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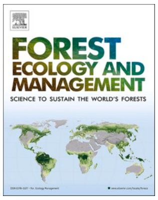

Evaluating effectiveness of girdle-herbicide containment of below-ground spread of oak wilt (*Bretziella fagacearum*)

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ABSTRACT

Oaks (*Quercus* spp) are one of the most important sources of timber, mast for wildlife, and ecosystem services across the eastern US. Increasingly, this genus is at risk from diseases including oak wilt, which is one of the most serious threats to oaks, caused by the fungus, *Bretziella fagacearum*. The upper Midwest has over 5 million ha of oak forests, much of which is on rocky glaciated soils where traditional methods of containing below-ground spread of oak wilt (e.g., vibratory plow lines) are not feasible. We evaluated an alternative containment method of girdling and herbicide (GH) of oak wilt infected trees as well as neighboring oak trees likely connected via root grafts. Our results demonstrated that GH was effective at controlling below-ground spread of oak wilt (overall success rate: 55 %). Best control was achieved when infection centers were small ($\leq$4 newly infected trees), where GH was 81 % effective at containing oak wilt. Containment was only 29 % in larger infection centers ($\geq$5 newly infected trees). The best predictor of success was the number of newly infected trees ($p = 0.02$) even when considering other factors that could dictate the size of infection centers (e.g., diameter of trees, or number of neighboring trees treated). Our results illustrate the importance of early and rapid management of oak wilt infections and offer a starting place for continued improvement of the GH methodology.

1. Introduction

The importance of oak (*Quercus* genera) to forests of the northeastern United States is difficult to overstate. In the eastern United States (US), oak forest types represent 45 % of growing stock volume and are some of the most economically valuable forests (Smith et al., 2009; Dey, 2014). Oaks are also considered to be keystone species (genus), making a strong contribution to community structure, key processes, and having disproportionate effects on other species (Fralish, 2002). Increasingly, forest management considerations have expanded from issues such as timber production and products, to biodiversity considerations, and now include countering anthropogenic sources of atmospheric carbon. Forests are one of a few large terrestrial opportunities to sequester anthropogenic carbon emissions and thereby slow the pace of climate change (Ridder, 2007; Bonan, 2008). It is estimated that oaks sequester more carbon than any other woody group in the continental US (Kossoy et al., 2015; Cavender-Bares, 2016) thus their management has implications for ecosystem services well beyond potential gains from afforestation or reforestation efforts (Palmer, 2021).

Oaks have been projected to increase in eastern US forests with a warming climate (Iverson et al., 2019). Counter to climate change projections, there is what has been described as an impending crisis in the decline of oaks in hardwood forests across North America (Lorimer, 1993; McShea et al., 2007). Declining oak abundance and distribution has been evident since the early 20th century due to a combination of factors including fire suppression, increased deer browse, and introduced diseases and pathogens (Abrams, 2003; McShea et al., 2007). Significant and widespread oak declines (reduced density and importance values) include white, northern red, and black oaks (*Quercus alba, rubra, velutina* respectively, Fei et al., 2011). In southern Wisconsin, red and black oaks (*Q. rubra*, *Q. velutina*) have declined nearly 50 % since 1950 (Rogers et al., 2008) and are predicted to decline further in the next generation of canopy trees (Taylor and Lorimer, 2003). Oaks are not regenerating due, in part, to a lack of disturbance, particularly fire (Abrams, 2005); however, mature oaks are also declining for a variety of reasons including various pathogens (Shifley et al., 2006).

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Maintaining forest resilience, or promoting forest resistance, involves management that promotes the capacity of an ecosystem to absorb disturbances. Disturbances are typically characterized as an episodic phenomenon in a disturbance-recovery paradigm, although disease-caused perturbations are somewhat unique (Menges and Loucks, 1984). Oak wilt (*Bretziella fagacearum*), for example, is one of the most destructive diseases to afflict oaks species in the US because of its ability to kill its host quickly after symptoms first appear (Wilson, 2005) as well as its persistence and ability to spread within stands over long time periods (Wilson, 2001; Juzwik et al., 2008). Oak wilt is a vascular disease that is particularly lethal for trees in the red oak group (section *Lobatae*). Oak wilt is transmitted over land into wounded but otherwise healthy trees by vectors, primarily sap beetles (*Coleoptera: Nitidulidea*), to form infection centers. Symptoms of oak wilt appear quickly after infection, with crown die-back occurring in the early growing season. Throughout the growing season crown die-back becomes more severe, and the symptoms of oak wilt become more apparent. Oak trees typically die within three to eight months after initial infection (Juzwik et al., 2011). Once oak trees are infected with oak wilt, local spread occurs through root grafts (Bruhn and Heyd, 1992); which is the primary means of spread, mortality, and persistence of oak wilt within stands (Juzwik et al., 1985). The disease is currently found in many eastern and midwestern states (Haight et al., 2011) and expected to expand northward with climate change, likely impacting eastern Canada in the next two decades (Pedlar et al., 2020) with potentially profound implications for oaks, oak management, and the myriad of ecosystem services provided by oak forests.

