Preparing Ontario for an invasive disease: A review of oak wilt management strategies in the Great Lakes region of the United States

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Executive Summary

Oak wilt is a disease of oak species (*Quercus* spp.) caused by the fungal agent *Bretziella fagacearum*. This vascular disease blocks xylem vessels and inhibits an oak tree's ability to transport water and nutrients, causing symptoms such as wilting of foliage and detachment of leaves during the growing season. This disease ultimately causes the death of many oak trees. Currently, oak wilt has only been found in the United States, although it is believed to have originated and been introduced to the U.S. from elsewhere. The death of trees combined with attempts to manage and prevent the spread of oak wilt has had a devastating economic impact in the U.S. as well as social and ecological impacts from the loss of oak trees. Oak wilt infection centres have been found within approximately 500 metres from the Canadian border separating the province of Ontario and the state of Michigan. There is a high risk of oak wilt introduction to Canada, specifically in southern Ontario, therefore the province must be prepared. In this paper, the best management practices used throughout the Great Lakes region in the U.S. will be presented and recommendations for Ontario will be provided. Based on management efforts, the states with the least risk of oak wilt spread are Michigan, Minnesota, New York and Wisconsin. Ultimately, Ontario will need to look at the successes of oak wilt management in the Great Lakes region in order to prevent the spread of oak wilt.

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1. Introduction

Oak wilt is a vascular disease of oak species (*Quercus* spp.) caused by the fungal agent *Bretziella fagacearum* (Juzwik, Appel, Macdonald & Burks, 2011). Oak wilt has only ever been recorded in the United States (U.S.), however certain characteristics of the pathogen such as its limited genetic variation suggest that it originated and was introduced from elsewhere, possibly Mexico, Central America, or South America (Juzwik, Harrington, MacDonald & Appel, 2008). In the U.S., oak wilt was first documented in Wisconsin in 1942 and is now found in 24 states, mainly in the Upper Midwest as well as Texas (Juzwik et al., 2008). There is no cure for oak wilt, therefore the disease has had devastating economic impacts on both urban and rural forests from loss of timber, loss of property value, tree removal costs, and implementation of expensive management strategies (Juzwik et al., 2011). For example, red oak timber in Michigan is estimated at a value of $1.6 billion and the cost of removing infected oak trees in just one county in Minnesota over a 9 year period ranged from $18-60 million, demonstrating the economic losses caused by oak wilt (Haight et al., 2011; Michigan DNR, 2018). The USDA Forest Service has confirmed that municipalities and individual homeowners have spent millions of dollars every year to remove, treat, and re-plant trees in areas affected by oak wilt (USDA Forest Service, 2013). In addition to the economic costs of oak wilt, there have also been cultural impacts, including loss of historic trees and featured landscape trees, as well as a loss of ecosystem services such as habitat, carbon sequestration, heat island mitigation and storm water runoff mitigation (Juzwik et al., 2011). Oaks are ecologically, culturally, and economically important trees across the North American landscape, therefore impacts from oak wilt are deeply harmful on many levels.

1.1 Oaks & Oak Wilt

There are four taxonomic divisions of the *Quercus* genus: *Cerris*, *Lobatae*, *Quercus* and *Protobalanus* (Juzwik et al., 2011). *Cerris* species are found in Asia, Europe, and the Mediterranean where *B. fagacearum* is not known to exist, whereas *Lobatae* (red oaks), *Quercus* (white oaks), and *Protobalanus* (intermediate or live oaks) are all found in the Americas and are susceptible to infection of oak wilt (Juzwik et al., 2011). Live oaks are found in the south and are not present in the Great Lakes states, therefore their symptoms and management in relation to oak wilt are outside the scope of this study.

Generally, the oak wilt disease will target a tree's vascular system by clogging or blocking xylem vessels and limiting the tree's ability to transport water and nutrients, causing the wilting of foliage and ultimate mortality of the tree (Garske, 2013; Koch, Quiram & Venette, 2010). White oaks and red oaks have distinct anatomical and reproductive differences, and therefore react differently and present slightly different symptoms to infection by oak wilt (Appel, 1995). Red oaks such as *Quercus rubra*, *Quercus ellipsoidalis*, and *Quercus falcata* are highly susceptible to oak wilt and can die within as little as three weeks after becoming infected (Appel 1995; Garske, 2013). Crown symptoms are most noticeable in the red oak group with wilting or bronzing of leaves starting from the top of the crown at leaf margins, followed by detachment of leaves during the growing season (Juzwik et al., 2011). Trees in the white oak group such as *Quercus alba* and *Quercus macrocarpa* are more resistant to oak wilt, which some have attributed to their ability to form more tyloses in their sapwood vessels when wounded or infected in comparison to red oak species (Garske, 2013). Species in the white oak group will display similar symptoms to species in the red oak group, however symptoms are typically

limited to one or a few branches at a time, and trees may not die for one or more years after infection (Juzwik et al., 2011).

1.2 Spread

1.2.1 Aboveground

One way that oak wilt spreads is aboveground through transmission by insect vectors (Juzwik et al., 2011). When species in the red oak group are infected with oak wilt, they provide the only source of inoculum for pathogen transmission by insect vectors in the form of fungal mats (Appel, 1995). Fungal mats are the reproductive structure of the *B. fagacearum* fungus which forms under the bark on the sapwood of trees infected by oak wilt (Appel, 1995). These fungal mats produce pressure pads which often causes the bark to crack open in that spot (Garske, 2013). The fungal mats produce a sweet-smelling or fruity odor, and once the bark cracks open from pressure, sap-feeding insects such as nitidulid beetles (Coleoptera: nitidulidae) are attracted to the scent and are able to access the fungal mats (Appel, 1995; Cummings-Carlson, Martin & Scanlon, 2010). The primary insects that act as vectors for the disease are *Colopterus truncatus* and *Carpophilus sayi*, however oak bark beetles (Coleoptera: Curculionidae: *Pseudopityophthorus* spp.) are also known to be lesser vectors (Ambourn, Juzwik & Moon, 2005; Juzwik et al., 2011). Once the nitidulid beetles visit fungal mats they collect spores on their bodies and are then attracted to fresh wounds on other trees, often spreading the oak wilt disease to healthy oaks (Juzwik et al., 2011). It is important to note that nitidulid beetles are not able to create fresh wounds on trees which are required for *B. fagacearum* to inoculate healthy trees (Juzwik et al., 2011). Therefore, the aboveground transmission of oak wilt depends on the ability of these insects to find oak trees that have been recently wounded (Juzwik et al., 2011). The aboveground spread of oak wilt through insect transmission is important in the creation of new infection centres (Ambourn et al., 2005).

