

Evaluation of the Root Rupture Method for Controlling Belowground Spread of the Oak Wilt Pathogen (*Bretziella fagacearum*) in Northeast Wisconsin, USA

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Abstract

Oak wilt, caused by the pathogen *Bretziella fagacearum*, is a destructive disease on oak (*Quercus*) species in the United States. Established methods to control the belowground spread of oak wilt are not appropriate in all circumstances; thus, forest health managers have a strong need for alternative methods for disease control. We evaluated the effectiveness of operational stump excavation treatments (i.e., “root rupture” method) applied between 2004 and 2014 to control belowground spread of oak wilt on two forests in northeast Wisconsin, USA. The root rupture method achieved a high level of disease control ($\geq 85\%$ of evaluated disease infection centers) for 5 years by harvesting red oak trees within infection centers and uprooting the stumps and associated root mass. The likelihood of disease control success depended on the initial size of the infection center that was treated, with larger infection centers being less likely to be contained with a single treatment than small infection centers. This study highlights the importance of early detection and prompt management in oak wilt suppression programs.

Study Implications: Forest management agencies and organizations in the North Central United States continue to face oak wilt epidemics. No single tool or treatment method ensures complete containment of oak wilt; thus, most managers carefully consider all the tools and techniques available to them and determine what best suits their budget and land use priorities. Stump excavation (i.e., “root rupture” method) is a cost-effective treatment for halting belowground spread of the oak wilt fungus, *Bretziella fagacearum*, that can achieve a high level of disease control. In northern red oak (*Quercus rubra*) stands with high economic value, this treatment can be applied as a group selection, with the value of the timber potentially offsetting the cost of treatment. The opportunity for complete disease control decreases as oak wilt infection centers increase in size; thus, monitoring and early control actions are critical.

Keywords: disease management, invasive species, forest health, northern hardwoods

Oak wilt is among the greatest threats to oak (*Quercus*) species in North America, particularly the North Central states and Texas (Juzwik et al. 2011). The causal pathogen, *Bretziella fagacearum* (syn. *Ceratocystis fagacearum* [Bretz] Hunt), can infect all oak species; however, members of the red oak group (*Quercus* section *Lobatae*) experience the highest annual rates of infection and mortality, often dying within weeks to months after the appearance of initial symptoms. Disease infection centers are established when contaminated beetles of the Nitidulidae family carry spores from diseased trees to fresh wounds on healthy trees (Ambourn, Juzwik, and Moon 2005; Jagemann et al. 2018; Juzwik, French, and Jerešek 1985). Once introduced to a healthy tree, the fungus may spread through root grafts between neighboring oaks, resulting in the outward expansion of areas of wilting trees (Gibbs and French 1980). Transmission through connected

root systems is thought to be responsible for most new infections in the Lake States and can result in rapid disease spread; thus, a large focus of oak wilt control programs is to prevent belowground spread of *B. fagacearum* among neighboring trees (Juzwik 2009). However, established methods to prevent belowground spread are not suitable for all disease suppression circumstances. As the range of oak wilt continues to slowly expand, there is a need to build on existing methods of controlling belowground spread to suit a wide variety of landscapes (Haugen et al. 2022; New York Department of Environmental Conservation Bureau of Invasive Species and Ecosystem Health 2019).

Belowground spread of *B. fagacearum* can be prevented by establishing a containment zone around diseased trees, either by severing or killing root systems between healthy and diseased oaks. One of the main challenges to preventing

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belowground disease spread is that the pathogen can reside in the roots of a healthy-appearing tree prior to the onset of symptom development. Early research on the movement of *B. fagacearum* in roots documented a lag between root inoculations and foliar symptom development that ranged from 45 to 547 days (Yount 1958). Similarly, a study in West Virginia found that only 50% of oak trees grafted to diseased trees developed symptoms within 1 year, whereas the remaining trees developed symptoms up to 3 years later (Rexrode 1978). To account for the potential delay in symptom development, the outermost boundary of the treated area is established beyond the location of the diseased tree(s) and encompasses healthy oak trees that may be infected but are not yet displaying symptoms. Before forest managers implement disease treatments, they first determine (1) how far the boundary of the treatment area should be placed from the diseased tree(s) and (2) what the best available options are for disrupting root systems. Because belowground spread contributes to most new infections, understanding where and how to place treatment areas is critical to effectively controlling the disease.

The placement of treatment boundaries is based on the likelihood that root grafts will occur in the stand and the level of risk for future oak wilt that forest managers are willing to accept. Although root grafts can form between different oak species (e.g., between northern red oak and bur oak), they are most common between individuals of the same species (Gibbs and French 1980; Parmeter, Kuntz, and Riker 1956). The likelihood of root graft formation is also affected by related factors such as local tree diversity, intertree distance, basal area of oaks, soil depth, and soil type (Bruhn, Pickens, and Stanfield 1991). As a result, stands with a high density of red oak species tend to have a high frequency of grafted root systems and an elevated risk for rapid oak wilt transmission (Gibbs and French 1980; Menges and Loucks 1984; Parmeter, Kuntz, and Riker 1956). Various models for treatment boundary placement, based on either experience or mathematical theory, are available for forest managers to use. The “rule of thumb” model developed by French and Stienstra (1978) involves placing the boundary beyond two “rings,” or layers of visually healthy oak trees. Mathematical models, based on statistical estimations of how far the pathogen moves within 1 year, calculate treatment boundaries based on tree diameter, intertree distance, soil type, and desired confidence in disease control (Bruhn and Heyd 1992). The likelihood of disease control is further improved when root disruption is coupled with the removal of red oak species within the treatment area, as they have the potential to produce the fungal spore mats that drive overland disease transmission (Juzwik et al. 2011; Wilson 2005). After a containment area is established, managers can choose to either remove all red oak species within the enclosed area (“cut to the line” option) or remove diseased trees on an annual basis (“monitor and remove” option) (Juzwik et al. 2010).