Studies of oak wilt have generally fit into two broad categories: epidemiological studies, including the impact of oak wilt on oaks, and models of the spread of the fungus (Collada and Haney, 1998). However, it has long been recognized that the future of oak wilt control is dependent on research on the effectiveness and comparisons of management techniques (Gillespie, 1971). However, gaps in understanding of effective controls and clarification of regional best management practices to contain oak wilt remain (Koch et al., 2010). Steps to control new oak wilt infections via overland spread, such as preventing wounding of oaks during periods of high susceptibility, have mostly been effective (Camilli et al., 2007). Controlling underground spread; however, is both more difficult and arguably more important; ca. 95 % of new infections are a result of transmission via root grafts (Juzwik et al., 1985). Once oak wilt is established, severing root grafts to prevent underground transmission of the oak wilt fungus is the primary means of control (Koch et al., 2010). Vibratory plows, bulldozers with ripper blades, or backhoes are typically used to disrupt grafted roots or common root systems (Appel, 2001). Placement of lines used to disrupt root grafts must contain all symptomatic as well as asymptomatic trees within root grafting distance of infected trees (Koch et al., 2010). There have been several issues with oak wilt management efforts, but often the most immediate is insufficient resources to adequately address the problem (Wilson, 2005). Tailoring oak wilt management on a site-by-site basis is needed to increase efficacy (Juzwik et al., 2004). This is particularly true in regions where local conditions (e.g., steep slopes, rocky soils) may prevent the use of heavy equipment, availability of heavy equipment is limited/cost-prohibitive, or transportation of heavy equipment to a site is unfeasible.

In Wisconsin, the greatest volume of any major tree species is the red oak group, which contains the greatest above ground biomass (ca. 98 million short tons) and carbon (ca. 59 above and belowground metric tons) of any tree species (Wisconsin Department of Natural Resources, 2018). Oak wilt, while most prevalent in the southern two thirds of the state, is now found in all but seven counties (Wisconsin Department of Natural Resources, 2020) and is responsible for much of the mortality in oak-hickory forests (Juzwik and Schmidt, 2000). As oak wilt continues to spread throughout rocky, glaciated soils in the northern part of the state where vibratory plow and other methods used to disrupt root grafts have more limited applicability, new methods of containment are necessary. Managers throughout this region have already begun experimenting with alternative control methods including modifying well-established vibratory plow containment methods (Bruhn and Heyd, 1992). One example is attempting to contain oak wilt spread by killing both infected and surrounding, apparently healthy trees connected by belowground root grafts, using a combination of girdling followed by applying herbicide to the girdled area. This study aimed to formalize these burgeoning oak wilt control efforts by systematically evaluating the girdle and herbicide containment of oak wilt infection centers, a practice that has become increasingly prevalent in the region.

2. Materials and methods

2.1. Study area & containment treatments

Our study area included an eight-county region of central and northern Wisconsin, USA (Fig. 1). In Wisconsin symptoms of oak wilt crown dieback being to appear in June, but become more apparent by July. We located active oak wilt infection centers from July through October.We selected 42 independent oak wilt infection centers within stands dominated by the northern red oak group ($\geq$60 % red oak group in overstory; *Quercus rubra*, *Q. velutina*, *Q. palustris,* and *Q. ellipsoidalis*) with basal areas > 8.04 meters^2/hectare (35 feet^2/acre). Each selected oak wilt infection center had to be > 500 m from any other known oak wilt infection centers. We collected both bole and branch tissues from all infected trees within each oak wilt infection center. Samples were tested for the oak wilt pathogen, *B. fagacearum,* using culture methods by placing surface sterilized wood pieces on acidified potato dextrose agar and using polymerase chain reaction (PCR) methods. Sequencing was performed by extracting DNA from the band (~280 bp) and *B. fagacearum* DNR sequences were identified with the NCBI BLAST tool through GenBank (Yang and Juzwik, 2017).

Oak wilt containment areas within infected stands were defined based on work from Bruhn and Heyd (1992), which determined the probability of root grafting based on diameters and distances among oak-wilt infected trees and neighboring trees. Bruhn and Heyd provide estimates for a 95 % and 99 % probability that the trees are grafted for both loam (Pemene) and sand (Grayling) soil models. For this study we exclusively focused on the 99 % probability distances and initially (i.e., 2015) used the suitable distance model (loam or sand) based on field soil texture analyses. We used Grayling based distances, for example, for loamy sand and sand, and the Pemene loam distances for sandy loam. However, in 2016, the second year of the study, we used only the Grayling (sand) distance model for all containment areas.

