SECTION III

CURRENT AND POTENTIAL MANAGEMENT PRACTICES

INJECTION, INFUSION, AND SYSTEMIC MOVEMENT IN TREES

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ABSTRACT

Management of oak wilt often includes the use of systemic fungicides delivered by tree injection. Classic theory of sap movement being limited only to upward movement doesn't explain the efficacy of trunk-injected fungicides, whose site of action is in the root system. Movement of the xylem-mobile dyes, acid fuchsin, and saffranin O, after lower trunk/root flare injection, was found to occur both upward into the xylem of stems, twigs, and leaves, and downward into the xylem of woody roots, at most times of year. Similar patterns of movement of xylem-mobile dyes were observed on the following species tested: American chestnut, black birch, eastern hemlock, eastern white pine, red maple, red oak, weeping willow, white ash, and white birch. Downward movement of dye into root systems involved all ages of xylem tissues present within a root while upward movement was confined to the most recently formed xylem growth ring.

Key words: *Ceratocystis fagacearum*, dyes, fungicides, oak wilt

Trunk injection of systemic fungicides is often part of the management plan for the control of oak wilt (Appel 2007). Triazole fungicides delivered by trunk injection have been found to be effective in suppression of the oak wilt pathogen, *Ceratocystis fagacearum* (Wilson and Forse 1997, Wilson 2005). The ability of all systemic chemicals to suppress pathogens or control insect pests is dependent upon their systemic movement within the tree after injection. For systemic chemicals to move in the tree's vascular system is therefore dependent on the movement of sap within the tree.

The movement of sap from the roots to the top of tall trees has fascinated both scientists and others who wondered how a tree works. It is hypothesized that it is the loss of water (evaporation) from the leaves that causes a tension, or "pull", on many tiny water columns within wood (Campbell, Reece and Mitchell 1999). Since water is also cohesive, these combined forces can pull the water in a tree upward sometimes over 300 feet (100 meters) from the roots (Zimmerman 1983). This explanation for upward sap movement is known as the "cohesion-tension theory" and is widely accepted by tree scientists (Salisbury and Ross 1992). Since no corresponding theory has been proposed to explain the possibility of downward sap movement, it has often been concluded that sap flow only occurred in the upward direction.

However, experimental field data from those who studied sap movement in plants and vascular diseases of trees have reported evidence of downward movement for over 250 years (Banfield 1941). Many of these researchers used dyes or spore suspensions to track the downward movement of sap in trees. Banfield's studies on American elms demonstrated that both upward and downward movement occurred from injection points on the elm trees at equal speed. Extensive studies of sap movement by Greenidge (1958) using a sap mobile dye on a wide variety of trees, including American elm, balsam poplar, balsam fir, American beech, yellow birch, ironwood, sugar maple, white spruce, and white ash, supported the evidence of downward sap movement found earlier by Banfield (1941) and others.

Further evidence of downward movement of injected chemicals came form microinjection studies with the antibiotic oxytetracycline, which has been used to relieve symptoms of numerous bacterial diseases of trees, including bacterial leaf scorch (Kostka, Tattar and Sherald 1985), peach X-disease (Cooley, Tattar and Schieffer 1992), and lethal yellows of coconut palm (*Cocos nucifera*) (McCoy 1983). High populations of systemic bacteria within the root system have been associated with diseases caused by systemic bacteria (Sinclair, Lyons and Johnson 1987, Cha and Tattar 1991, Blanchard and Tattar 1997). However, it has puzzled scientists how a systemic chemotherapeutant, such as oxytetracycline, or a systemic fungicide, such as propiconazole, could be effective if xylem movement of injected materials only occurred in the upward direction. Preliminary studies by Tattar and Tattar (1999) presented evidence for downward movement in the xylem of trees following trunk injection with the use of xylem-mobile dyes.

The objectives of this study were (1) to determine the direction and magnitude of movement of trunk-injected materials within the xylem of trees using xylem-mobile dyes and (2) to determine how time of year of injection influences dye movement.