1.2.2 Belowground

The second method of oak wilt spread is belowground through root grafts and is believed to be the method responsible for the majority of losses from oak wilt (Appel, 1995). In a Minnesota study, it was discovered that root grafts were responsible for approximately 90% of new infections (Koch et al., 2010). Root grafts typically form between oaks of the same species when roots from different trees graft together and allow for the transport of xylem contents between the individuals (Juzwik et al., 2011). The belowground spread of oak wilt will often start at an existing infection centre and then spread outwards, infecting new trees in a circle around the original infection centre (Juzwik et al., 2011). The speed of oak wilt transmission through root grafts has been said to depend on the diameter of the trees, the distance between trees, and the soil or drainage characteristics of the land (Bruhn, Pickens & Stanfield, 1991; Cummings-Carlson et al., 2010). Typically, there will be higher instances of root grafts in shallower, sandier soils when compared to deep, loamy soils (Cummings-Carlson et al., 2010).

1.3 Problem Definition

In 2016, oak wilt was found on Belle Isle in Detroit, Michigan, just over approximately 500 metres away from Windsor, Ontario in Canada (Nienhuis & Wilson, 2018). Although oak wilt has not yet been recorded in Canada, this disease has been identified as an imminent threat to Canadian forests, specifically forests in southern Ontario, and as such the movement of oak material into Canada is federally regulated by the Canadian Food Inspection Agency (CFIA)

through the federal Plant Protection Act (Nienhuis & Wilson, 2018). In Canada, oaks are an important part of the Deciduous Forest, Garry oak ecosystem, Great Lakes-St. Lawrence and Acadian forest regions as well as a valuable shade tree in urban areas (Canadian Food Inspection Agency, 2011; Erickson, 1993). Impacts from invasive species are the second greatest threat to Ontario's native biodiversity, and unfortunately Ontario has the most invasive species and the greatest risk of new introductions in all of Canada (Nienhuis & Wilson, 2018). This is mainly because Ontario imports many international goods and is close to major international shipping routes such as the Great Lakes-St. Lawrence Seaway, allowing for more incidences of accidental introduction of new species (Nienhuis & Wilson, 2018).

Due to Ontario's proximity to areas infected with oak wilt in the U.S., the province is at great risk of experiencing the same devastating effects to their urban and rural forests from oak wilt (Nienhuis & Wilson, 2018). Currently in Ontario, the focus is on prevention and education with examples of collaboration with neighbouring states in the Great Lakes region. Across the literature on oak wilt, it is widely agreed upon that early detection and prevention of the spread of new infection centres is the best way to manage oak wilt, as opposed to trying to eradicate it once it has already become established (Appel, 1995; Haight et al., 2011; Juzwik et al., 2011). If Ontario is going to avoid the costly consequences of oak wilt in the event that it does cross the border into Canada, oak wilt research will need to be applied to a Canadian context and lessons will need to be taken from different states' management techniques.

2. Goals & Objectives

The goal of this research will be to present the background knowledge and strategies used by the states in the Great Lakes region to act as a guide for the prevention and management of any future possible outbreaks of oak wilt in Ontario. The focus will be on oak wilt management specifically in the Great Lakes region because the states in this area share similar geographic and climate characteristics with Ontario (Great Lakes Coastal Resilience, 2016). The expected outcome of this research is that a useful collection of information concerning oak wilt management best practices in the U.S. will be able to inform management strategies or response plans for future outbreaks of oak wilt in Ontario.

Objectives:

1. Conduct a literature review of how the eight Great Lakes states (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin) are currently managing oak wilt
2. Create a matrix for these states displaying the level of oak wilt management for different criteria
3. Quantify which states' management strategies have the least risk associated with the spread of oak wilt
4. Examine current treatment options and recommendations to minimize the risk of oak wilt spread in Ontario

3. Methods

3.1 Literature Review

First, a comprehensive literature review of the spread, management, and prevention of oak wilt in the U.S Great Lakes region was conducted in order to describe oak wilt management best practices. The resources that were used for this analysis include peer-reviewed journal

articles, library catalogues, university publications, government websites and reports, professional websites, and other credible sources of information, where applicable.

3.2 Matrix Creation

Second, a matrix was created based off of the most common and ambitious examples of state-led oak wilt management activities apparent throughout the eight Great Lakes states. The criteria that were chosen were pruning guidelines, harvest guidelines, nursery stock restrictions, firewood restrictions, quarantine zones, replacement trees, state-university partnerships, reporting systems, cost-share programs, oak wilt management plan, aerial surveys, public education, and research. In order to create the matrix, research was conducted on each of the eight Great Lakes states' oak wilt management efforts primarily through each state's Department of Natural Resources (DNR) or other environmental regulatory agency (Department of Environmental Conservation in New York, Department of Conservation and Natural Resources in Pennsylvania). Supplementary materials were also used such as peer-reviewed journal articles as well as other government reports and publications, including annual federal 'Forest Health Highlights' reports for each state. All information used in the matrix was obtained from publicly-available information and sources, and it is important to note that government officials were not contacted in order to fill any specific knowledge gaps for the matrix. The matrix is intended to demonstrate how each of the eight Great Lakes states are currently managing oak wilt in their jurisdictions based off of publicly available data.

4. Results

4.1 Literature Review

4.1.1 Detection

Early detection and confirmed diagnosis of oak wilt infection centres are important first steps to the management and suppression of oak wilt (Juzwik et al., 2011; Wilson, 2005). Aerial surveys are commonly used to locate new oak wilt infection centres since oaks exhibiting wilting or defoliation in the middle of the growing season, as well as infection centres spreading outwards in a circular formation, are easily seen from an aerial view (Koch et al., 2010). Although oak wilt does present symptoms in both red and white oaks, a confirmed diagnosis of oak wilt must be achieved in a lab where samples are placed in a pure culture and results are achieved within 5-14 days (Juzwik et al., 2011). In the U.S., state universities typically have these plant diagnostic labs which will accept samples from the public in order to diagnose oak wilt (Wilson, 2005).

4.1.2 Prevention

Preventing the introduction and spread of new oak wilt infection centres is more favourable and less costly than trying to eradicate oak wilt once it has become established (Juzwik et al., 2011). In order to prevent the aboveground transmission of oak wilt through insect vectors, it is important to avoid pruning and harvesting activities that may cause fresh wounds on healthy oak trees during the period when nitidulid beetles are most active (Juzwik et al., 2011). The high-risk period for the transmission of oak wilt by nitidulid beetles in the Great Lakes region is April to mid-July (Ambourn et al., 2005; Juzwik et al., 2011). However, some studies have found that it is still possible for contaminated nitidulid beetles to spread oak wilt outside of this high-risk period as late as October or even November (Ambourn et al., 2005; Juzwik, 1986).