Trees with visible symptoms of oak wilt or trees with vascular cambium that was moist, with streaking and tight bark (evidence that trees had been killed within 1–2 years) were classified as newly infected trees (Juzwik et al., 2011). Trees that have died from oak wilt in years prior to newly infected trees were located in the interior of the expanding oak wilt infection area. We confirmed the oak wilt pathogen and implemented oak wilt containment treatments within three weeks of first identifying oak wilt infections. The treatment method required measuring diameters and the distances between neighboring oaks and all newly infected oak trees to determine the area of containment. Within determined containment areas, we used a chainsaw to double girdle all red oak trees (live-newly infected, as well as already dead, and apparently healthy neighboring trees) with girdles ca. 15 cm apart and 8 cm deep. Girdles were applied to the tree bole between 20 cm and 60 cm above soil surface. The girdle height was selected to provide safety to the chainsaw operators and provide consistency across the treated trees. We herbicide treated tree girdles in containment areas with a mixture of 25 % Element 4 (Triclopyr 4) and 75 % diesel using a handheld sprayer to girdles for 42 total girdle-herbicide treated containment areas. The herbicide was applied directly after the girdles were created. Both girdles on each treated tree were drenched with the herbicide solution. An average of 142 ml of herbicide solution was used per tree, with an

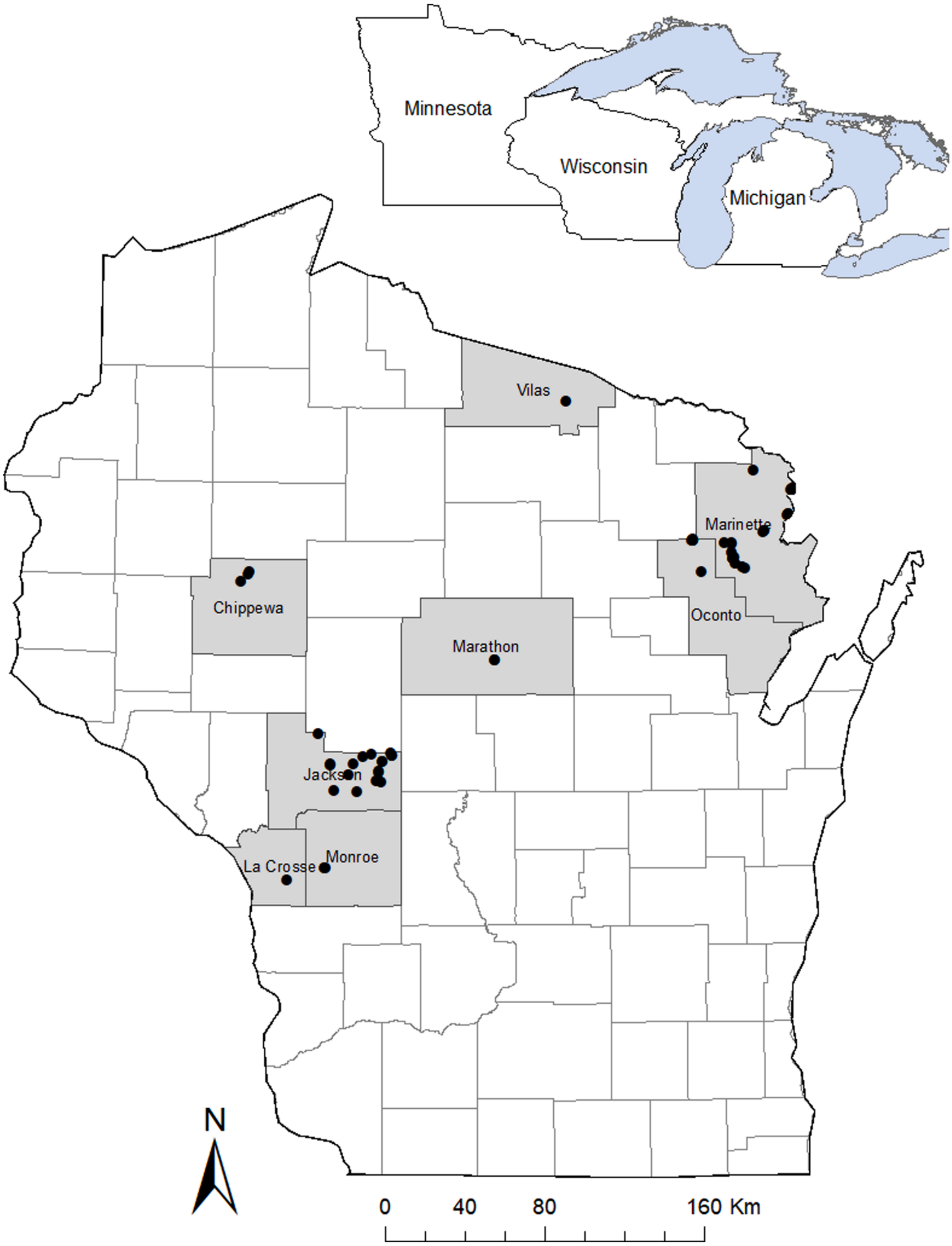

Fig. 1. Locations of girdle herbicide oak wilt containment study sites ($n = 42$) within Wisconsin, USA.

average of 5833 ml of herbicide solution used per containment area. The number of treated containment areas in 2015 included three in July, nine in August, eight in September, and five in October. In 2016 we treated six containment areas in August and 11 containment areas in September.