MATERIALS AND METHODS

The trees used in these studies were growing in the Shade Tree Laboratory Nursery in Hadley, MA and in the Cadwell Memorial Forest in Pelham, MA. Both these research facilities are part of the University of Massachusetts at Amherst. The trees ranged in size from 2 inches (5 cm) to 10 inches (25 cm) in stem diameter at 4.5 feet (1.4 meters) above ground. The following species were injected: red maple, *Acer rubrum*, eastern white pine, *Pinus strobus*, red oak, *Quercus rubra*, eastern hemlock, *Tsuga canadensis*, white birch, *Betula alba*, black birch, *B. lenta*, American chestnut, *Castanea dentata*, white ash, *Franxinus americana*, and weeping willow, *Salix babylonica*.

Tree injection wounds were made with a battery-powered drill (800 rpm) using an 11/64 inch (6 mm) high speed steel drill bit. Injection holes were made in the lower trunk and root flare areas and hole depths were between 1/4 inch (6 mm) and 1/2 inch (12 mm). In one study conducted during the 1997 summer season, however, injection wounds were made at 4.5 feet (1.4 meters) above ground to American chestnut and red oak trees. An unpressurized glass reservoir container, with an exit port at the bottom of the container, was filled with 25 to 50 ml of dye solution. The reservoir delivery system was attached via plastic (Tygon) tubing to a hollow plastic tube which was inserted into the injection wound, immediately after a drill-hole injection was made. The following xylem-mobile dyes at 2% w/v were each used during these experiments: acid fuchsin, gentian violet, and safranin O.

Trees were injected with the test dye solutions in late spring during leaf expansion through mid fall after leaf drop. Experiments were conducted over an 8-year period from 1998 through 2005. Dye injection studies were started either from 0800 to 1000, or from 1400 to 1600. In most experiments, injectors were left in the tree for 24 hours. Trees were harvested immediately after injector removal. In some experiments, dyes were injected in the morning, the experiments were terminated approximately 6 hours after injection, and trees were harvested in the afternoon. While in other experiments, trees were injected in the afternoon and harvested the next morning, approximately 16 hours after injection. Soil temperature was measured at 5 cm (2 inches) below ground, using a soil thermometer, at the starting time of each injection.

On most trees 10 cm (4 inches) and smaller in diameter, the woody roots were severed with a root ax and/or hand saw and the entire tree was examined. Soil was removed from roots by washing and the bark was peeled from the woody roots and stem. In some larger trees the root flare was exposed by removal of soil and only the large roots were cut with a chainsaw, approximately 20 to 50 cm (8 to 20 inches) from the trunk. All stem and root sections were photographed as soon as possible after the bark was removed.

Dye movement in both upward and downward directions in the xylem was assessed by visual examination of the leaves and by estimating the amount of xylem tissue stained by the injected dye after the bark was removed. We were usually able to follow patterns of dye movement throughout the test trees from the leaves to the roots.

RESULTS

The first studies were conducted in the fall during and after onset of leaf coloration and continued after leaf drop of deciduous trees. Dye patterns, regardless of species, were always bimodal, with some dye movement upward into the stem and downward into the roots from the injection sites at the root flare. Dye movement in the initial studies was approximately split between upward movement and downward movement. Later fall studies displayed progressively greater downward dye movement as soil temperatures declined from approximately 15°C (60°F) to 5°C (40°F). After complete natural leaf fall, dye movement was primarily downward until experiments were terminated in early November. These dye patterns were consistent with all the species studied, in both deciduous hardwoods and conifers. In addition, the dye patterns were also similar regardless of the dye solution used. Acid fuchsin and saffranin O were most easily observed.

Studies were also conducted during leaf expansion in late spring and continued into the summer when full leaf size of deciduous trees was attained. Our initial results were similar to early fall studies, with dye movement evenly split between upward and downward directions. Experiments conducted during summer were remarkably similar to those of late spring, but even with a progressive increase in upward movement, we always noted substantial downward movement. During moisture limiting soil conditions, downward movement was found to increase. Cross sections of roots revealed dye movement into several years of xylem tissue while stem cross sections of the same trees revealed dye confined only to springwood vessels of the current growth ring.

In an attempt to determine the speed of downward movement or upward movement, dye reservoirs were left on trees for fewer than 24 hours. However, even when dye reservoirs were in place for only 6 hours during day experiments and 16 hours during night experiments, bimodal movement was found. We noted on several occasions that, after downward movement into the roots, the injected dye would then reverse direction in the roots and progress upward on the opposite side of the stem.