It has also been recognized that due to climate change and the shifting of seasons, spring temperatures often occur earlier than what has been perceived in the past, therefore some recommend not pruning as early as March, or whenever temperatures get as warm as 10° C (50° F) (Wisconsin DNR, 2018b). If it is necessary to prune an oak during this period, or if a wound occurs naturally such as through wind damage, then a tree wound paint or wound dressing should be applied immediately (Wilson, 2005).

People can also help prevent the spread of oak wilt by not moving firewood (Wilson, 2005). Firewood from infected red oak trees are still able to form fungal mats and contribute to the aboveground spread of oak wilt (Wilson, 2005). This is particularly dangerous when infected firewood is transported to an area that was previously unaffected by oak wilt (Wilson, 2005). It is believed that oak wilt was introduced to the previously uninfected states of New York and Texas through transportation of infected firewood or logs (Wilson, 2005). Oak wilt has now been found in four counties in New York (New York DEC, 2018a) and 76 counties in Texas (Texas A&M Forest Service, 2018), demonstrating the importance of not moving firewood. There is also a possibility of oak nursery stock becoming infected with oak wilt and spreading the infection long distances following commercial sale (Wilson, 2001). Although nursery stock has not been as widely recognized as a means of spreading oak wilt as other methods such as movement of firewood, it is still a possibility and therefore restrictions on the movement of oak nursery stock could reduce this risk (New York DEC, 2018b).

4.1.3 Root Graft Barriers

The goal of installing root graft barriers is to disrupt root grafts in order to stop the belowground spread of oak wilt (Koch et al., 2010). This is executed by using machinery such as a vibratory plow or trencher to sever root connections between infected trees and healthy oaks (Wilson, 2005). For trenching to be successful, a root graft barrier must be at least 4-5 feet deep and strategically placed in order to surround all symptomatic and asymptomatic trees that are likely to be infected by oak wilt and to sever the connections between them and healthy trees (Bruhn et al., 1991; Cummings-Carlson et al., 2010). Root graft barrier location should be selected by oak wilt professionals and it is suggested that they should be chosen in August when it is likely that most infected trees will have displayed symptoms (Cummings-Carlson et al., 2010). The diameter of the trees, the distance between the trees, and the type of soil or drainage characteristics in the area will all determine the likelihood of root grafts, and thus where a root graft barrier will need to be applied (See Appendix) (Cummings-Carlson et al., 2010).

It is possible for re-grafting of roots to occur over time, therefore trench inserts can be applied as a supplementary method of management that will help to extend the life of root graft barriers (Koch et al., 2010). Trench inserts should be water-permeable such as Typar or BioBarrier so that root growth is not directed around the barrier, as this can facilitate re-grafting (Bruhn et al., 1991). This additional measure can be particularly useful in urban areas that want to limit the disruption caused by re-applying root graft barriers or in areas with valuable landscape trees that need extra protection (Bruhn et al., 1991).

4.1.4 Tree Removal

After root graft barriers have been put in place, red oaks that have the potential to produce fungal mats must be removed from inside the root graft zone to prevent the aboveground spread of oak wilt (Koch et al., 2010). Although it is possible to only remove trees that have been confirmed as infected, there is a risk of infected trees appearing asymptomatic and being left

behind, contributing to the spread of oak wilt (Koch et al., 2010). It has thus been suggested that all oak trees within a root graft barrier zone should be removed in order to be certain that all infected trees are cut (Koch et al., 2010). It is important to note that root graft barriers must be put in place before infected trees are cut because the removal of living infected trees can accelerate the movement of the fungus into adjacent trees through existing root grafts (Wilson, 2005). Once trees have been felled, the wood must be debarked, burnt, dried, chipped, covered with plastic, or undergo an accepted chemical treatment in order to ensure that fungal mats are not able to form on the wood (Koch et al., 2010).

4.1.5 Girdling & Herbicides

An alternative method to root graft barriers is the use of girdling and herbicides to limit the spread of oak wilt (Cook, 2018). Along the perimeter where a root graft barrier would have been placed, all infected trees should be double-girdled approximately 2 inches into the wood by chainsaws and then have an herbicide such as Garlon applied to the cuts (Cook, 2018; Cummings-Carlson et al., 2010). The goal is that the applied herbicides will be able to kill roots and thus stop the spread of oak wilt through root grafts (Cook, 2018). Studies in the Great Lakes region have shown that this method is not as effective as installing root graft barriers and removing infected trees because herbicides are not generally able to kill roots completely or quickly enough (Cummings-Carlson et al., 2010). However, this method is an important tool in areas where trenching and installing root graft barriers is not economically or logistically feasible (Cummings-Carlson et al., 2010).

4.1.6 Fungicides

The fungicide propiconazole is another management tool that has been used to treat oak wilt either preventatively or therapeutically, although fungicides are not able to cure trees of oak wilt (Koch et al., 2010). Fungicide treatment is an important tool used in the management of oak wilt, particularly when trying to manage on a smaller scale for individual trees, such as important landscape trees in urban areas (Koch et al., 2010). For oak trees that have not yet been infected, preventative treatments can be applied by injecting propiconazole at root flares before infection and repeating injections every 2-3 years (Koch et al., 2010). Evidence suggests that preventative treatments have been able to delay or prevent symptoms and mortality of both white and red oak groups, with stronger success rates in the white oak group (Koch et al., 2010).

Therapeutic treatments applied to already infected trees are not able to cure the tree of oak wilt, however treatments have been found to delay the development of symptoms and decrease mortality of trees in the white oak group (Koch et al., 2010). Therapeutic treatments are less successful on trees in the red oak group, however it is possible to delay symptoms on red oak trees if the treatment is applied early enough so that less than 25% of the crown has wilted from infection (Koch et al., 2010). Propiconazole injection can prevent the formation of fungal mats and can prevent or slow the symptoms of oak wilt for years, which is valuable in the management of oak wilt (Koch et al., 2010).

4.1.7 Oak Wilt Management Plans

Oak wilt management plans are useful guiding documents that can help a state strategically coordinate oak wilt management activities (Hasset et al., 2018). It is beneficial to have an official guiding document that explains the highest priority areas, regulated areas, the state's goals, plans for eradication measures, prohibited or required actions, and strategies for

research and education within the state (Hassett et al., 2018). Management plans can help to enact consistent management activities and designate roles and responsibilities, creating a more efficient process (Hassett et al., 2018). Without knowing what the problem is or how the state will proceed to manage it within a designated period of time, it is difficult to strategically manage oak wilt across the landscape.

