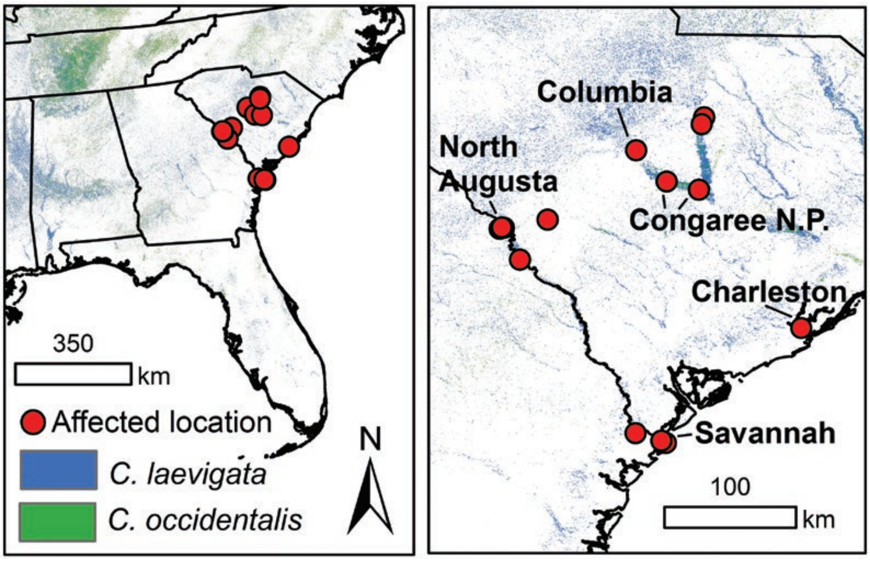

Figure 1. Locations in South Carolina and Georgia known to be experiencing particularly high levels of sugarberry mortality. Areas shaded in blue and green reflect the distributions of *Celtis laevigata* (sugarberry) and *C. occidentalis* (hackberry), respectively.

United States based on five years of observations from a site representative of other symptomatic areas (Figure 1). Our objectives are to document patterns of dieback and mortality over five years of observation and observe the efficacy of systemic insecticide treatments targeting two species of insects found feeding on weakened trees.

Methods

Long-Term Monitoring

Beginning in October 2015, we established a long-term monitoring site at a single location (33°29’24”N 81°58’48”W) bordering the Savannah River in North Augusta, South Carolina. The site was centered on the neighborhood of Hammond’s Ferry, which is encircled by a paved trail (hereafter referred to as the Greenway). The Greenway passes through a variety of habitats including mulched landscape beds containing trees along the river to forested uplands adjacent to the floodplain. The climate of this region is subtropical with an average annual temperature of 17.7°C and an average annual rainfall of 1.1 m (usclimatedata.com; last accessed June 2020). Forests along the Greenway are dominated by sugarberry, often making up 70–80% of the canopy, and additional trees present in the canopy include *Acer negundo* L., *Liquidambar styraciflua* L., *Pinus taeda* L., *Platanus occidentalis* L., *Prunus serotina* Ehrh., *Quercus nigra* L., and *Quercus phellos* L.

It was clear based on our initial observations that our study area had experienced severe sugarberry mortality for several years, with conspicuous clumps of dead trees, trees that had already fallen, and many living trees that were clearly stressed. At the time of our initial visit (October 2015), almost all dead and dying trees were sugarberry. Regardless of setting and proximity to the river, sugarberry in all environments along the Greenway showed the same symptoms of small yellowing foliage, crown thinning, and branch dieback. Despite being late in the season, some trees had dropped their foliage and were putting out new growth. Although many trees showed worsening symptoms, some healthy trees with full canopies and dark green leaves were also present.