In a study of the effect of the height of injection on systemic dye movement, American chestnut and red oak were injected at 4.5 feet (1.4 meters) above ground. Most of the acid fuchsin dye moved upward into the branches and foliage and only small amounts of dye moved downward, compared with similar trees that were injected at the root flare on the same dates and times.

DISCUSSION

Downward movement within xylem can be explained by the normal condition of the functioning xylem elements, which are under negative pressure or tension, and is consistent with the cohesion-tension theory of xylem movement. A break in the xylem elements, due to an injection wound, would allow movement of the injected solution in either upward and/or downward directions according to the forces within the xylem elements at the time of injection.

The results of this study agree with those of Banfield (1941), Greenidge (1955), and others who reported downward movement of dyes and fungal spores in the xylem of many tree species. The findings of the current study, based on dye delivery by trunk injection, combined with those of earlier researchers, can help to explain how materials injected into the sap stream at the root flare can have efficacy in the root systems of trees. This information is especially useful in explaining the control of root problems achieved using trunk injection of antibiotics, fungicides, insecticides, and micronutrients during the growing season with active leaf transpiration. For example, these findings may help to explain why trunk injection was found to be effective in the treatment of pathogens that are primarily transmitted through the root system, such as oak wilt (caused by *Ceratocystis fagacearum*), since the early 1990s (Osterbauer and French 1992, Appel 1994).

Osterbauer and French (1992) reported that location of injection sites on the root flare may have resulted in movement of the propiconizole into the root system since they could not detect the fungicide above a height of 3.0 meters. Although these researchers did not conduct any propiconizole assays of root tissues, results obtained in this study would support their conjecture of downward movement of the injected fungicide. One may also conclude from the results of the current study that downward movement of injected systemic chemicals is favored by placing injection sites in the root-flare zone.

Multi-year xylem sap distribution in roots would appear to explain vascular disease control beyond one growing season achieved using injectable fungicides, such as that reported by Osterbauer and French (1992) with propiconizole. Dye movement was found across the entire cross section of root xylem following lower trunk injection . It appears that portions of trunk-injected materials are transported downward into the roots and are then transported upward in the sapstream in the following season or seasons. This theory could also account for the efficacy of fall-injected materials in the following spring.

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EFFECTIVE LONGEVITY OF PROPICONAZOLE FOLLOWING INJECTION INTO *QUERCUS RUBRA*

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ABSTRACT

Propiconazole was injected into *Quercus rubra* to determine duration of efficacy against *Ceratocystis fagacearum*, the fungus that induces oak wilt. Eleven and 13 trees were treated preventatively in 2002 and 2003 respectively; these trees were subsequently inoculated with a conidial suspension of *C. fagacearum* at 0, 9.5, 14, 21.5, 23, 24, or 34 months following fungicide injection. Five- to six-foot (1.5- to 1.8-m) deep trenches isolated treatment groups. Control trees were located throughout the site and included trees either injected with fungicide, inoculated, or untreated and non-inoculated. Propiconazole-injected trees inoculated in May 2005, as late as 34 months following initial fungicide treatments, did not express wilt symptoms for at least three months; however, all untreated, inoculated control trees developed symptoms within six weeks. As of August 2006, over one year after final inoculations, 14 of the 24 treated and inoculated trees (including five of eleven trees inoculated at 34 months) remained symptomless. Results suggest that inhibition of *C. fagacearum* may occur even at 34 months post-injection.

Key words: *Ceratocystis fagacearum*, fungicide, oak wilt

Oak wilt is a lethal disease of oaks caused by the fungus *Ceratocystis fagacearum* (Bretz) Hunt. The pathogen invades the xylem inducing tylosis and gummosis in the host, which, in addition to fungal material, results in the blockage of water through sap tissues. Overland spread of *C. fagacearum* occurs via insect vectors, while local spread is primarily through root grafts that form between neighboring trees of the same species. Intravascular injections with a wide variety of antibiotics and fungicides have had limited success in treating or preventing oak wilt (Phelps, Kuntz and Ross 1966, Appel 1995). In 1987, however, Appel determined that live oaks (*Quercus fusiformis* and *Q. virginiana*) injected with the triazole fungicide, propiconazole, had significantly lower disease levels compared to untreated trees. Based on this study, propiconazole injection was deemed to be an effective treatment for oak wilt and was registered for use on live oaks in Texas (Appel 1995).