We collected detailed site information for each containment area including slope, amount of herbicide solution used, time required for treatment application, oak basal area, total basal area (all species), and in-field soil texture analysis following NRCS procedures (Thien, 1979). We also collected soil samples for lab analysis of soil particle size using a hydrometer per Gavlak et al. (2005). Field-based soil texture analysis was used to delineate the appropriate Bruhn and Heyd (1992) containment model (sand vs loam) in 2015, but not in 2016 as we only used the sand distance model. Laboratory analyses were conducted in 2015 and 2016 and allowed us to calculate the percent of sand, silt, and clay after the containment area was treated to corroborate our field-based texture analysis.

Each year, for four years following the treated girdle-herbicide (GH) containment areas, field crews returned to monitor effectiveness and look for oak wilt infected trees within 200 m of the treated containment area. We recorded all newly infected oak wilt trees surrounding our treated containment areas. Treatment outcome was deemed successful if no new oak wilt infected trees were detected for the entire four years after treatment.

In addition to our 42 selected oak wilt containment areas, in 2015 seven additional oak wilt infection centers were selected for observation without performing the GH treatment. These seven infection centers had oak wilt confirmed using the same laboratory procedures and fit the same species composition, basal area criteria, and distance from neighboring oak wilt infection center that our 42 selected containment areas contained. Further, all site information collected for our 42 containment areas was also collected for these non-treated infection centers. We visited these seven infection centers for four years (2016–2019), similar to our 42 selected containment areas. The purpose of these seven infection centers was to observe the rate of oak wilt spread in the absence of any containment treatment.

2.2. *Statistical analysis*

To evaluate outcomes of GH treated containment areas we used competing logistic regression models, with a binomial response variable of either success or failure. To do this we used generalized linear mixed regression models with a binomial distribution, using the lme4 package in program R (version 3.5.0; R Core Team, 2018). Predictor variables included number of newly infected trees (at the time of treatment), number of treated trees, average diameter breast height (DBH; 1.37 m above ground) of treated area, stand slope, stand soil type, soil model used (sand vs loam), year of treatment (2015, 2016), month of treatment (July–October), and county of containment treatment ($n = 8$). We compared different models using Akaike's Information Criterion selection (AIC; Burnham and Anderson, 2002). A global model was first constructed using all possible predictor variables, then a series of pared down models were created to test against each other as well as the global model to determine the most important variables determining success (or failure) of oak wilt containment using the GH treatment method. We used the MuMIn package (Bartoń, 2017) to perform model comparisons using the lowest AICc value and considered any models within $\Delta\text{AICc} \leq 2$ to be equivalent. The best model was selected based on the lowest AICc value and had the fewest predictor variables. We examined residuals plots to assess model assumptions of normality, linearity, and homogenous variance. We report models that were within 6 ΔAICc units of the best fit model. Predictor variables of the final, best fit model were analyzed using pairwise t-tests to evaluate whether there were significant differences between GH containment success and failure for model variables.

3. Results

We implemented 42 GH treated containment areas within oak wilt infected stands from 2015 ($n = 25$) to 2016 ($n = 17$) treating 2,270 red oaks among containment areas (248 of them newly infected oak wilt trees, 2,022 apparently healthy surrounding treatment trees). Containment areas ranged in size between 0.003 and 1.740 ha, with an average containment area of 0.18 ha. The number of GH treated trees ranged between 6 and 151 with an average of 48 trees per containment area. was All containment areas had a high basal area of oak ($\mu = 40.5$ m^2 ha^{-1}), on primarily level, sandy sites, which facilitates high levels of root grafting and underground spread of oak wilt (Juzwik et al., 2008).

Our best fit model included the number of newly infected trees, average stand DBH, stand slope, and year of GH treatment, which were all significant ($p < 0.05$) predictor variables within the model. This best fit model was four times better in describing GH outcome than the next best model, as shown by the AICc weights (Table 1). The five models that were within six ΔAICc units were all variations of the best fit model, minus either slope, year, or stand DBH variables. The only predictor variable included in all six of the top models was the number of newly infected trees.

The overall success rate of using the GH treatment method across all 42 oak wilt containment areas was 55 %. However, GH containment was 81 % successful for stands that had four or fewer newly infected trees. For stands that had five or greater newly infected trees, success of GH was only 29 %. The number of newly infected trees was significant in describing oak wilt containment success (Fig. 2a; $p = 0.02$). Overall, of the 42 stands treated with the GH procedure, 23 of those stands showed successful containment of oak wilt after four years. Of the 19 stands that had containment failure, three stands had new oak wilt infections beyond our containment area after year one, nine stands showed new infections in year two, four stands had new infections in year three, and three stands had new infections in year four (Fig. 3). Year-two of post-treatment monitoring was different for containment areas that were treated in 2015 vs 2016 and it follows that the year in which GH containment areas were applied was significant (Fig. 2b; $p = 0.03$). The overall success in containing oak wilt was 68 % in 2015 and 35 % in 2016. We applied GH containment areas to 13 stands with four or less visibly symptomatic trees in 2015 and only one stand showed oak wilt containment failure, for a success rate of 92 %. In 2016, eight stands were treated that had four or less visibly infected trees and three stands had failure for a containment success rate of 63 %. Overall, success of GH containment was significantly different between 2015 and 2016 ($p = 0.04$). We tested for interactions between year of treatment and number of newly infected trees but did not find a significant interaction effect.