4.1.8 Public Education

Education of the public is important to raise awareness of what symptoms to look for, how to limit the spread of oak wilt and how to manage oak wilt on infected properties (Kokotovich & Zeilinger, 2011). Education is especially important in areas that have not yet been infected but are at high risk of infection, or recently infected areas where people may not know much about oak wilt (Hassett et al., 2018). State efforts should be made to not only educate local landowners, but also professionals such as loggers, arborists, and landscapers through workshops and conferences so that they can learn prevention strategies such as when not to prune or harvest (Hassett et al., 2018).

4.1.9 Cost-share programs

Oak wilt management activities such as tree removal and implementation of root graft barriers can be expensive (Kokotovich & Zeilinger, 2011). There is a risk of private landowners finding oak wilt management on their properties too expensive and therefore not implementing appropriate management activities, effectively contributing to the spread of oak wilt across the landscape. Cost-sharing programs provided by the state or in collaboration with the federal government provide an incentive for landowners to manage oak wilt on their property, as the state will pay for a portion of the costs (Shields, 2017). Another option for states to help mitigate the loss of trees and further reduce the financial burden of oak wilt management is by providing replacement trees for landowners following the removal of an infected oak on their property (Hassett et al., 2018).

4.1.10 Research

There is already a large research base on oak wilt available, although additional region-specific research is required. For example, Michigan State University is conducting research on the best Michigan-specific oak wilt control measures, since what works well for one state may not always be the best for management in another state (Michigan DNR, 2017). There is also a stated need for additional research on oak wilt vectors and whether trees are vulnerable to infection in the early spring and fall (Michigan DNR, 2017). If a state can research the best management practices as well as the main causes of oak wilt spread in their state, there is a better chance of limiting the impact of oak wilt in that region.

4.2 Matrix

Throughout this research on oak wilt management in the U.S., the most common and most ambitious examples of oak wilt management enacted by the eight Great Lakes states emerged as the criteria for the creation of the matrix. The specific indicators used for each criterion in the matrix (Figure 1) can be seen below in Table 1. In order to read the matrix in Figure 1, it is important to note that in general black and darker colours indicate the least risk of oak wilt spread, whereas white and lighter colours indicate the most risk of oak wilt spread. Specific explanations of criteria and indicators can be found in Table 1.

Table 1. Criteria and specific indicators created for the oak wilt management matrix

CRITERIA	QUESTION	INDICATORS	
Pruning Guidelines	What time period does the state recommend avoiding pruning activities on oaks?		Recommends not pruning March - November
			Recommends not pruning April - October
			Recommends not pruning March - July
			Recommends not pruning April-July
Harvest Guidelines	Does the state provide restrictions and/or recommendations for harvesting activities that reduce risk of oak wilt spread?		The state provides restrictions or recommendations for harvesting activities
			The state does not provide restrictions or recommendations for harvesting activities
Nursery Stock Restrictions	Does the state have restrictions on the movement of oak nursery stock?		The state has restrictions on movement of oak nursery stock
			The state does not have restrictions on movement of oak nursery stock
Firewood Restrictions	What are the state's laws or recommendations concerning the movement of firewood?		The state has a firewood movement law specific to oak wilt
			The state has non-legally binding recommendations concerning the movement of firewood & oak wilt
			The state has firewood restrictions or recommendations, but oak wilt is not mentioned
Quarantine Zones	Does the state have oak wilt quarantine zones to reduce the risk of spread?		The state implements quarantine zones to limit the spread of oak wilt
			The state does not implement quarantine zones in areas affected by oak wilt
Replacement Trees	Does the state provide replacement trees to landowners who have removed an infected oak on their property?		Yes, the state provides replacement trees to landowners
			No, the state does not provide replacement trees to landowners
State University Partnerships	Does the state have a partnership with a state university which helps to disseminate information and test possible oak wilt samples for the public?		Yes, the state is partnered with its affiliated State University with respect to oak wilt info and sample testing
			No, the state is not partnered with its affiliated State University with respect to oak wilt info and sample testing
Reporting System	Does the state have an oak wilt reporting system for the public in place such as a telephone number or e-mail to contact in case of suspected new cases of oak wilt?		Yes, the state has a reporting system for oak wilt in place
			No, the state does not have a reporting system for oak wilt in place
Cost-Share Program	Does the state have cost-sharing programs or grants available to provide funding to individuals or regions who conduct oak wilt management		Yes, there are cost-sharing programs and/or grants available for oak wilt management
			No, there is no evidence of current cost-

	activities?		sharing programs or grants for oak wilt management
Oak Wilt Management Plan	Does the state have a specific document dedicated to a management plan for oak wilt within the state?		Yes, the state has created an oak wilt management plan
			No, the state has not created an oak wilt management plan
Aerial Surveys	Does the state conduct aerial surveys and to what degree do these surveys focus on oak wilt?		The state conducts aerial surveys specifically to identify oak wilt
			The state conducts aerial surveys for a number of reasons & mentions oak wilt as one reason
			The state conducts aerial surveys, but oak wilt is not mentioned specifically
			The state does not appear to conduct aerial surveys
Public Education	Does the state provide public education concerning oak wilt in the form of public service announcements, clinics, workshops, training, etc.?		The state does make an effort to provide public education on oak wilt
			There is no evidence of the state providing public education on oak wilt
Research	Does the state make an effort to conduct state-specific research on oak wilt?		The state's DNR (or equivalent department) or State University researches oak wilt
			No evidence of state-supported oak wilt research