Osterbauer et al. (1992 and 1994) subsequently studied injection treatments in other species of red oak (subgenus *Erythrobalanus*) and white oak (subgenus *Leucobalanus*) in Minnesota and found that propiconazole could protect a treated tree for up to two years against root-graft spread. Additional research on propiconazole injection treatments has shown that white oaks typically respond well to fungicide injection and can often be treated therapeutically, whereas red oaks often succumb to wilt despite treatment if they already are infected (Osterbauer and French 1992, Osterbauer, Salisbury and French 1994, Eggers et al. 2005). Therefore, red oak injections are usually limited to high value trees with little or no symptoms of disease. Due to the high cost of treating trees (an average tree may cost a few hundred dollars to treat including chemical and labor costs), additional knowledge regarding the activity of propiconazole within a tree in relation to its distribution and to the distribution of the pathogen within the host is necessary for effective management strategies.

As the fungus can remain viable for several years in the roots of wilted trees, and spread through root grafts may take several years to occur, it is difficult to predict where the pathogen is within the root system at any given time (Yount 1955, Rexrode 1978). In addition, disease progression in root-infected trees is often delayed in comparison to trees inoculated above ground (Cobb, Fergus and Stambaugh 1965). Therefore, symptomless trees in naturally-infected stands may or may not already have the pathogen within their roots. Previous research has focused on the efficacy of propiconazole injection against root-graft transmission of *C. fagacearum* in stands where oak wilt was present. We investigated the longevity of propiconazole activity in a wilt-free oak stand in Michigan where root-graft transmission was prevented by trenching prior to experimentation.

MATERIALS AND METHODS

All oaks (*Quercus rubra*) used in the study were located on the same site on the Michigan State University campus and ranged from 16 to 51 cm diameter at breast height (dbh), with the average dbh equal to 30 cm (standard error ± 2.4). Trees at the site were arranged in six rows and had been established for several decades. The soil consisted primarily of Colwood-Brookston loam (62%) with Capac loam comprising the rest (38%). These series are characterized by deep, poorly drained, fine loamy soil. Five- to six-foot (1.5 to 1.8-m) deep trench lines were made using a Davis Fleetline 70+4 trencher, which isolated treatment groups by disrupting potential root grafts (Figs. 1 and 2). The experiment was replicated twice, first in July 2002 (Replicate 1) and then in June 2003 (Replicate 2). Forty-two trees were utilized in the study and an additional 21 trees at the site were maintained as negative controls (untreated and non-inoculated). Treatments consisted of trees injected with propiconazole and then inoculated with a wild-type *C. fagacearum* isolate, with the time interval between chemical injection and fungicide inoculation ranging from 0 (inoculated immediately following fungicide injection) to 34 months. Untreated, positive control trees were inoculated with the wild-type strain throughout the course of the study.

Since none of the fungicide-treated and inoculated trees from Replicate 1 developed symptoms by 2005, these 11 trees were inoculated a second time and included into a 34-month inoculation treatment. Therefore, at the conclusion of this study, all non-control trees from Replicate 1 had been inoculated twice: once at 0, 9.5, 14, 21.5, or 24 months after injection, and then again at 34 months post injection. In Replicate 2, trees from treatment groups 0, 9.5, and 14 months also remained symptomless in 2005 and so were incorporated into the 23-month treatment in 2005. Thus, the 23-month treatment group in Replicate 2 consisted of seven previously-inoculated trees and three trees that were only inoculated once, 23 months after fungicide treatment. Trees from Replicate 2, 24-month treatment, were inoculated only once at 24 months following injection.

Fungicide treatments with Alamo® (propiconazole 14.3%) were carried out via pressurized macro-injection into root flares with a 12V Flowjet pump according to the fungicide product label (Novartis Crop Protection, Greensboro, NC) in July 2002 (Replicate 1) and June 2003 (Replicate 2) (Fig. 3). Injection pressure was maintained at 20 pounds per square inch (psi). Trees were treated with 20 ml of fungicide diluted in one liter of water per 2.5 cm (1 inch) of tree dbh (2.8 g active ingredient per 2.5 cm dbh or 0.09 oz per inch dbh), which is the manufacturer's recommended dosage for trees under high disease pressure. Injection wounds were painted with wound paint the day after injection before being covered again with soil.