Selecting an appropriate method to sever root systems and establish the disease treatment area depends on human land use, soil type, equipment availability, cost, and availability of experienced operators. A successful treatment stops the movement of *B. fagacearum* by disrupting the continuous xylem between neighboring trees that have grafted root systems. Approaches to disrupting connected root systems include cutting roots with a long blade, digging a trench, or applying herbicides to kill the root tissue (Bruhn, Wetteroff, and Haugen 2002; French and Stienstra 1978; Jones 1971;

Bronson et al. 2023; Wilson and Lester 2002). Managers in the Lake States have historically used vibratory cable plows (with a 60-inch blade) to cut through connected root systems (French and Stienstra 1978; Juzwik et al. 2010). The blade on a vibratory plow is inserted into the soil and pulled along the outermost boundary of the treatment area, functionally separating the root systems within the treatment area from the surrounding forest; however, this method is most effective when used on soils with sandy-loam or loamy-sand textures. Oak wilt infections located on glacial till soils with buried rocks and boulders present a challenge to the use of vibratory plows because of the damage that can occur to the blade from hitting boulders and interruptions in the line from “skipping” over impassible boulders. Sites with rolling topography or steep slopes also limit the safe use of traditional vibratory plows, which can require specialized tracked plows. Beyond physical site limitations, vibratory plows and operators who are skilled in oak wilt management are not readily available in all regions where the disease is present, creating a need for a simple alternative method to contain belowground spread of *B. fagacearum*.

Stump excavation (i.e., “root rupture” treatment) was proposed in the early 2000s as an alternative treatment for preventing the spread of oak wilt in settings that cannot be treated with a traditional vibratory plow. The practice of uprooting stumps following harvest has been successfully used for managing root rot diseases such as *Armillaria* root disease in the Pacific Northwest United States, with the added benefit that it requires neither specialized equipment nor deep experiential knowledge of the disease to implement (Roth, Rolph, and Cooley 1980). The treatment strategy involves harvesting all infected oaks and healthy oaks (>4 or 5 in. diameter at breast height; DBH) in the treatment area around the infection center using a mathematical model for treatment boundary placement (Bruhn and Heyd 1992). The stumps are then pulled completely out of the ground with an excavator, severing any root grafts within the treatment area.

This case study aims to document the efficacy of the root rupture method for controlling oak wilt in sites where traditional vibratory plowing is not feasible. Root rupture treatments were implemented in the mid- to late-2000s as an operational treatment on oak wilt infection centers in Wisconsin on the Chequamegon-Nicolet National Forest (CNNF) and Menominee Forest (MF), where uneven topography and buried boulders restrict the use of vibratory plows. The CNNF, acquired and established by the USDA Forest Service (Forest Service) in 1933, has many northern red oak stands that originated in the early 1920s following widespread exploitative harvest of red and white pine (*Pinus resinosa* and *P. strobus*, respectively) and repeated fires (Dunham, Moffat, and Howell 2021; Elliot 1977; Stearns 1997). As a result, many of the region’s hardwoods remained and stands are now dominated by large diameter northern red oak. Oak wilt was identified in 1997 at a campground in the CNNF and the disease was treated with a vibratory plow; however, many infection centers were subsequently found scattered in active timber sale units where the topography and soil conditions precluded the use of vibratory plows.

Neighboring the CNNF is the MF, which is managed by Menominee Tribal Enterprises (MTE) and located on the 235,560 ac Menominee Indian Reservation. This piece of the ancestral lands of the Menominee Nation was protected from outside timber liquidation that occurred during the 19th

century; the present-day MF remains host to diverse forest types that offer a rare glimpse of the landscape that once covered this region of Wisconsin (Pecore 1992). Tribal members have managed timber resources using a sustained-yield concept since the late 1880s, which emphasizes maintaining diverse species and habitats to provide simultaneous economic, cultural, and ecological benefits (Mausel, Waupochick, and Pecore 2017; Pecore 1992). Sections of the MF where red oak species are dominant or mixed with other hardwoods were designated for oak wilt treatments beginning in 2009.

Despite several years of disease treatment and collection of monitoring data on the CNNF and MF, a formal evaluation of the root rupture method was never completed. Although the root rupture treatments were implemented as operational treatments rather than as part of a scientific study, the data present an opportunity for retrospective evaluation. The objectives of this study were to use the monitoring data to (1) evaluate the success rate of the root rupture method in preventing oak wilt spread beyond established infection centers 5 years after operational treatment and (2) determine whether infection center size influences treatment outcomes.