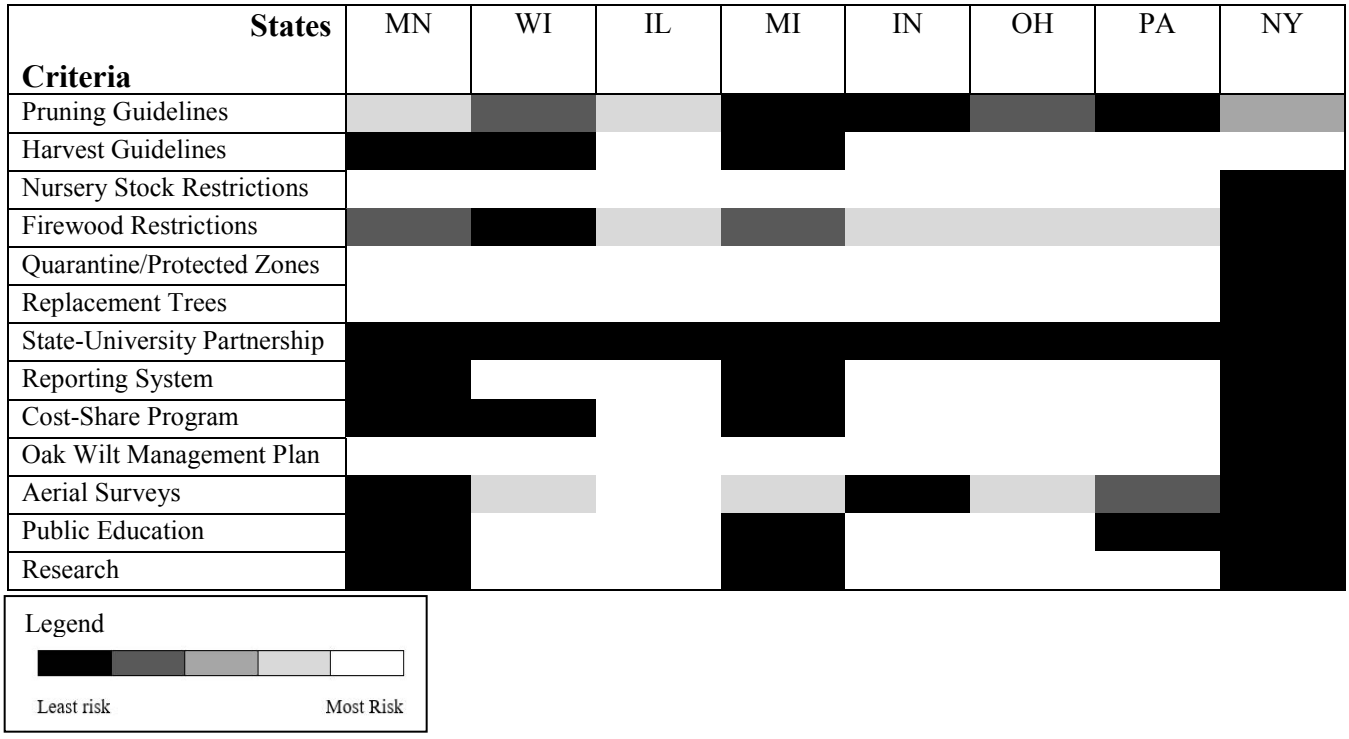

Figure 1. Matrix depicting oak wilt management activities carried out by each of the eight states in the Great Lakes region. Generally, black indicates least risk of spreading oak wilt and white indicates most risk of spreading oak wilt. For specific indicators for each criterion, please see Table 1.

5. Discussion

5.1 States with High Risk

Illinois and Ohio have the most risk associated with their oak wilt management efforts. Ohio has relatively strong pruning guidelines by recommending not pruning from April to October whereas Illinois only recommends not pruning during the high-risk period from April to July (Bonello, 2009; Miller, 2012). Pruning guidelines that only recommend not pruning in the high-risk period are sufficient, however there is still a risk of aboveground spread by nitidulid beetles in the late summer and fall (Juzwik, 1986). Both Illinois and Ohio have firewood movement restrictions that do not explicitly mention oak wilt at all, but rather focused exclusively on other pests such as Emerald Ash Borer (EAB) or gypsy moth (Don't Move Firewood, 2018; Illinois Department of Agriculture, 2018). Some states may see EAB or gypsy moth as a higher priority, however it is dangerous not to mention oak wilt at all in firewood movement restrictions as firewood movement does provide a significant risk of spreading oak wilt to unaffected areas (Juzwik et al., 2011).

Ohio does conduct aerial surveys, however oak wilt is not mentioned specifically as a forest health issue that is looked for during these surveys (Ohio DNR, 2014). Illinois does not appear to currently be conducting aerial surveys at all, which can limit the state's ability to find new infection centres and monitor the rate of spread. Neither Illinois or Ohio have harvest guidelines, nursery stock restrictions, quarantine zones, replacement trees, reporting systems, cost-share programs, oak wilt management plans, public education efforts, or research efforts. The absence of all these criteria can increase the risk of oak wilt spread in these states.

Indiana and Pennsylvania have somewhat less risk associated with their oak wilt management efforts when compared to Illinois and Ohio. Indiana and Pennsylvania both have the strongest pruning guidelines of avoiding pruning from March through November (Creswell, Ruhl, Beckerman & Sadof, 2018; Moorman, 2014). Indiana is also found to conduct yearly aerial surveys specifically for the purpose of identifying oak wilt (Indiana DNR, 2017). Pennsylvania also conducts yearly aerial surveys to assess forest health as well, and oak wilt is included as one of the multiple indicators that are looked for (Pennsylvania DCNR, 2017). In Pennsylvania, the state contributes to public education on oak wilt through the Penn State University Extension which held a community tree workshop in 2018 that discussed oak wilt (Pennsylvania Land Trust Association, 2018). Indiana does not appear to have any public education efforts regarding oak wilt. Similar to Illinois and Ohio, Indiana and Pennsylvania both do not appear to have harvest guidelines, nursery stock restrictions, quarantine zones, replacement trees, a reporting system for the public, cost-share programs, an oak wilt management plan, or state efforts to research oak wilt. The absence of these management efforts can increase the risk of oak wilt spread in these states.

5.2 States with Low Risk

Minnesota, Wisconsin, and Michigan's oak wilt management efforts have less risk of oak wilt spread within their state borders when compared to the high risk states. These three states are the only states in the Great Lakes region to have harvest guidelines that aimed to limit the spread of oak wilt through harvesting activities (Michigan DNR, 2016; Minnesota DNR, 2018b; Wisconsin DNR, 2018c). Of the three states, Minnesota's harvest guidelines are the least comprehensive as the Minnesota DNR simply recommends that timber harvesting near valuable oak forests in the high-risk zone should be postponed from April 1-July 15 in the southern half of the state and April 15-July 15 in the northern half of the state (Minnesota DNR, 2018b). In

Michigan, harvesting guidelines are somewhat stronger as harvesting on state properties is prohibited between April 15-July 15 (Michigan DNR, 2016). Private landowners are encouraged to adhere to the same guidelines, although harvesting is not prohibited on these private properties in Michigan (Michigan DNR, 2016).