In general, trees absorbed the fungicide solution within a few hours; however, a few trees took much longer and often did not take up the full amount of product even when pressure was increased or the injection apparatus was left connected to the tree overnight. These trees typically received less than two-thirds of the attempted injection amount. Though these trees were retained in the study, their lack of full absorption was noted and any significant variations in results were considered.

Inoculations were performed with one wild-type strain, "Westcott", recovered from a diseased tree in Ogemaw County, Michigan in 2001. Conidia from Westcott cultures grown on plates containing potato-dextrose agar (PDA) were collected by placing 1-2 ml of distilled water onto the plate and gently rubbing the surface with a glass rod. The resulting suspension was strained through Miracloth™ and the concentration was adjusted to 10^5 conidia/ml with water and 20% glycerol. This suspension was divided into 1 ml aliquots and maintained at -80º C. The conidial suspension was thawed at room temperature for one hour prior to inoculation studies. Viability of spores was periodically assessed by serial dilution onto Petri dishes containing PDA; spore viability was consistently greater than 90%. For tree inoculations, a 2.5 cm-deep hole was drilled into the north side of the trunk at 1.5 m above ground with a 6 mm (¼ inch) bit. One ml of the 10^5 conidia/ml suspension was then placed in the hole with a pipette. The suspension was generally absorbed within 5-10 minutes, and holes were subsequently covered with tape to prevent insects from entering the wound.

Trees were visually assessed monthly (May through October) for symptoms of oak wilt to determine the timing between inoculation and initial symptom development. Symptomatic branches from trees expressing disease symptoms were sampled for the presence of *C. fagacearum* by flame sterilizing samples after dipping in 90% ethanol, removing the outer bark, and then placing pieces of sap wood onto plates containing either PDA or glucose-phenylalanine agar. Final inspection of trees was done in early August 2006, 15 months after final inoculations. For the purposes of this study, trees were rated as either diseased (1) or healthy (0).

The relationship between treatment parameters and disease development was analyzed by exact conditional logistic regression using the LOGISTIC procedure in SAS version 9.1 software SAS Institute Inc., Cary, NC). Disease was modeled as a function of replicate (1 or 2), month (when inoculation occurred), the number of times a tree was inoculated (once or twice), and whether trees received fungicide prior to injection. Significance of treatment variables to the model was determined according to a Score test and exact parameter estimates were analyzed to determine the type of effect each predictor variable had on disease occurrence. A p value ≤ 0.05 was used to determine statistical significance.

RESULTS AND DISCUSSION

All 17 positive control trees from both replicates developed wilt symptoms within six weeks following inoculation and were completely wilted within the same year (Table 1). Thirteen of the 21 negative control trees were incorporated into other studies in 2005 leaving eight non-inoculated controls in 2006. None of these trees developed wilt symptoms over the course of the study, indicating that the trench lines initially established in 2002 remained effective and that insects were not moving inoculum.

Possible wilt symptoms on treated trees first appeared in late fall of 2005, but as these symptoms developed just before fall coloration, wilt was not confirmed until the following year.

All symptomatic trees sampled in 2006 were positive for *C. fagacearum*. Of the propiconazole-treated trees from Replicate 1, only six of eleven trees showed disease symptoms in 2006. All six symptomatic trees had been inoculated twice: two at 14 and 34 months after fungicide injection, two at 21.5 and 34 months, and two at 24 and 34 months.

Four of the 13 treated and inoculated trees from Replicate 2 displayed symptoms in 2006: one of the three trees that had been inoculated once only at 23 months and three of the seven trees that were inoculated twice (one at 0 and 23 months and two at 14 and 23 months) All four of the trees from Replicate 2 that expressed wilt symptoms in 2006 failed to absorb the full amount of fungicide when injection was attempted. Only one tree in this study that did not take up the full amount of propiconazole did not develop wilt symptoms. Two of the three trees inoculated once at 23 months and all of the 24 month trees (Replicate 2) remained symptomless over one year after inoculation. Yet, the untreated control trees inoculated at 24 months developed wilt symptoms in 2005, the same year they were inoculated.