Stand DBH was significant in our best fit model (Fig. 2c; $p = 0.04$). Average stand DBH for successful oak wilt containment areas was 35.6 cm, while containment areas with oak wilt containment failure had an average of stand DBH of 26.8 cm. Slope of the oak wilt containment areas was also a significant predictor variable in determining GH treatment outcomes (Fig. 2d; $p = 0.04$). Slopes for all 42 stands ranged from 0 to 22 degrees, with an average slope of 5.8 degrees. Average slope for successful GH containment areas was 4.6 degrees, while average slope for stands with oak wilt containment failure was 7.3 degrees.

Half ($n = 21$) of our containment areas had loamy soils, which we define as sandy loam, silt loam, and loam. The remaining half ($n = 21$) had sandy soils, which we define as loamy sand and sand. Laboratory analysis highlighted that our in-field texture soil delineations were incorrect for 18 stands. Misidentified soil types did not cause us to use the wrong soil distance model to estimate containment size in most cases; however, in 2015, misidentified soil led to two containments areas that were larger than required, and three containment areas that were smaller than required. Due to these difficulties in correctly identifying soils in the field, starting in 2016 we used the sand distance model for all containment areas regardless of field soil type. This resulted in our use of the sand model on loamy soils (as determined with laboratory soil analysis) for seven containment areas. Overall, given 18 instances where incorrect distance models were used, there was only

Table 1
AIC model selection outputs for top models within 6 delta AIC units of the best model.

Model	Intercept	DBH	Newly inf. trees	Slope	Year	df	logLik	AICc	Delta	Weight
1	−4257	−0.10	0.40	0.18	2.11	5	−17.16	46.0	0.00	0.5
4	−3482		0.38	0.11	1.73	4	−19.85	48.8	2.79	0.12
2	−4391	−0.06	0.30		2.18	4	−19.89	48.9	2.86	0.12
3	−0.36	−0.08	0.30	0.18		4	−19.96	49.0	3.01	0.11
6	−4006		0.32		1.99	3	−21.26	49.1	3.16	0.1
7	−2.73		0.33	0.13		3	−22.24	51.1	5.11	0.04