In October 2015, we selected a total of 131 trees ranging widely in size (11–69 cm in diameter) for our long-term monitoring of dieback and mortality and labeled each with a uniquely numbered aluminum tag. Although all trees that could be relocated were used to assess mortality after five years, a subset of these trees (n = 72) was used for monthly monitoring over a three-year period (2016–2018). The trees selected for monthly observations were also randomly assigned to one of four insecticide treatments (see below). To monitor sugarberry canopy conditions over time, each tree was evaluated with a crown class rating system adapted from Solomon et al. (1997). The rating categories are as follows (Figure 2): (1) no discernable crown loss, (2) <10% crown loss, (3) 11–33% crown

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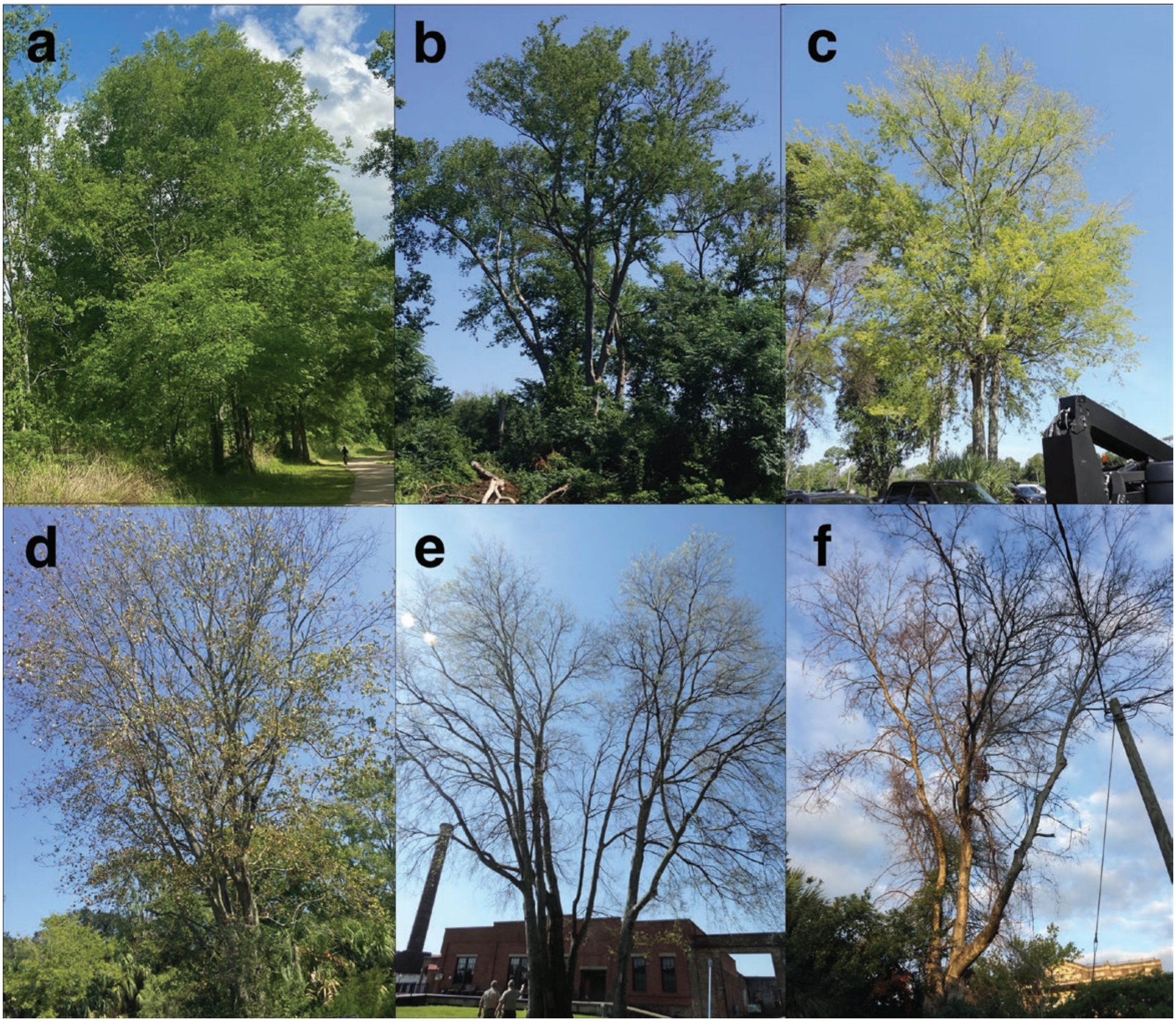