Methods

Study Areas

The operational treatments were applied in northeast Wisconsin on approximately 10,000 ac of the MF and the 344,000-acre Lakewood-Laona Ranger District of the CNNF in Menominee and Oconto Counties (figure 1). These forests are situated on the eastern region of the Forest Transition Ecological Landscape, which spans approximately 200 miles east to west across Wisconsin (Wisconsin Department of Natural Resources 2015). The two forests are directly adjacent to each other, with the treated regions of the forests being approximately 27 miles apart from center to center in a straight line. Forests in this part of the ecological landscape are dry-mesic to mesic with varied soils that are generally characterized as sandy loam to loam with buried and surface boulders. These forests commonly feature a mix of pine species, red maple, oak, and aspen. Red oak stands on the CNNF that received root rupture treatments were primarily on the AVb (*Acer-Viburnum*) habitat type with relatively few hardwood associates (Kotar, Kovach, and Burger 2002). Oak wilt pockets on the MF were in stands of red oak and other mixed hardwood species. Common habitat types featuring red oak on the MF include PARVAa—Vb (*Pinus-Acer-Viburnum*), AVb, AFBv (*Acer-Fagus-Viburnum*), ATM (*Acer-Tsuga-Mianthemum*), and AFAd (*Acer-Fagus-Adiantum*) (Kotar, Kovach, and Burger 2002; Menominee Tribal Enterprises 2012).

Root Rupture Treatments

We examined treatments that were applied from 2004 through 2012 on the CNNF and from 2009 through 2014 on the MF. For both forests, field crews surveyed for diseased trees annually from August through September. They identified wilting trees by the appearance of leaf bronzing from the margin to the midrib, downward progression of symptoms in the crown, and premature leaf abscission. In the same year, they marked and flagged boundaries for the treatment areas based on the 95% probability Grayling soil equation from the statistical model developed by Bruhn et al. (1991). Within the treatment area, they marked (banded with paint and butt marked) all

diseased oaks and healthy red oaks larger than 4 (CNNF) or 5 (MF) in. DBH for future removal (Carlson, Martin, and Scanlon 2010). Any remaining small diameter trees were left standing as they were presumed to be seed-origin trees (not sprout-based or coppice regeneration) that were not grafted to the larger trees. During winter months (generally between October and December), but prior to March 15 of the following year, logging contractors harvested red oak trees (including oak wilt-killed trees) within the marked boundary. Following tree harvest, they extracted stumps and root masses out of the ground using a mid-sized excavator equipped with a bucket designed for digging through frost or compacted soil (frost bucket) and thumbs for grabbing the stumps out of the ground (figure 2). The stumps were overturned and pushed into the hole from which they were removed. During treatment operations, staff inspected the sites to ensure all stumps and root masses were fully excavated, flipped upside down, and severed from the remaining underground roots. Loggers removed all merchantable wood from the site and the wood was processed prior to April 1 to prevent the formation of fungal spore mats. Nonmerchantable wood (e.g., large branches) was cut into 4 ft. lengths to expedite drying time, which prevents the formation of fungal spore mats.

Monitoring and Data Collection

Field crews monitored the treated sites annually between July and late August on the CNNF and between August and September on the MF for the occurrence of newly symptomatic trees near the treated areas. New oak wilt infections were identified by the same suite of symptoms described previously. When newly infected trees were identified near previously treated sites (within ~66 ft. from the treatment boundary), the crew assessed the tree(s) for evidence of potential overland transmission (e.g., recent wounding or broken limbs). Knowledge of separate, active oak wilt infections present in the vicinity was also used to judge whether the newly infected tree(s) likely resulted from insect spread rather than belowground through connected roots. If field crews suspected the new infection was the result of insect spread, the tree(s) were considered a new infection and the site was marked for treatment. If evidence suggested belowground spread was more likely, the crew marked the site for retreatment using the same method and statistical model previously described. In general, forest managers monitored the sites for a minimum of 5 years. Current management guidelines recommend a 5–6-year monitoring period, which reflects the duration of documented vibratory plow treatment effectiveness, time in which root grafts are thought to reform, and the estimated belowground survival of *B. fagacearum* in roots (Juzwik et al. 2010; Wilson and Lester 2002; Wisconsin Department of Natural Resources 2023; Yount 1955). If disease infection centers were re-treated, a new 5-year monitoring period was initiated. Field crews and managers collected annual data on the status (healthy or diseased) of treated sites and the number of trees removed during treatments. In addition to ground surveys of previously treated sites, MTE foresters conducted part of the annual oak wilt survey with the assistance of unmanned aerial vehicles (UAVs).

Study Design

A total of 202 oak wilt infection centers on the CNNF and 293 centers on the MF were treated with the root rupture method between 2004 and 2011 and between 2009 and