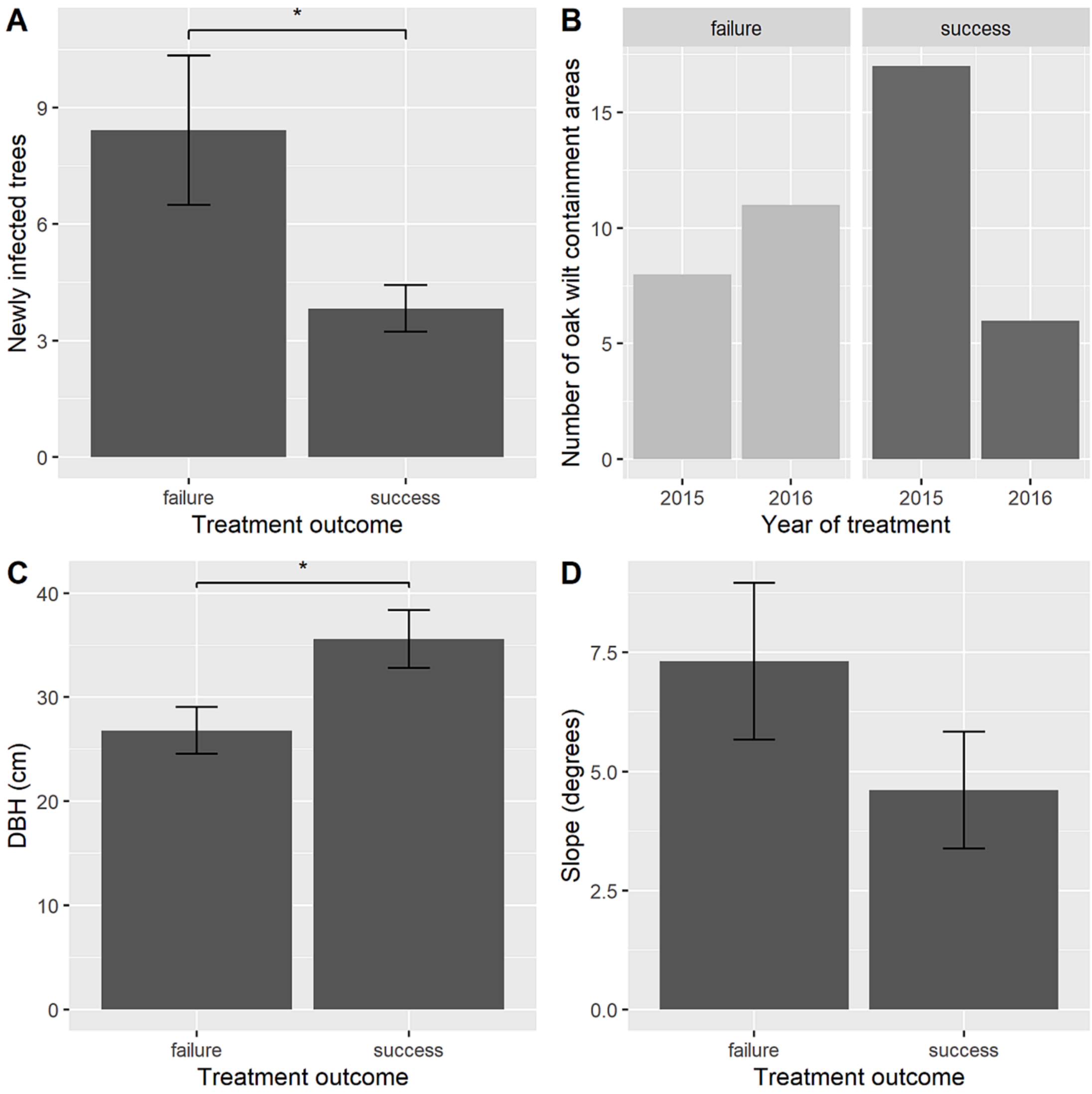

Fig. 2. Predictor variables that influenced the success or failure of the girdle-herbicide oak wilt containment treatment method. All four variables were included in the best model and were significant ($p < 0.05$) in explaining treatment outcome (a. number of newly infected trees, b. year of treatment, c. diameter at breast height (DBH), d. slope). * Indicates statistical differences ($p < 0.05$) between failure and success of oak wilt treatment outcome within the individual predictor variables.

three instances where the model may have underestimated the distance needed for GH treatments.

4. Discussion

Oak wilt is one of the most important diseases of oaks in the eastern United States and has been particularly destructive in the North Central states (Juzwik et al., 2011). Underground spread accounts for most of the trees killed by the oak wilt pathogen. In Minnesota, for example, an estimated 90 % (Cook, 2001; Wilson, 2005) to 95 % (Juzwik et al., 1985) of oak wilt infections are via underground spread. While preventing overland spread is relatively effective by reducing damage to oaks during high transmission periods (spring and early summer), options for controlling underground spread (e.g., trenching or vibratory plow to disrupt root grafts) are generally more labor and cost intensive, and have limited applicability on rocky or steep sites. This study set out to address that problem by evaluating a girdle-herbicide (GH) method of containing below ground spread. We designed a study that tested conditions most conducive for the spread of oak wilt (flat, sandy sites with high red oak density) and found that GH containment of oak wilt is possible and may be an alternative, cost-effective strategy to slow or stop disease spread within oak forests. The GH containment method we tested was effective in limiting underground spread of oak wilt for four years post treatment, especially for containment areas with four or fewer newly infected trees (81 % containment success). Conversely, containment areas with five or greater newly infected trees failed 71 % of the time. It follows that the number of newly infected trees was the single greatest predictor variable across all models in describing success or failure of the GH treatment outcome.

While we did not investigate mechanisms of below ground spread (or containment) of oak wilt, there are contributing factors that may help explain low rates of containment with a greater number of newly infected trees, i.e., five or more. The methods used to measure and calculate an appropriately sized containment area may be too conservative when considering five or more newly infected trees. The infection radius of wilting and asymptomatic but infected trees, for example, is variable and depends on rate of oak wilt spread (Appel et al., 1989; Koch et al., 2010). Some researchers have proposed that below ground oak wilt spread is between 15.2 m and 18.3 m per year (Wilson, 2001; Gleason and Mueller, 2005; Wilson, 2005). However, Bruhn and Heyd (1992) suggest that below ground oak wilt spread is a function of soil type and combined tree size, and thereby can be highly dynamic. Treated trees in this study ranged up to 55 m radius from the newly infected trees in the center of the containment area but averaged just 13