Figure 2. Examples of sugarberry crown ratings: (a) full dark green canopy (rating = 1: no discernable crown loss), (b) green canopy and thin branch tips (rating = 2: <10% crown loss), (c) bright yellow leaves and thin branch tips and branches (rating = 3: 11–33% crown loss), (d) small yellow leaves and thin canopy (rating = 4: 34–66% crown loss), (e) sparse yellow leaves (rating = 5: 67–99% crown loss), and (f) dead (rating = 6). (Photos by E.M. Poole.)

loss, (4) 34–66% crown loss, (5) 67–99% crown loss, and (6) dead. The canopy conditions of trees at the beginning of our monitoring period ranged widely, with 4, 29, 21, 33, and 44 trees receiving initial ratings of 1, 2, 3, 4, and 5, respectively. To understand inter- and intraannual variation in crown conditions, monthly evaluations were conducted by the same individual (M.D. Ulyshen) for three years thereafter (2016–2018). Final mortality was recorded for all tagged trees after five years in September 2020.

Insecticide Trial

During our initial visit in October 2015, two species of insects were attacking sugarberry in large numbers: a native buprestid beetle (*Agrilus macer* Leconte) and a nonnative aphid (*Shivaphis celti* Das). Although we have since determined the beetle is a secondary pest on these trees (Poole et al. 2019) and research on the role of the aphid is currently being conducted, we decided to initiate an insecticide trial at the outset to determine if trees chemically protected from these or other insects experienced lower rates of mortality.

We randomly assigned all 72 trees used in our monthly monitoring to one of four insecticide treatments. Sixteen trees were treated with emamectin benzoate, a compound known to be effective against another *Agrilus* species, emerald ash borer (Smitley et al. 2010). For this treatment, 10 ml of ArborMectin

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was injected per 2.54 cm DBH (i.e., diameter at breast height) using Rainbow Q-connect with a maximum system pressure of 40 psi. For injection points, one 6 mm hole was drilled for every 5.01 cm DBH. Holes were created as low on the root flare as possible to maximize coverage/distribution, and injection depths were 1.91–2.54 cm. After the first ArborMectin treatment on October 22, 2015, no additional treatments were given because of observed damage to the bark of treated trees (M.D. Ulsyhen, unpublished data).

A total of 17 trees were treated with imidacloprid, a chemical known to be effective against a wide variety of insect pests of plants including aphids (Nicholas 2003, Benton et al. 2015). For this treatment, we used Xytect 2F (21.4%) to soil-inject 5 ml of imidacloprid in 250 ml of solution per 2.54 cm DBH with a Maruyama MS75 two-cycle backpack sprayer and Rainbow Treecare Scientific Advancements HTI Soil Injector. Injection sites were evenly distributed around the tree, as close to the base as possible. Sixteen additional trees were treated with both chemicals following the same methods described above. All trees assigned to imidacloprid treatments were treated on the following dates: October 22, 2015; April 3, 2017; and April 22, 2020. The remaining 23 trees were untreated control trees.

Analysis

We used all 131 of the trees selected initially to calculate total mortality after five years. For the 72 trees used in regular monitoring, we calculated percentage mortality and average canopy rating for each time period. All calculations were made after excluding trees that were felled by the city because of safety concerns and before we could confirm mortality. We calculated average canopy ratings with dead trees included as well as after excluding dead trees. All trees from the insecticide trial were used to describe patterns of mortality over the five-year period.