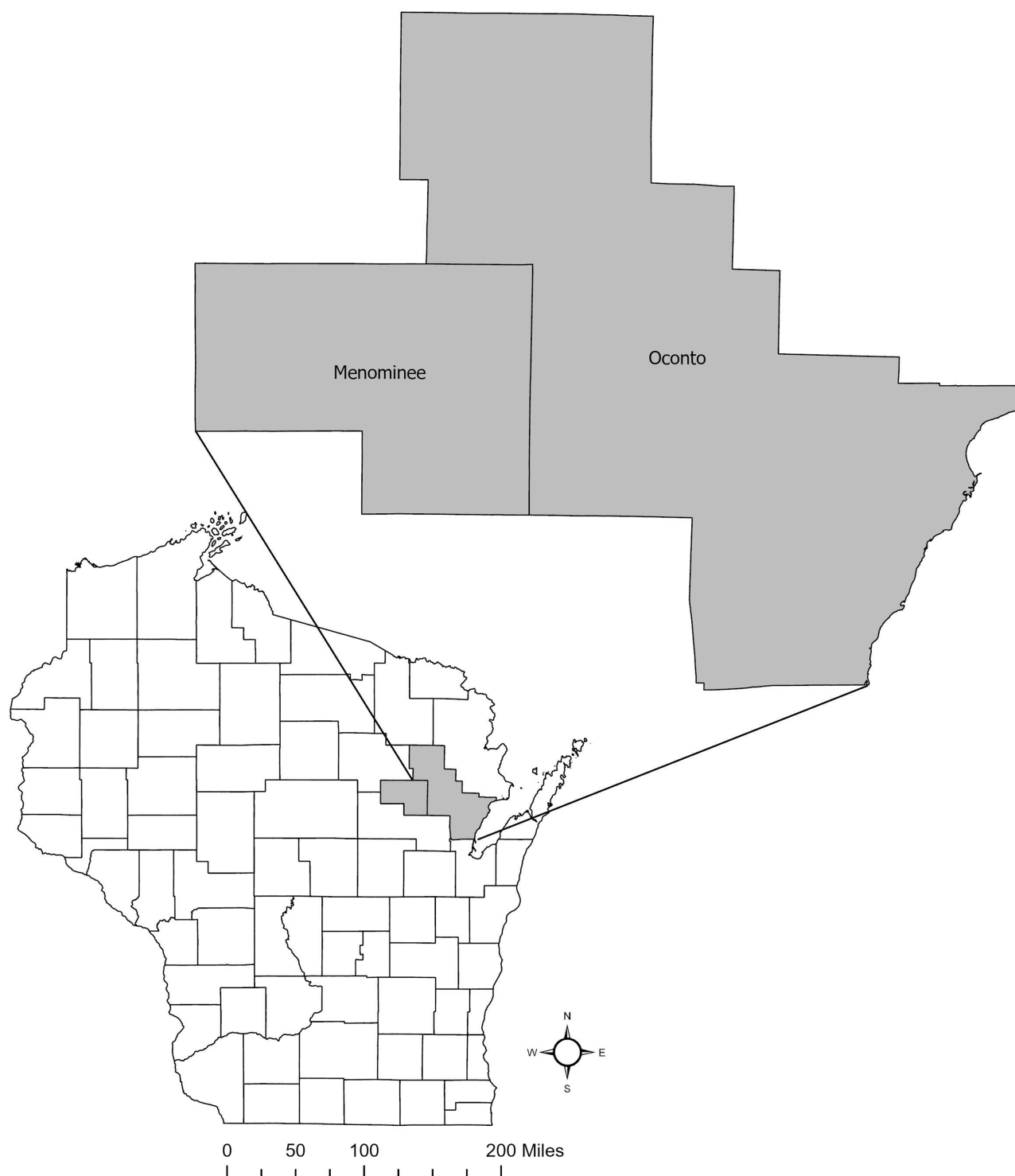


Figure 1 The Lakewood–Laona Ranger District of the Chequamegon–Nicolet National Forest (CNNF) and the Menominee Forest (MF) are in northeast Wisconsin in Oconto and Menominee Counties, respectively.

2014, respectively (Table 1). For our evaluation, we selected for analysis 186 treated sites from the CNNF and 292 treated sites from the MF. Although forest managers generally monitored treated sites for 5 years, interruptions in monitoring occasionally occurred. Sites selected for this analysis had at least five continuous years of annual disease monitoring data after the most recent root rupture treatment. For our evaluation, we considered infection centers that had coalesced into a single infection center as an individual site. We also considered

several large infection centers (≥ 300 oak trees removed) on the CNNF as a stand replacing harvest and excluded them from the study. These stands did not contain any red oak species directly adjacent to treated areas that could develop future disease via root graft spread. Because data for the number and diameters of wilting trees were not available, we used the number of trees removed as a proxy and refer to this as infection center size. As previously stated, boundary of the treatment area was delineated using a mathematical model



Figure 2 Root rupture treatments were implemented on the Chequamegon–Nicolet National Forest (CNNF) and Menominee Forest (MF) during winter months before March 15. *Q. rubra* trees (>4 in. DBH for CNNF; > 5 in. DBH for MF) were harvested and the stumps and root masses were dug out with an excavator. The excavator was equipped with a narrow bucket (frost bucket) that is used for digging into frost and/or compacted soil and thumbs for grabbing stumps. A) Photo from the MF of stump and root mass being pulled from the ground and flipped upside down. B) Photo from the CNNF of an oak wilt infection center after completed root rupture treatment.

for the 95% Grayling soil equation for which the tree diameters, intertree distances, soil types, and confidence levels were variables (Bruhn, Pickens, and Stanfield 1991).

Efficacy of Root Rupture Treatments

We calculated the overall success of the root rupture treatment as the proportion of infection centers at each forest

Table 1. Number of sites with oak wilt centers on the Chequamegon–Nicolet National Forest (CNNF) and Menominee Forest (MF) treated using the root rupture method. Sites were selected for study if they were monitored for at least 5 years after the first treatment or subsequent retreatment and if they contained fewer than three hundred trees removed.