The Wisconsin DNR established the most comprehensive harvest guidelines out of these three states by creating a rule-based online guide for site-specific harvesting (Wisconsin DNR, 2018c). This guide was developed by a diverse group of stakeholders including industry, counties, DNR foresters, biologists, silviculturalists, the federal U.S. Forest Service and a variety of associations (Wisconsin DNR, 2018c). The Wisconsin DNR insists that the guidelines should be used on state properties or if the property is a part of a county forest program or the Managed Forest Law program (Wisconsin DNR, 2018c). Restrictions or guidelines on logging can be helpful in limiting the spread of oak wilt, although it can be assumed that it may not seem attractive to states to limit their logging activities for three months out of the season, and thus lose time and money. This may be one reason that the majority of the Great Lakes states do not enforce harvesting guidelines, particularly on private lands.

Wisconsin, Michigan, and Minnesota each have cost-sharing programs that could encourage local governments and individual landowners to take part in oak wilt management activities (Kokotovich & Zeilinger, 2011). In Wisconsin, communities may be eligible for cost-sharing programs such as the Urban Forestry Grant Program which has worked with municipalities to protect oaks from oak wilt in the past (Wisconsin DNR, 2017). In Michigan, the Invasive Species Grant program aims to control invasive species in Michigan through collaboration between the Michigan DNR, Michigan Department of Environmental Quality, and the Michigan Department of Agriculture and Rural Development (State of Michigan, 2018). In 2018, two grants were approved through this program specifically mentioning oak wilt management (State of Michigan, 2018). These two grants were *Oak Wilt Management and Education Through Collaboration* for the Aboriculture Society of Michigan ($344,761) and the *BCK CISMA Strategic Plan Implementation* for the Barry Conservation District ($370,480) (State of Michigan, 2018). In 2017, the Manistee Conservation District in Michigan also received a grant from the Michigan Invasive Species Grant program to prevent and treat oak wilt, which allowed for the grant to pay for 85% of landowner's treatment costs in 9 counties in Michigan (Shields, 2017).

From 1991-2008, the Minnesota DNR collaborated with the U.S. Forest Service through the ReLeaf program which provided grants to local governments and private landowners to treat local oak wilt infection centres (Kokotovich & Zeilinger, 2011). The ReLeaf program used $4.2 million of federal funds and $7.4 million of state and private landowner funds to implement root graft barriers and remove infected trees (Juzwik et al., 2011). The program was successful in reducing the density of oak forest affected by oak wilt to 0.5 ha/km^2, and 3 years after the treatment, 70-99% of treatment sites showed no further expansion of oak wilt infection centres (Juzwik et al., 2011). The ReLeaf program is an example of a successful cost-sharing program that assisted landowners with the costs of oak wilt management and reduced the spread of oak wilt. Funding for the program was uncertain and variable, which may have been the cause of the program's end in 2008 (Carroll, 2004). After the end of the ReLeaf program, the Minnesota DNR stated that they expected that oak wilt infection centres would get larger and spread further since oak wilt management activities were now entirely dependent on individual landowners and their willingness or ability to finance oak wilt control measures (Division of Forestry, 2011). Although the ReLeaf program no longer exists, there are still some cost-sharing opportunities for

landowners of private forest land in Minnesota through the Minnesota DNR Cooperative Forest Management program (Minnesota DNR, 2018a). This program provides financial support for private forest managers practicing good forest stewardship on their woodlots, which could include oak wilt management activities (Minnesota DNR, 2018a).

The presence of harvest guidelines and cost-sharing programs can lower the risk of oak wilt spread in these three states. Minnesota, Wisconsin and Michigan also each have pruning guidelines, firewood restrictions, and aerial surveys to some degree (Juzwik & Russell, 2018; Michigan DNR, 2018; Wisconsin DNR, 2018a). Additionally, Minnesota and Michigan have a reporting system in place for the public to report new infection centres as well as public education and research efforts made by the state (Division of Forestry, 2017; Michigan DNR, 2017; Michigan State University, 2018; Minnesota DNR, 2018b; Odom, 2017). Recently, Michigan DNR has even collaborated with the CFIA and Ontario Ministry of Natural Resources and Forestry (OMNRF) to hold information sessions in Windsor to increase awareness and prevent spread (Michigan DNR, 2017). The presence of all these oak wilt management efforts in Minnesota, Wisconsin and Michigan reduce the risk of oak wilt spread in these states and make them more risk-adverse than states such as Ohio and Illinois.

5.3 New York: The Most Risk-Adverse State

The state with the least risk of oak wilt spread in the Great Lakes region is New York. New York has the strongest fulfillment of some of the most common criteria such as firewood restrictions, aerial surveys, public education, research, cost-share programs, and a reporting system for the public. Additionally, New York also demonstrated some of the most ambitious examples of oak wilt management that no other states had such as the creation of an oak wilt management plan, quarantine zones, nursery stock restrictions, and replacement trees. Therefore, the state of New York has the least risk of spreading oak wilt throughout the Great Lakes region.

New York is the only state in the Great Lakes region that has a strategic oak wilt management plan with the goal of preventing, detecting, and managing oak wilt throughout the state (Hassett et al., 2018). This management plan also includes guidelines for quarantine zones, nursery stock restrictions, and the provision of replacement trees to landowners (Hassett et al., 2018). Within the New York State Oak Wilt Management Plan, the establishment of quarantine zones are also discussed (Hassett et al., 2018). New York Environmental Conservation Law section 9-1303 established quarantine zones in the state which allows a quarantine to be placed around a neighbourhood, town, or county with confirmed cases of oak wilt in order to reduce the risk of spreading oak wilt to unaffected areas (New York DEC, 2018b). This law also gives the New York Department of Environmental Conservation (DEC) the authority to enter onto public and private lands to carry out oak wilt management activities on those lands (New York DEC 2018b, New York DEC, 2018c). This is possibly one of the strongest oak wilt management laws within the Great Lakes region as it gives the DEC the authority to conduct oak wilt management activities on private land. In other states, the decision to manage oak wilt on private land is mainly up to private landowners who may choose not to carry out oak wilt management activities (New York DEC, 2018b). New York currently has quarantine zones in all of Suffolk County as well as Canandaigua, Glenville, and Brooklyn (New York DEC, 2018c).

New York is also the only state in the Great Lakes region that has restrictions on the movement of nursery stock (New York DEC, 2018b). Oak nursery stock over two years of age within designated quarantine zones in New York is only allowed to be moved outside of quarantine zones with a permit from the New York State Department of Agriculture and

Markets, Division of Plant Industry (New York DEC, 2018b). Nurseries are required to specify their production practices and must maintain records of their inventory and sales of oak materials (New York DEC, 2018b). New York is also the only one of the Great Lakes states to provide replacement trees for landowners who have removed infected oak trees on their properties (Hassett et al., 2018). The provision of replacement trees helps to reduce the financial burden on private landowners with the additional benefit of mitigating the loss of green infrastructure, canopy cover, and ecological benefits from trees in the state (Hasett et al., 2018).