All fungicide-treated trees that developed wilt had delayed symptom development both initially and after symptoms appeared. Symptoms were not obvious for at least 3-13 months after inoculation and were confined to scattered branches where the disease progressed slowly. This is contrary to what was observed in the untreated control trees, which expressed symptoms within six weeks following inoculation that progressed rapidly from the top of the crown, downward.

The number of times a tree was inoculated and whether or not a tree received fungicide prior to inoculation significantly contributed to the disease model; however, month ($p = 0.43$) and replicate ($p = 0.28$) were not significant explanatory variables and were excluded from the model. Based on parameter estimates, trees that did not receive a fungicide injection and those trees inoculated twice had greater incidence of disease, while fungicide-treated trees (regardless of month) had decreased disease incidence. The null hypothesis that one inoculation had no effect on disease cannot be rejected ($p = 1.00$).

These results indicate that propiconazole potentially remains effective for at least 24 months and provides some level of protection up to 34 months post-injection. Interestingly, Osterbauer and French (1992) were only able to detect propiconazole using a thin layer chromatography assay up to 12 months following injection. A double (instead of a single) band was observed in sample lanes at 16-18 months post-injection, similar to that found in the fungicide standard lanes when older supplies of propiconazole were analyzed, suggesting degradation of the product. At 20 months post-injection, no propiconazole was detected in any samples. Our results demonstrate that the product may still inhibit fungal growth even after 34 months and that the amount of propiconazole injected may influence the length of efficacy of the product, as Osterbauer and French (1992) used much lower rates in their studies. Additionally, the TLC assay they used may not have been sensitive to low levels of propiconazole that would still affect *C. fagacearum.*

Propiconazole is a triazole-fungicide, one of the classes of sterol-biosynthesis inhibiting fungicides. Wilson and Forse (1997) determined that propiconazole, at sufficiently high levels, was fungicidal to *C. fagacearum*. Therefore, in this study, the pathogen was potentially killed due to high initial levels of the fungicide in trees inoculated soon after injection. However, at lower concentrations of sterol biosynthesis inhibitors, the inhibition of fungal spore germination is incomplete (Kuck and Scheinpflug 1986, Latteur and Jansen 2002, Nogueira et al. 2002). Thus, propiconazole may delay active colonization of the fungus until it degrades to low enough levels, at which point the pathogen can spread throughout the tree. Incomplete distribution of the fungicide within a tree would also contribute to this effect.

In addition to its fungistatic effects, triazoles, including propiconazole, are known to have plant growth regulating properties (Kuck and Scheinpflug 1986, Wetztein et al. 2002, Hanson et al. 2003). Phelps, Kuntz and Ross (1966) reported that indole 3-acetic acid, a natural growth regulator, delayed symptom development in northern pin oak (*Q. ellipsoidalis*) up to 12 months or more when injected into the trunk. Although indole 3-acetic acid is an auxin and thus stimulates growth, whereas propiconazole has a growth retardation effect, by changing the balance of growth regulation in the plant (perhaps enhancing the tree's ability to cope with stress or interfering with the production of tyloses in response to the pathogen), disease development is affected. Thus, it is possible that propiconazole works in two ways to inhibit disease development – first by interfering in ergosterol-biosynthesis and secondly by affecting growth regulation within the host.

Interestingly, the effects of propiconazole on disease development are similar to those found with other compounds tested for the control of wilt. Phelps, Kuntz and Ross's (1966) research on northern pin oak shows that a few antibiotics and/or chemicals prolonged the incubation period of the disease up to 24 months. The pattern of symptom development on such treated trees differed from untreated trees in that wilt symptoms developed slowly, often branch by branch, and sometimes over one to two years. Similar results of a temporary delay effect were found with trials using thiabendazole for wilt (Appel 1995). We also observed this effect on the treated trees in our plot that eventually developed symptoms: symptoms were initially confined to particular scattered branches and progressed much more slowly than would be expected (in comparison to inoculated controls). Phelps, Kuntz and Ross (1966) also reported that, despite a prolonged incubation period, the fungus was isolated from 75% of symptomless trees 12 months after inoculation. This demonstrates the ability of the fungus to remain within a tree without inciting disease, further supporting the idea that propiconazole may have ultimately only delayed disease development in our plot. However, given that approximately half the trees inoculated for a second time at 34 months post-injection did not develop symptoms over one year later, it may be that by suppressing pathogen growth long enough, a tree could fundamentally be protected.