Location	Year of first treatment	No. of sites treated	No. of sites selected for analysis
CNNF	2004	88	84
	2005	23	23
	2006	16	14
	2007	10	10
	2008	7	7
	2009	19	17
	2010	9	5
	2011	17	14
	2012	13	12
	2014	55	55
MF	2009	9	9
	2010	37	36
	2011	94	94
	2012	98	98
	2014	55	55

where treatments prevented disease spread within 5 years. To understand the likelihood of disease control after root rupture treatments, we analyzed treatment outcomes as a function of the number of trees removed and treatment year using a generalized linear mixed effects model. We ran the model using the lme4 package in R with the number of trees removed during the first treatment as a continuous fixed effect and treatment year as a categorical fixed effect (Bates et al. 2015; R Core Team 2021). Due to the operational nature of the oak wilt treatments, we believed that disease identification and treatment precision improved annually as forest health staff gained experience. Our analysis was designed to examine differences in treatment outcome over time; therefore, we treated year as a fixed effect rather than a random effect that would control for disease spread due to interannual variation in weather. Infection centers differed in size between the two forests, resulting in a high correlation between the forest location (CNNF and MF) and number of trees removed in the initial infection centers ($X^2 = 287.84$, $p = 1.971 \times 10^{-15}$); thus, the forest location was treated as a random effect. The model was checked for zero-inflation and residuals were checked for assumptions of normality (Hartig 2022). Post hoc pairwise comparisons were calculated using the emmeans package and a Sidak p -value adjustment was used to control for multiple comparisons between treatment years (Lenth et al. 2022).

Results

Overall, the infection centers treated at the CNNF were larger than those at the MF. The average number of trees removed for treatment was 74.41 ($SE = 4.49$) and 18.53 ($SE = 0.91$) for the CNNF and MF, respectively (figure 3). Following the initial root rupture treatments, 63% of the infection centers on the CNNF and 93% of the infection centers on the MF did not develop further disease symptoms within 5 years of the treatment (Table 2). The infection centers that did not

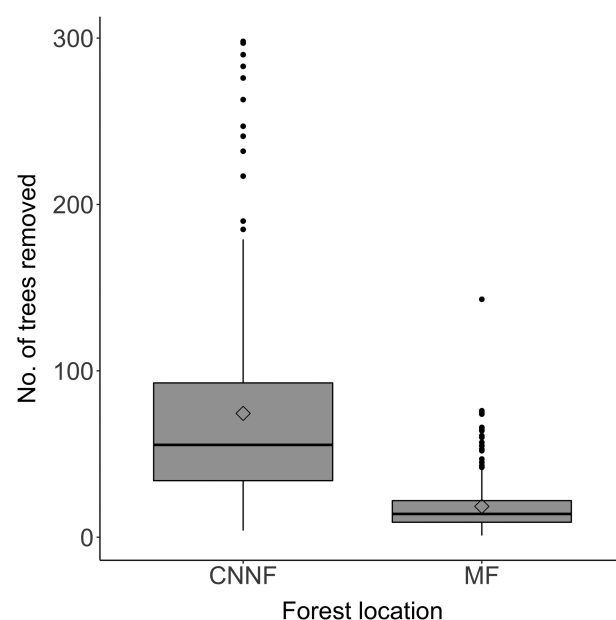


Figure 3 Boxplot of the number of trees removed during root rupture treatments on the Chequamegon–Nicolet National Forest (CNNF) and Menominee Forest (MF) for all years of the observational study. The average number of trees removed (open diamonds) for oak wilt treatment was higher in the CNNF than MF. Median number of trees removed is represented by solid horizontal lines and whiskers depict the interquartile range.

develop further disease symptoms after a single root rupture treatment were, on average, smaller in size than those that developed new disease symptoms. The mean number of trees removed on infection centers where a single treatment was successful was 32.17 ($SE = 1.84$), whereas the average for infection centers that were not contained was 72.78 ($SE = 7.43$). The likelihood of successful disease control after one root rupture treatment decreased as the size of the infection center increased ($p < .05$; Table 3; figure 4). The odds of treatment success decreased by 0.81% for each additional tree that needed to be removed within the calculated treatment boundary. The likelihood of disease control also varied by year, with the highest estimated treatment success in 2010, 2011, 2012, and 2014 (Table S1; figure 5).

The majority of the infection centers in which treatments were not successful developed new symptoms within 2 years after the initial treatment ($n = 44$ of 77 treatment failures on the CNNF; $n = 12$ of 22 treatment failures on the MF). Of the seventy-seven infection centers on the CNNF for which the root rupture treatment failed, seventy-one were re-treated and were, on average, similar in size to the originally treated sites ($F_{1,69} = 0.905$, $p = .302$). Due to the low number of re-treated infection centers on the MF, we could not compare the size of re-treated infection centers to the size of the original sites. After the application of additional root rupture treatments, the cumulative success of disease control was 85% and 96% for the CNNF and MF, respectively.

Discussion

Strategies to control forest diseases such as oak wilt require a tailored approach that carefully balances landscape constraints, land manager needs, and economic costs. In this study, we found that stump extraction (i.e., “root rupture” treatment) resulted in a high level of oak wilt control in

Table 2. Number and proportion of total infection centers where belowground spread of oak wilt was controlled following one or more root rupture treatments at the Menominee Forest (MF) and Chequamegon–Nicolet National Forest (CNNF) in Wisconsin.