To compare rates of mortality among the different insecticide treatments, we performed logistic regression with the GENMOD procedure in SAS (Stokes et al. 2000) using the final mortality data collected in September 2020. Our analysis included the following contrasts: treated (any insecticide) versus control, imidacloprid versus other, emamectin benzoate versus other, and imidacloprid versus emamectin benzoate.

To test the reliability of our crown classification ratings, we assessed interrater reliability by calculating Cohen's kappa using the irr package in R (Garner et al. 2019). Two observers (M.D. Ulyshen and E.M. Poole) independently scored the trees monthly from April to September in 2018. Any tree cut down or rated by either observer as a 6 (i.e., dead) was excluded from analysis, resulting in a final data set of 276 observations. Because the data are ordinal, we calculated weighted kappa using squared weights.

Results

Long-Term Monitoring

Symptomatic trees were characterized by thinning canopies, small and chlorotic leaves, and branch dieback (Figure 2). After five years, 36 of the original 131 monitoring trees in North Augusta had been cut down before we could confirm mortality. Of the remaining 95 trees, 51.6% had died. Similarly, of the 72 trees used in regular monitoring, 13 were cut down, and only 49.2% of the remaining trees were still alive after five years (Figure 3). Trees continued dying throughout our monitoring period. Crown ratings generally increased (indicating deterioration of crown conditions) over time, although there was considerable variability in ratings among observation dates. Most notably, crown ratings tended to improve from fall to spring observations, with many trees appearing healthier in the spring compared with the previous fall (Figure 3). Despite seasonal variation in crown conditions, our monitoring data reveals a fairly steady deterioration in crown conditions and increasing mortality over the five years of observation (Figure 3).

The rate at which trees died after first appearing symptomatic (i.e., receiving a crown rating of 3 or higher) was highly variable. Of the 25 trees that first became symptomatic after May 2016 and then died by September 2020, more than half (52%) died within one year of appearing symptomatic. Among these, six (24%) died within three months of first appearing symptomatic. Of the remainder, 32% died within one to two years, 12% died within two to three years, and 4% died within three to four years. Moreover, of the 28 trees that were alive but symptomatic at the end of the monitoring period, all were symptomatic for more than two years, and 28.6% were symptomatic for at least four years.

Insecticide Treatment

Of the 72 trees used in the insecticide trial with regular monitoring, 13 were cut down and removed before we could confirm mortality. We therefore limited our analysis to the remaining 59 trees. After five years, 30 (50.8%) of these trees had died. Based

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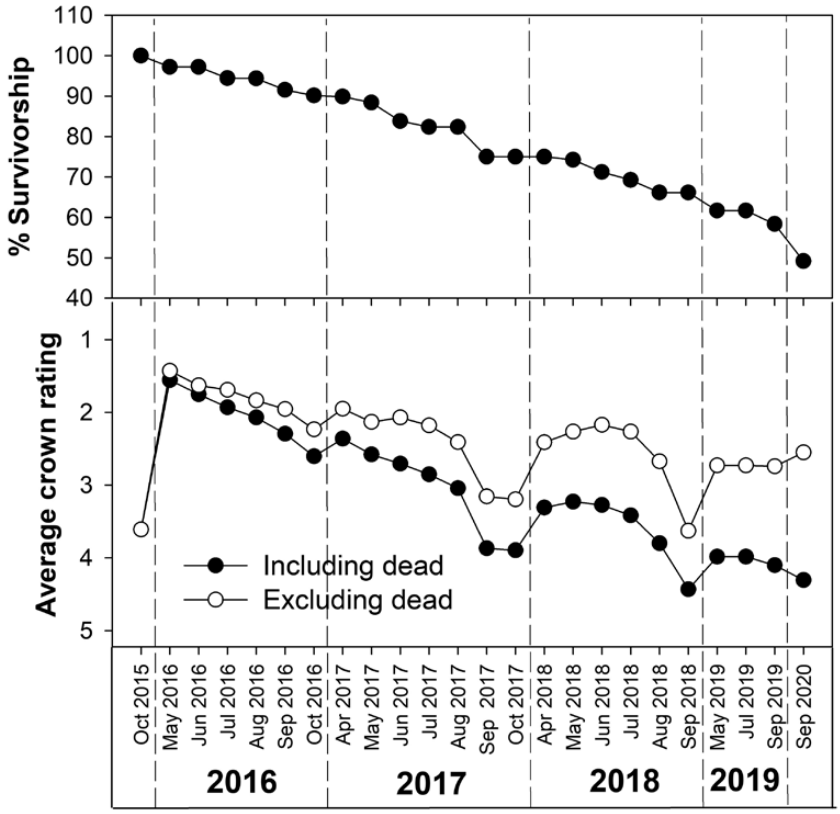