5.4 Criteria Organization

In Figure 2, the criteria from the matrix have been organized from most common to least common. New York was the only state to have an oak wilt management plan, offer replacement trees, create quarantine zones and have nursery stock movement restrictions. These criteria are thus the least common and most ambitions examples of oak wilt management in the Great Lakes region. In contrast, every state had a partnership with their respective state university in terms of testing samples and disseminating information. Every state also had pruning guidelines and a firewood movement restriction to some degree, although they were not always specific to oak wilt in each state. These criteria are the most common and least ambitious criteria, but they can also be seen as building blocks or important first steps of oak wilt management since every state saw it important to have these to some extent.

These criteria should not be seen as an exhaustive list of all management efforts, nor a list of something that would be appropriate for all states. For example, oak wilt was only found in New York in 2008 and has a relatively small spread throughout four counties in the state, therefore efforts to limit spread and establishment are appropriate. It would be less appropriate for a state such as Illinois where oak wilt has been established since the mid-1900s and is found in every county in the state to invest a lot of resources into oak wilt management, as there is a much lower chance of eradicating oak wilt. It is also important to note that state management of oak wilt is highly dependent on the availability of federal and state resources in general, as management for oak wilt requires funding, effort, and time. Oak wilt management is not only in competition with the management of other invasive pests but is also a reflection of entire state budgets available.

6. Recommendations for Ontario

6.1 Recommendations

The following recommendations have been created for Ontario's current and future management of oak wilt:

1. Continue with public education & research
2. OMNRF to be responsible for the creation of a provincial management strategy
3. Collaboration between federal and provincial governments should be used for monitoring and financial support
4. Oak wilt management in the Great Lakes region, such as the example put forward by the state of New York, should be used as a guiding example for the province
5. Promote the development of oak wilt professionals in the province and/or continue to foster relationships with oak wilt professionals in the U.S.

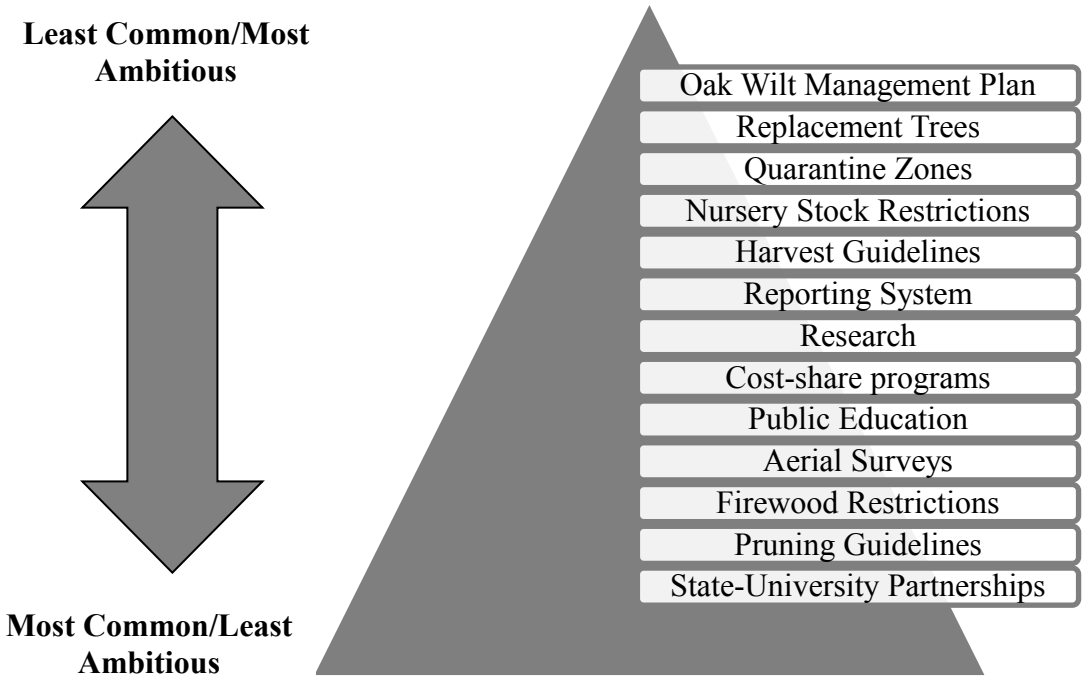

Figure 2. Matrix criteria organized from least common to most common.

First, the province of Ontario should continue with and expand on efforts to educate the public about oak wilt through workshops and public service announcements, as well as invest in region-specific oak wilt research on timing and methods of spread. Second, it has been acknowledged in the U.S. that individual municipalities do not have the funding and resources available to manage oak wilt at a municipal level, therefore it is recommended that oak wilt should be managed at a provincial level in Canada (Kokotovich & Zeilinger, 2011**).** The provincial government, likely through the OMNRF, will therefore need to be responsible for creating a province-wide oak wilt management strategy in order to designate roles and appropriate actions in the event of an oak wilt outbreak. Third, cost-sharing programs have been proven to be an effective method of improving public participation in oak wilt management activities in the Great Lakes region. Therefore, collaboration between the Canadian federal government and Ontario's provincial government should also be used to help implement monitoring and fund cost-sharing programs.

Fourth, oak wilt management in the Great Lakes region as described in this paper should be used to guide Ontario's strategies. Particularly, New York has provided an excellent example of how a newly-infected state can reduce the risks of oak wilt spread. Ontario could learn from this example in case of future oak wilt infections in the province. Fifth and finally, access to oak wilt professionals will be important in the future as they are familiar with the symptoms and diagnosis of oak wilt as well as how to properly manage the disease. This can be achieved through continued education of professionals in Ontario in order to appropriately train individuals for the diagnosis and treatment of infected oaks. Continued collaboration with existing professionals outside of Ontario in states such as Michigan to assist with education efforts will also be important.

6.2 Partnerships

The OMNRF should be the head of strategic planning, however strategic partnerships will be important to oak wilt management in the future. The federal government through Natural Resources Canada and the CFIA will be important partners for monitoring and funding of oak wilt management activities. Provincial government entities such as the Ontario Invasive Species Centre and the Ontario Ministry of the Environment, Conservation, and Parks can help provide funding, education, connections, and management support. Municipal governments in municipalities where oak wilt is found to occur will be important participants in managing oak wilt on a local scale. Conservation authorities have also been used in the U.S. to assist in the implementation of projects, therefore conservation authorities such as the Essex Region Conservation Authority in Windsor could be used to help with oak wilt eradication efforts. Finally, partnerships with universities could be useful for research, information dissemination, and diagnosis of lab samples.