No. of treatments applied	CNNF		MF	
	No. of sites	Proportion of sites	No. of sites	Proportion of sites
One	117	0.629	272	0.928
Two	32	0.172	9	0.031
Three	7	0.038	0	0.000
Four	2	0.011	1	0.003
Cumulative success	-	0.850	-	0.962
Not retreated ^a	28	0.151	11	0.038

^aSymptomatic trees were identified after the initial treatment, but the infection center was not retreated during the timeframe of this analysis. Data were not included in the cumulative success calculation.

Table 3. Results of generalized linear mixed effects model testing the effect of the number of trees removed and year on the success of the initial root rupture treatment. Forest location (Chequamegon–Nicolet National Forest or Menominee Forest) was treated as a random effect. The reference level for comparison is 2004.

Variable	Estimate	Standard Error	Z value	p-value
Intercept	0.773	0.271	2.846	<0.001
No. of trees removed	-0.008	0.003	- 3.092	0.002
2005	-0.561	0.499	-1.123	0.261
2006	0.298	0.615	0.485	0.628
2007	0.222	0.697	0.318	0.750
2008	0.661	0.886	0.745	0.456
2009	0.192	0.468	0.410	0.682
2010	1.174	0.479	2.451	0.014
2011	1.996	0.437	4.571	<0.001
2012	2.621	0.513	5.108	<0.001
2014	1.967	0.650	3.028	<0.001

infection centers across the CNNF and MF, particularly if repeated treatments were applied. In addition to demonstrating success of the root rupture treatment, this study revealed the complex considerations managers face when approaching disease treatment and the implications of historic stand management on present-day disease incidence and disease management outcomes.

Differences in Treatment Success Between Forests

Across the CNNF and MF, belowground spread of oak wilt was contained in the majority of infection centers (>62%) with one treatment, yet treatment outcomes were different between the two forests. In general, infection centers on the CNNF were larger than those on the MF, contributing to a lower likelihood of treatment success based on our model estimates. Despite the proximity and large red oak component of the two forests, management over the last circa 180 years varies substantially between the two forests, which now differ in terms of species and age class diversity. The land on which the CNNF is located was subjected to exploitative, large-scale lumbering in the mid-1800s after the Menominee Tribe were forced to cede much of present-day central Wisconsin (Elliot 1977; Stearns 1997). After the Forest Service established the CNNF in 1933, management shifted to focus on high-quality northern red oak; thus, many present-day stands are dominated by large, even-aged red oak. In contrast, stands on the

MF were, and continue to be, managed by the Menominee Tribe and MTE with sustained-yield silvicultural prescriptions that simultaneously maximize diversity (e.g., species composition, age class distribution, structural diversity) and cultural benefits (Menominee Tribal Enterprises 2012; Pecore 1992). The belowground spread of *B. fagacearum* is in part related to the density and size of red oak species on a stand (Menges and Loucks 1984). Thus, the lack of species diversity and uniformly large size-class of red oak on the CNNF increases the likelihood of root grafting and the rate of disease spread.

Differences in oak wilt treatment outcomes between the CNNF and MF may also be attributed to differences in disease detection methods between the two land managers. In general, annual oak wilt monitoring had two components: ground surveys of areas adjacent to previously treated sites and a broad survey for new infections that resulted from aboveground insect spread. New infections from aboveground spread are especially challenging to detect as they can occur up to 0.6 miles, or occasionally further, from an infected tree (Juzwik et al. 1985; Menges and Loucks 1984; Shelstad et al. 1991). As a result, new infection centers can remain unnoticed for several years until additional trees become infected and die. The assistance of UAVs in annual surveys likely allowed MTE foresters to identify and treat small infection centers, thus increasing the opportunity of successful treatment.

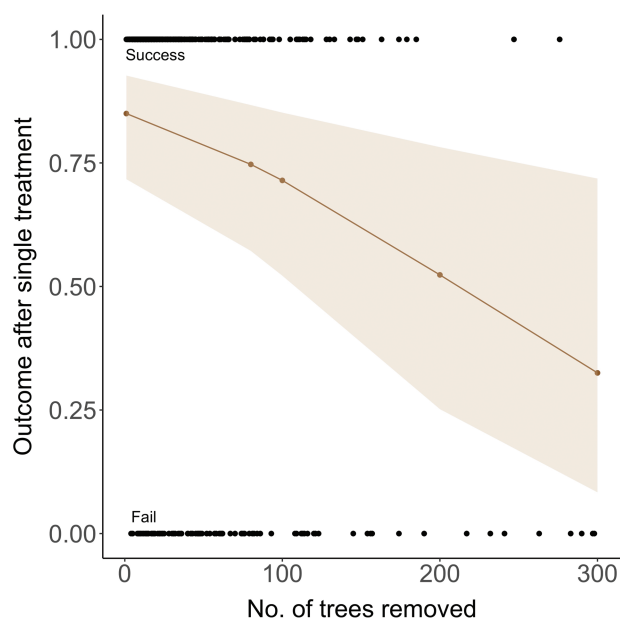


Figure 4 Predicted outcome (solid line) of disease treatments following a single root rupture treatment based on infection center size and 95% confidence interval (shaded envelope). The predicted outcome is based on generalized liner mixed effects model estimates and are plotted against binary experimental data (solid circles on top and bottom; treatment success or failure). Treatment “success” denotes that a new belowground infection did not occur adjacent to the treated area within 5 years of initial treatment. The number of trees removed was determined according to Bruhn 95% confidence Grayling soil model (Bruhn, Pickens, and Stanfield 1991; Carlson, Martin, and Scanlon 2010).