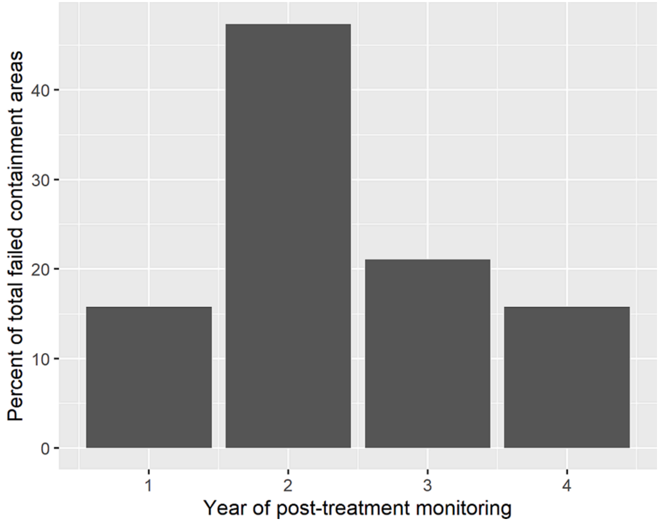

Fig. 3. Percent of total failed containment areas by year of post-treatment monitoring. (2016–2020). Twenty-five containment areas were established in 2015 and 17 in 2016 thus year one through four of monitoring was between 2016 and 2019 and 2017–2020 respectively.

m with no differences in average distances between successful (μ = 13.5 m) or failed (μ = 12.1 m) containment. Nevertheless, it is conceivable that with a greater number of newly infected trees, the oak wilt pathogen is more established in grafted oak root systems and rate of spread, a continual process, is not captured as well by estimates of root grafting among trees. Blaedow and Juzwik (2010) demonstrated the importance of self-grafts in lateral spread of the oak wilt pathogen in the root system and implicated the spread of oak wilt through networks of grafts. It is possible that the complicated network of root grafts created by the larger number of newly infected trees makes it more difficult to contain the oak wilt pathogen using our GH treatment method. If there are trees that contained oak wilt in their roots, but have yet to show visible symptoms of crown-dieback, then the distance model used could be underestimating the true distance needed to kill the necessary number of oaks for successful containment. The rate of root death caused by the GH treatment method may have been different for relatively new (with fewer newly infected trees) versus well established oak wilt infection centers, thereby influencing spread dynamics. It is important to note that overland spread could have contributed to containment failure of oak wilt for infection centers that had five or more newly infected trees. Having a greater number of newly infected trees would suggest a greater amount of oak wilt pathogen available to sap beetles. While trees infected after treatments were implemented were all within grafting distance of the initial infected trees, and no notable injuries were observed, we cannot completely rule out new infections caused by overland spread.

Bruhn et al., (2003) conducted an herbicide study on oak species, with the purpose of studying the length of time it takes to kill root systems when the tree is girdled and herbicide is applied to a penetrating frill into the tree's xylem, not unlike this study. Their results showed crown dieback was nearly 100 % during their earliest observation at 10 months after treatment, but it took 35 months to completely kill the root system. We also observed nearly complete crown dieback within the first year of post-treatment monitoring; however, new oak wilt infections occurred in every year of our four-year post-treatment monitoring (Fig. 3). Typically, failed containments using root rupture or other root graft severing methods (e.g., trenching, vibratory plow lines) show failure quickly after treatment, likely because of intact roots where transmission was not impeded, or due to new root connections forming across the trench or other root barrier (Wilson, 2005). Root regeneration within backfill soil, for example, takes at least 3–4 years after roots are severed (Wilson, 2005). Trench inserts have been studied as a way to provide longer term protection against root regrafting and transmission (Wilson and Lester, 2002) though these methods are expensive, more suitable for individual trees and urban settings and likely not applicable for forests more generally. Conversely, our GH treatment method may have taken three years to kill root systems thereby limiting its efficacy over time. It is not known if complete root mortality is necessary or if a compromised root system can functionally limit transmission of pathogens. To be significant in the disease cycle, root grafts must be functionally "organic," meaning that they allow movement of xylem contents among roots (Epstein, 1978; Juzwik et al., 2011).

An "effective" treatment confers a statistically significant advantage compared to untreated controls; however, when controls were unreported or unavailable Koch et al., (2010) considered treatments as potentially effective when desired outcome were met in ≥ 75 % of applications, often measured at the scale of individual trees. It is not unusual for studies of destructive pathogens to be observational and/or lack systematic controls. This study identified seven independent oak stands with oak wilt infection centers in 2015 and purposely did not include these infection centers as part of our GH containment treatment. Instead, our intention was to monitor these infection centers similarly to our GH treated infection centers, to observe oak wilt spread in the absence of any containment treatment. Of the seven stands, six stands showed spread of oak-wilt to new trees that did not have visible signs when the stands were first surveyed in 2015. It is uncertain why one stand without any GH treatment still showed no signs of oak wilt spread, but it is notable that the number of newly infected trees was only two, the smallest number of newly infected trees for all the oak infection centers that did not have the GH treatment. Notably, it is difficult to draw conclusions from a limited sample size, especially for a variable process (in space and time) such as oak wilt infection. Oak wilt in Texas, for example, has been found to affect approximately 80 % of oaks in a stand challenged with active oak wilt infection centers with common root systems (Wilson, 2005). It is unknown whether the remaining uninfected trees have a resistance to the pathogen or more limited root grafting, but this uncertainty adds complexity to evaluating success or failure of containment efforts. Similarly, Himelick and Fox (1961) found that while most oak wilt infection centers remained active year to year, some infection centers remained dormant for up to six years then reactivated, suggesting that variability may be confounded with a long period of possible transmission (Eggers et al., 2005).