Figure 3. Long-term (2015–2020) monitoring data from North Augusta, SC. Top figure shows percent survivorship over time. Lower figure shows average crown rating of trees, with scores ranging from 1 (completely healthy) to 6 (dead) (see "Methods"). Trees that were cut down before we could confirm mortality were not included in these calculations. Average ratings were calculated both including and excluding dead trees (black and white symbols, respectively). Vertical dashed lines separate calendar years.

on logistic regression, mortality did not differ among the four treatments ($X^2[3, n = 59] = 1.02$, $p = 0.80$). Moreover, mortality did not differ between treated (any insecticide) versus control ($X^2[1, n = 59] = 0.01$, $p = 0.94$), imidacloprid versus all other treatments ($X^2[1, n = 59] = 0.57$, $p = 0.45$), emamectin benzoate versus all other treatments ($X^2[1, n = 59] = 0.57$, $p = 0.45$), or imidacloprid versus emamectin benzoate ($X^2[1, n = 25] = 0.99$, $p = 0.32$).

Interrater Reliability

Our assessment of interrater reliability resulted in a Cohen's weighted kappa of 0.85 ($z = 14.4$, $p = 0.0$), indicating significantly better agreement than expected by chance.

Discussion

The southeastern United States is currently experiencing one of the most severe, protracted, and extensive episodes of *Celtis* mortality ever reported from North America. The problem has been ongoing for at least 10 years and is now affecting large parts of Georgia and South Carolina. Although the mortality data reported here come from just a single site, these patterns appear consistent with what we have observed throughout the affected area. Over five years of observation, at least 51.6% of our monitoring trees died. If we assume the additional hazardous trees removed by the city had or would have also died, the mortality over this period of time would be close to 65%. By the end of this monitoring period, the crown conditions of the remaining trees continue to deteriorate, and mortality shows no sign of slowing.

Based on our canopy class ratings, trees were highly variable in terms of how quickly they died after first becoming symptomatic. Although some died within just a few months, others were still alive after being symptomatic for several years. Continued monitoring will be required to determine if complete recovery is possible for affected trees, particularly when neighboring trees have died, potentially reducing competition for those remaining (Zhang et al. 2017). Only one of our monitoring trees exhibited notable improvement over

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our observation period. After receiving ratings of 3–4 throughout 2016 and 2017, it was rated as 2 in 2018 and 2019. That tree was covered in *Agrilus macer* egg masses in October 2015 and was one of the trees randomly assigned to the emamectin benzoate and imidacloprid treatment. Although it is possible the tree benefited from the insecticide treatments, untreated trees have been shown to recover after being heavily attacked by *A. macer* (Poole et al. 2019). The fact that certain trees are capable of rallying a defense, at least temporarily, after being stressed enough to be attacked in high numbers by a secondary pest, offers some hope of recovery for a small subset of affected trees.