6.3 Legislation

Legislation that will be important to oak wilt management in Ontario include the Invasive Species Act and the Pesticides Act. The Invasive Species Act gives the province a legislative framework to regulate invasive species (Neinhuis & Wilson, 2018). Through this act, prohibited or restricted species are listed, and the ministry has the power to designate invasive species control areas on both public and private lands (Neinhuis & Wilson, 2018). Oak wilt is not currently listed under the Invasive Species Act, however if it does become a problem in Ontario the disease should be added so that the provincial government has the full power to manage it across the landscape (Neinhuis & Wilson, 2018). Second, the fungicide propiconazole is listed as a Class 9 pesticide in Ontario and is therefore banned under the Pesticides Act (Ministry of the Environment, Conservation and Parks, 2015). This fungicide is used as an important tool for oak wilt management in the U.S. and therefore it would be an extremely useful tool to use in Ontario's oak wilt management. It is therefore recommended that propiconazole become available for use by trained tree care professionals in Ontario in order to manage oak wilt.

7. Conclusion

Oak wilt is an incurable disease that has had devastating impacts on urban and rural forests in the U.S. There is a high risk that oak wilt will be introduced to Canada, specifically southern Ontario, due to Ontario's close proximity to infection centres across the border. Preventing the spread of oak wilt is much easier and less costly than trying to eradicate oak wilt once it has been established across the landscape. Therefore, Ontario now has an opportunity to prepare for the possibility of an oak wilt infection by learning from neighbouring states in the Great Lakes region. Minnesota, Wisconsin and Michigan represent states that have a low risk of oak wilt spread due to the high effort put into oak wilt management activities in these states. The state in the Great Lakes region with the overall lowest risk of oak wilt spread was New York. New York had strong fulfillment of the most common oak wilt management criteria and additionally introduced innovative and ambitious strategies to combat the spread of oak wilt. This level of effort may be due to the fact that oak wilt was found in New York relatively recently in 2008. As a newly-infected state, New York can provide a good example of oak wilt management efforts for Ontario in the event that oak wilt does come to Canada.

Ontario should continue with public education and research efforts as well as begin strategically planning for oak wilt at the provincial level. Collaboration and partnerships between

different levels of government as well as oak wilt professionals and non-government organizations can be useful in the future of oak wilt management in the province. If Ontario prepares now, the negative impacts of oak wilt on Canadian forests can be prevented for generations to come.

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Appendix

Placement of Root Graft Barriers

The diameter of the trees, the distance between the trees, and the type of soil or drainage characteristics in the area will all determine the likelihood of root grafts, and thus where a root graft barrier will need to be applied (Cummings-Carlson et al., 2010). Figure A1 demonstrates how a root graft barrier should be chosen. First, the diameter at breast height (DBH) of an infected tree and the DBH of a nearby seemingly healthy tree should be measured and the two values should be combined, followed by the measurement of the distance between the two trees (Cummings-Carlson et al., 2010). Depending on the location's soil type, if the trees are closer than the inter-tree root graft distance listed in Figure A1 for the combined DBH, then the barrier should be placed outside of the healthy tree, effectively including it in the red root graft zone depicted in Figure A2. If the trees are further than the listed inter-tree distance in Figure A1, then the barrier should be placed inside of the healthy tree, excluding it from the red root graft zone depicted in Figure A2 (Cummings-Carlson et al., 2010). This is one strategy of placing root graft barriers, however others suggest that a constant distance should be used based off of annual rates of oak wilt advance such as 15.2-18.3 m in the midwestern U.S. (Koch et al., 2010). Studies conducted in 1994 showed that vibratory plowing ranged from being 76-100% successful in stopping the belowground spread of oak wilt (Koch et al., 2010).

Figure A1. Root grafting distances, based on a 99% confidence level (Hassett, Kotary & Cole, 2018, p. 4)

Combined DBH (in.)	Inter-tree root graft distances (feet) for soil types		
	Sandy soils (ft)	Loamy-sand soil (ft)	Sandy-loam/loam soil (ft)
2	5.1	4.1	2.9
4	10.2	8.1	6.0
6	15.3	12.2	8.9
8	20.4	16.3	11.8
10	25.5	20.3	14.8
12	30.6	24.4	17.7
14	35.7	28.5	20.6
16	40.8	32.5	23.7
18	46.0	36.6	26.6
20	51.1	40.6	29.5
22	56.2	44.7	32.5
24	61.3	48.8	35.5
26	66.4	52.8	38.5
28	71.5	56.9	41.4
30	76.6	61	44.3
32	81.7	65	47.4
34	86.8	69.1	50.3
36	91.9	73.2	53.2
38	97.0	77.2	56.2
40	102.1	81.3	59.1
42	107.2	85.4	62.0
44	112.3	89.4	65.1
46	117.4	93.5	68.0
48	122.5	97.5	70.9
50	127.6	101.6	74.0

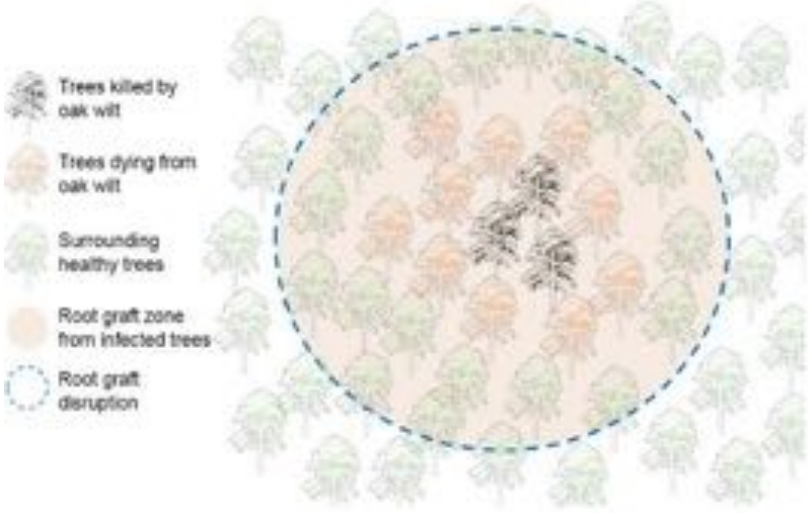

Figure A2. Diagram of root graft zone and root graft disruption in relation to infected and surrounding trees (Hassett et al., 2018, p. 4).