As the majority of research on oak wilt has focused on the host-pathogen interaction above ground, there remain many unanswered questions regarding the movement and colonization of the pathogen in the root systems. Evidence of pathogen movement through root grafts may take one to three years (Rexrode 1978) and seemingly dormant disease centers may begin wilting again after several years, presumably due to root-graft spread. Additionally, root-inoculated trees often display delayed wilt symptoms up to one year from inoculation (Cobb, Fergus and Stambaugh 1965). Thus, it is difficult to determine when and how the pathogen enters the root system and what happens once it is there. Defensive reactions in response to *C. fagacearum* are less extensive in the roots than in other parts of a tree (Struckmeyer et al. 1953). This suggests that the pathogen may be able to colonize parts of the root system, which has implications for disease development in fungicide-treated trees. There is evidence that propiconazole is distributed to the root system of injected trees (Tattar and Tattar 1999, Blaedow et al. 2005), but it is unclear to what extent and how this affects pathogen growth and movement within the root system.

Natural infection with *C. fagacearum* is most likely to occur through branch wounds or root graft movement; thus, the results from this study must be interpreted accordingly. Our experiment tested the effectiveness of propiconazole injection against non-root graft spread of the pathogen as trees were inoculated in the bole. The observed inhibitory effect may break down with natural overland infections, which probably occur in the crown, as it is believed that the fungicide is not translocated or distributed evenly throughout the upper canopy (Osterbauer and French 1992). While it has been documented that bole inoculations have greater inoculation success than crown-inoculated trees (Jones 1964, Cobb, Fergus and Stambaugh 1965), it is also probable that the greatest amount of fungicide was distributed within the trunk. Therefore, the observed delay in symptom development may or may not be related to the initial distribution of the fungicide in relation to the inoculation site, underscoring the need for further clarification of this relationship.

CONCLUSION

The possible dual inhibitory effects of propiconazole and advances in delivery via macro-injection have made propiconazole a promising fungicide treatment for oak wilt. However, since the early work by Osterbauer and French (1992) on propiconazole injections in red oaks, it has been apparent that red oak treatments are somewhat unpredictable. Our results show that propiconazole injection was an effective preventative treatment for oak wilt in some cases up to 34 months following injection; however, disease pressure apparently affects the duration of efficacy, as intimated by disease occurrence in trees receiving two inoculations. All but one of the treated trees that developed symptoms had been inoculated twice and did not express obvious symptoms for over a year after final inoculations, whereas all positive control trees developed symptoms within six weeks, indicating that treated trees inoculated at the same time were delayed in symptom development. Additionally, all symptomatic trees from Replicate 2 had not taken up the full amount of fungicide administered. Given these results, the effective longevity of propiconazole appears to be dependent on several factors including the amount injected, the level of disease pressure, where the pathogen enters a tree, and the relative distribution of the pathogen and fungicide within a host tree.

ACKNOWLEDGEMENTS

We would like to thank Clifford Zehr and Mario Mandujano for their assistance with the trenching and fungicide injections, respectively.

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Table 1. Proportion of wilting trees in August 2006 per replicate. Treatments consisted of trees injected with propiconazole and then inoculated with *Ceratocystis fagacearum* at A) 0 (inoculated same day as injected), 9.5, 14, 21.5, 23, or 24 months later and B) once at 0, 9.5, 14, 21.5, or 24 months and a second time at 23 or 34 months. Positive, untreated control trees were inoculated at the respective time (in months) after experiments began. Replicate 1 began in July 2002, while replicate 2 was initiated in June 2003. A '-' indicates treatment was not included in that replicate.