The worst mortality episode previously reported for any *Celtis* species in North America occurred in Louisiana in the late 1980s and early 1990s (Solomon et al. 1997), about two decades before mortality was first noticed in Columbia, South Carolina. Based on the images provided by Solomon et al. (1997), the symptoms observed in that incident were dissimilar to what we observed in this study. Symptomatic sugarberry trees in Louisiana were characterized by severe dieback from branch tips and the extensive production of epicormic shoots, whereas we observed more uniform crown thinning and epicormic shoots were rare. Solomon et al. (1997) concluded a small nonnative insect, *Tetragonocephala flava* Crawford, was the most likely cause of mortality. This psyllid has piercing-sucking mouthparts and damage from this type of insect is often from probing damage caused by feeding, the excretion of honeydew which results in sooty mold growth on leaves, or virus transmission. However, we have not observed that species at any of our study sites.

Because all trees appear susceptible regardless of their size and location, it seems likely an insect or disease is contributing to the observed mortality. None of the insecticides tested in this study improved tree survivorship, however, suggesting the mortality may not be driven by insects. Because recent work concluded the native buprestid beetle, *A. macer*, is a secondary pest on sugarberry (Poole et al. 2019), the inefficacy of emamectin benzoate is not surprising. An ongoing study shows imidacloprid is effective at controlling the Asian woolly aphid (*S. celti*) under controlled conditions (unpublished data, E.M. Poole), which often attacks sugarberry in large numbers throughout our study area. The fact that the three imidacloprid applications administered in this study did not improve survivorship suggests aphids may not be contributing significantly to the observed mortality. However, it is possible that more frequent applications were needed to provide adequate protection in this study, especially considering the potential for reduced uptake by stressed trees. Populations of *S. celti* build up over the season and can be an obvious source of stress to trees by late summer. In addition to the impact of aphid feeding on sugarberry foliage, the production of honeydew results in thick layers of sooty mold forming on leaves, which appears to be associated with premature leaf fall (E.M. Poole, pers. observation). Although it is possible that *S. celti* is playing an important role in this situation, additional work is underway to clarify the extent of the stress and damage from aphids.

Since the cause of mortality remains unknown, it is currently not possible to determine exactly when areas first became affected or how quickly the problem is spreading throughout the Southeast. However, we do know that unusual sugarberry mortality was first noticed in Columbia, South Carolina, and Savannah, Georgia, in 2009 (A. Boone 2009, pers. commun.) and 2019 (C. Bates, pers. observation), respectively. These cities are approximately 200 km apart, suggesting a considerable rate of expansion. The patterns of mortality observed in these areas are consistent with those reported here from North Augusta and presumably share the same cause(s). We suspect the problem has reached far beyond the areas depicted in Figure 1. For example, we observed considerable sugarberry dieback and mortality in Columbus, Georgia (~230 km west of Savannah) in the summer of 2020 (E.M. Poole, pers. observation). Since sugarberry is found throughout the southeastern United States, this problem has the potential to spread over large areas, which indeed could already be occurring unnoticed. If other species of *Celtis* are also susceptible, it could become a forest health challenge throughout much of North America.

The loss of sugarberry from southeastern forests and cities will have many negative ecological and economic impacts. In addition to being an important tree to wildlife, the loss of these trees will likely exacerbate the spread and dominance of invasive shrubs (e.g., *Ligustrum sinense* Lour.) in the understory. Moreover, much like other tree mortality events (Kovacs et al. 2010), communities are likely to incur high costs to remove threats posed by dying sugarberry trees. For example, an estimated 813 sugarberry trees were removed by the city of North Augusta since 2015, accounting for 45–86% of all trees removed yearly from 2015 and 2020. The costs of these removals amount to more than $400,000, at the rate of $500 per tree removal (R. Kibler 2020, Superintendent of Property

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Maintenance–North Augusta, pers. communication). Such considerations underscore the importance of ongoing efforts to identify the cause(s) of this mortality and develop management strategies.

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

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