An interesting result of this study was more effective GH containment of oak wilt in 2015 versus 2016 (Fig. 2b). This finding remained true even after normalizing containment areas by newly infected trees. Annual weather conditions have been attributed to oak wilt spread and mortality with hotter, drier conditions believed to exacerbate oak wilt by furthering water deficiency in the canopy as well as greater transmission of materials via root systems (Wilson, 2001). Somewhat contradictory to this, in 2016, Wisconsin experienced as much as a 45 % increase in summer rainfall compared to 2015. A faster rate of spread of the oak wilt pathogen in the root systems could be explained by a temperature cooling effect created by water in the root systems and negative pressure created by nearby living trees (Tainter, 1995; Blaedow and Juzwik, 2010). This finding is, nevertheless, surprising and warrants further examination.

Similarly, this study illustrated that stands with both greater DBH and less slope significantly contributed to containment success (Fig. 2). Generally, higher levels of root grafting, and therefore spread of oak wilt, occur on level sites (Juzwik et al., 2011). While we found more successful containment on less steep slopes, our stands were selected to be primarily flat sites overall (e.g., < ca. 10 %). GH containment efficacy increased for stands with larger DBH and decreased in stands in which smaller stem DBH predominated (Fig. 2c). Our GH treatment method is based on DBH of visibly symptomatic trees plus neighboring oak tree DBH, so larger trees generally resulted in larger areas treated with all other things equal (i.e., number of newly infected trees). Stand DBH and stem density are often inversely related, either of which could contribute to the effectiveness of the GH treatment due to root grafting. It follows that in our sites there was a negative relationship between stem density and DBH, with stands having higher DBH having fewer trees per hectare. Root grafts play a less significant role in disease development in hardwood stands comprised of numerous species likely due to limited interspecific root grafts (Epstein, 1978; Gibbs and French, 1980; Juzwik et al., 2011). Our oak stand sites were diverse ranging from smaller diameter sprout origin oaks to large seed origin stands. Larger diameter oak stands may have been further along the developmental pathway to more mixed species composition stands, particularly in the understory (Loewenstein et al., 2000).

Oak wilt has proven to be a manageable disease in the relatively few areas where consistent and long-term suppression programs have been implemented (Juzwik et al., 2011). The use of vibratory plow to physically severe root grafts has been the standard procedure for containing oak wilt spread. Early reports of vibratory plow methods were effective 54 % of the time with infection spreading beyond the line once in every 46.6 m of line installed (Shelstad, 1988; Koch et al., 2010). As personnel gained experience and equipment was improved, treatment efficacy increased (Wilson, 2005) and this method is between 76 % (Billings et al., 2001) to 88–100 % effective at preventing local spread (Cook, 2001; Koch, 2010). We view the results from this evaluation of the efficacy of GH containment as a starting place to creating more locally tailored oak wilt management. This project suggests that early recognition of newly infected trees remains critical for more effective management (Juzwik, 2000; Appel, 2001) and for management options. The GH treatment method has the potential to increase treatment compliance and efficacy and serve as another tool to help increase best management practices across landownerships.

5. Conclusions

This study shows that the girdle and herbicide (GH) methodology is an efficient way to contain oak wilt. The GH treatment method was highly effective in containing oak wilt, when applied to oak wilt containment areas with four or fewer newly infected trees. Oak wilt infection centers with five or greater newly infected trees had a significant increase in containment failure. The difference in containment effectiveness may be the result of differences in the amount of oak wilt pathogen belowground, difference in the rate of spread, or differences in the time required for complete root mortality (Bruhn et al., 2003). Further work is needed to better understand the relationship between the number of newly infected trees and belowground oak wilt spread. Such work would allow refinements to the Bruhn and Heyd (1992) distance model and provide greater effectiveness in containing oak wilt for stands with more newly infected trees. The GH treatment method has the potential for improvement by incorporating future research results and observation data from the field. Finally, long-term monitoring of treated oak wilt containment areas is necessary. Monitoring detected new oak wilt infections all four years after treatment. As new methodologies for treating oak wilt emerge, it is important to have long-term studies to adequately gauge containment effectiveness.

6. Product disclaimer

The use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement or approval by the U.S. Department of Agriculture or the Forest Service.

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CRediT authorship contribution statement

Dustin R. Bronson: Conceptualization, Methodology, Investigation, Validation, Supervision, Project administration, Formal analysis, Writing - original draft, Writing - review & editing. **Jed Meunier:** Conceptualization, Methodology, Investigation, Validation, Supervision, Project administration, Funding acquisition, Data curation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Teresa R. Pearson:** Methodology, Investigation, Validation, Supervision, Data curation, Writing - review & editing. **Kyoko Scanlon:** Conceptualization, Validation, Project administration, Funding acquisition, Data curation, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data presented in this study are publicly available by request.

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