Understanding Why Treatments Fail

There are several reasons why treatments may fail (or appear to fail) that arise from (1) difficulty recognizing diseased trees and (2) wrongly identifying the source of new infections. Theoretically, treatment area boundaries calculated using the statistical model should include all grafted trees with less than 95% probability of survival for at least 1 year (Bruhn, Pickens, and Stanfield 1991). However, only 63% and 93% of treated infection centers (CNNF and MF, respectively) showed no evidence of further belowground spread after one treatment. One of the largest challenges in accurately identifying oak wilt is that *B. fagacearum* can infect root systems for up to 3 years before the foliar symptoms are evident (Rexrode 1978). Consequently, trees infected with the oak wilt fungus that are not yet displaying symptoms may not be accounted for when calculating where to place the treatment boundary. Similarly, the survival of *B. fagacearum* in root systems after tree death is not well understood, thus older oak wilt-killed trees may be overlooked when placing treatment boundaries (Skelly and Wood 1974; Yount 1955). Other biotic and abiotic stressors (e.g., two-lined chestnut borer damage, drought) are known to cause symptoms that appear similar to that of oak wilt and can occur simultaneously with the disease (O’Brien et al. 2011). If symptoms on diseased trees are not visible or are mistaken for other disorders, then the resulting treatment boundary will not account for the true extent of the infection center. In this way, such treatment “failures” result from a failure to accurately diagnose oak wilt rather than a failure of the root rupture treatment itself.

Despite the best efforts of forest health professionals to differentiate between new overland introduction by Nitidulid

beetles and root graft spread, field technicians may have trouble determining whether a new symptomatic tree is truly the result of a treatment failure. Incorrectly attributing a new wilted tree outside of the treatment boundary to root graft spread would inflate the proportion of treatment failures, particularly in years with damaging spring storms that lead to spikes in the frequency of overland infection (Juzwik and Schmidt 2000; Ostile 2020). Success of oak wilt containment efforts on the CNNF and MF lands increased over time for the evaluated infection centers, which likely reflects an improvement in oak wilt identification by managers and field crews.

Our study revealed that the disease was more likely to be controlled in infection centers treated during the later years (2010 through 2014) of the study than early years (2005 through 2009). Oak wilt was identified on the CNNF nearly 10 years before the conception of the root rupture control program; thus, forest health managers faced many large disease infection centers that had remained unmanaged for several years. Although difficult to quantify, it is reasonable to suspect that large infection centers also presented greater opportunity for human error when marking treatment boundaries than small infection centers. Minor errors in delineating treatment boundaries may have failed to encompass the full extent of the belowground infection. It is likely that the accuracy of oak wilt identification and root rupture treatments improved as control programs matured, resulting in smaller infection centers and fewer treatment failures in later years.

Practicality and Cost Considerations for Forest Managers

Uprooting stumps for disease control creates a high visual impact to the landscape and substantial soil disturbance. Typical root rupture treatments resemble a large canopy gap or a small group selection with root- and soil-exhumed mounds. Characteristics of these treatments resemble small-scale wind events and may be aligned with natural disturbance-based management, creating an unexpected silver lining of oak wilt management in this region (Kern et al. 2019; Seymour, White, and deMaynadier 2002). Anecdotally, managers on the CNNF and the MF have observed diverse advanced and seed-origin regeneration, including red oak, paper birch, and white pine in root rupture-treated sites (figure 6). MTE foresters have also used the treated infection centers as an opportunity to plant climate-adapted tree species to diversify the forest and reduce the risk imposed by future climate conditions (Janowiak et al. 2014).

Treatment cost is an important factor to consider when deciding how to best manage diseases on the landscape. Estimating the cost of root rupture treatments is complex for several reasons. First, land managers may either choose to contract with a logging company to harvest the trees and pull the stumps or the procedure can be done in-house, incurring little cost beyond the hourly rate to rent an excavator. Second, in regions with high quality red oak, the cost of implementing treatments can be greatly offset by profits made from wood utilization. In the case of the CNNF, trees removed were packaged into Stewardship Contracts, a Forest Service legislative authority that enables timber managers to bundle timber sale contracts within service contract work. In this arrangement, the CNNF offers high value timber with a requirement that the contractor uproot the stumps after harvest; thus, infection

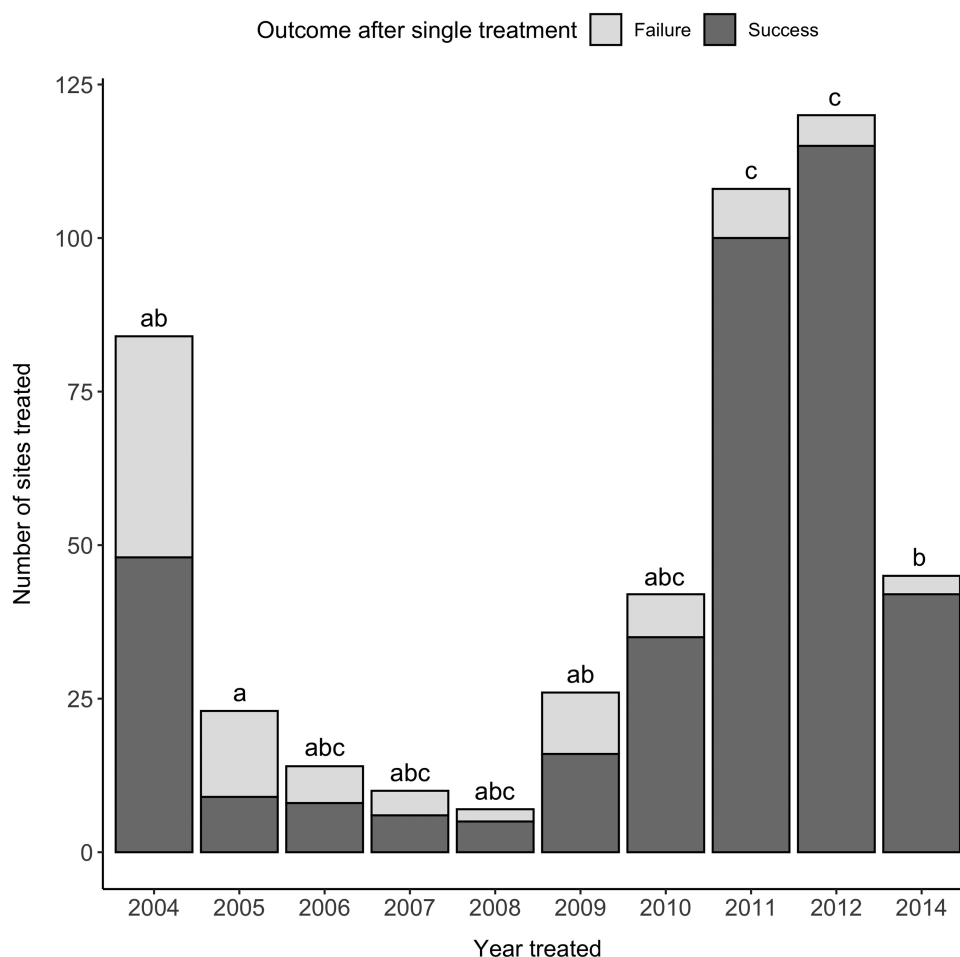


Figure 5 Outcomes (success or failure) after a single root rupture treatment on oak wilt infection centers in the Chequamegon—Nicolet National Forest (CNNF) and Menominee Forest (MF) for each year of this observational study. Treatment “success” indicates that a new infection did not occur (or was not detected) adjacent (within 66 ft.) to the treatment area within 5 years of initial treatment. Letters represent differences ($\alpha = 0.05$) based on the Sidak p -value adjustment to control for multiple comparisons.

centers on the CNNF were usually treated with an overall financial net gain. The MTE also has a unique advantage in that they can harvest trees and implement the treatment with both their own loggers and equipment. Further, the harvested wood can be processed internally at a mill owned by the Menominee Indian Tribe of Wisconsin, where the lumber can either be used or sold.

Comparison to Established Oak Wilt Treatments

There are limited reports of on the efficacy of belowground oak wilt containment efforts on comparable terrain. In this study, individual root rupture treatments resulted in a lower rate of disease control than published rates of the “monitor and remove” strategy (84% of evaluated disease centers) on similar soil types and slopes in Minnesota (Juzwik et al. 2010). However, the infection centers in the vibratory plow evaluation were smaller on average (based on the calculated number of trees removed) than the infection centers in this study. Reported success rates of other oak wilt control methods are varied. For example, evaluations from the 1970s in Pennsylvania and West Virginia describe > 84% containment over 4 years after felling oaks and treating the stumps with herbicides, whereas a recent trial testing the use of double frill

girdle and herbicide applications found that the disease was only contained in 55% of treated infection centers (Bronson et al. 2023; Jones 1971). This observational study provides valuable insight on the relationship between infection center size and treatment outcome; however, our analysis would be strengthened by including basal area or density of infected and healthy red oak trees removed rather than using number of trees removed as a proxy for infection center size. Although such data were not available for this study, future evaluations of belowground disease control should consider reporting basal area of diseased oaks and of oaks removed to allow for more direct comparisons between methods.

As the range of oak wilt continues to slowly expand, there is a pressing need to expand on existing disease control strategies by developing creative, effective alternative management tools. The root rupture method achieved a high degree of disease control with the potential of encouraging diverse regeneration that is less susceptible to widespread disease outbreak. Our evaluation of operational treatments indicates that the likelihood of treatment success decreases as infection centers increase in size. Thus, the best approach to managing oak wilt may be a proactive management program aimed at early disease detection followed by prompt treatment.



Figure 6 Seed-origin and advanced regeneration in a treated infection center on the Menominee Forest (MF) and Chequamegon–Nicolet National Forest (CNNF). A) Regeneration 2 years after root rupture treatment on MF. B) Regeneration 14 years after root rupture treatment on the CNNF.

Supplementary Materials

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

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Data Availability

Data presented in this study are publicly available by request.

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