A

	Treatment (months)						***Control trees***	
	0	***9.5***	***14***	***21.5***	***23***	***24***	***0***	***24***
Rep 1	0/3	0/2	0/2	0/2	-	0/2	4/4	3/3
Rep 2	0/2	0/2	0/3	-	1/3	0/3	4/4	2/2

B

	Treatment (months)		***Control trees***	
	23	***34***	***24***	***34***
Rep 1	-	6/11	3/3	4/4
Rep 2	3/7	-	2/2	-

Figure 1. Trenches, dug with a Davis Fleetline 70+4 trencher, were used to isolate treatment groups.

Figure 2. Five to six-feet-deep (1.5-1.8 m) trenches break potential root grafts between neighboring trees. Trenches are approximately 4-6 in. (10-15 cm) wide.

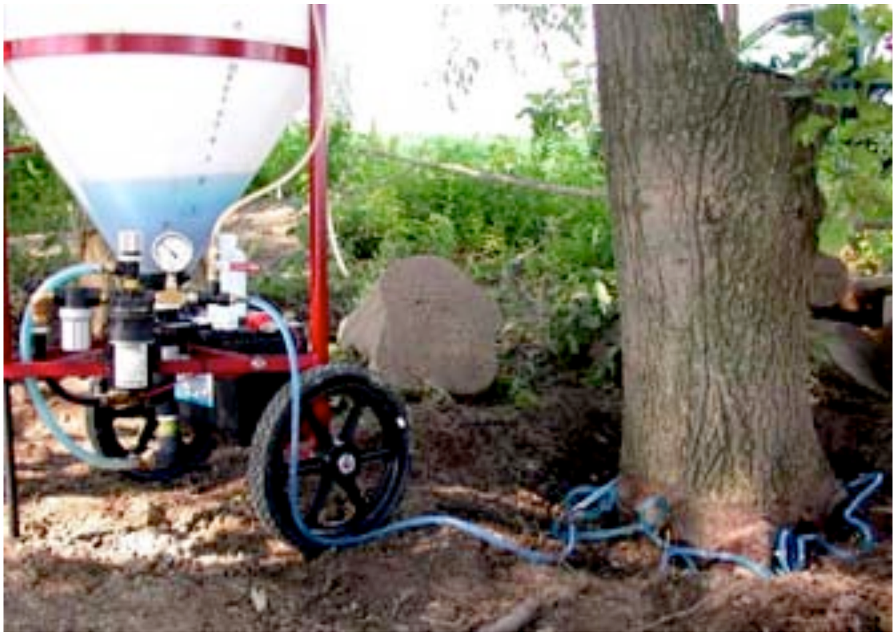

Figure 3. Injection apparatus used for propiconazole injection treatments. The fungicide solution was pumped out of the storage tank and into 2.5 cm-deep holes drilled into the xylem of the root flares.

ATTEMPTS TO DEVELOP AN OAK WILT RESISTANT LIVE OAK

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ABSTRACT

Oak wilt, caused by *Ceratocystis fagacearum,* was confirmed in Texas in 1961 and has since been found in 60 Texas counties. Much of the epidemiology of oak wilt in Texas has been elucidated. Protocols have been developed to hinder local and long distance spread of the pathogen, to treat infected high-value live oak trees, and to protect high-value trees situated next to diseased trees. What is lacking in the arsenal to defeat this epidemic in Texas is resistant live oak (*Quercus fusiformis*) stock. One unique aspect of the Texas epidemic is the apparent, partial resistance in live oak to the disease. This suggests that either genetic or environmental components are responsible for variable survivability to the pathogen. Previous research at Texas A&M University found evidence for heritable, genetically-determined resistance and for phenotypic markers (allozymes) associated with disease tolerance. In order to expand on these findings, we used clone and seedling crops to test for genetically- determined resistance to the pathogen. In one study, resistance of clone groups and seedling groups was tested for a potential correlation with prior levels of disease tolerance exhibited by the parental post-epidemic trees. We also conducted population experiments to test prior findings of a correlation between survival and two allozyme alleles (genetic markers). Some half-sib groups and some clonal groups do perform better than other groups when grown in greenhouses and inoculated with the pathogen. This makes a strong case for the presence of genetic resistance. However, no significant correlation between prior parental tolerance under natural disease conditions and seedling tolerance was found. We attribute this finding to a strong environmental component in determining the survival of live oak trees in natural settings. In the study comparing allozyme allele frequencies between pre- and post-epidemic populations, we found no evidence of markers linked to resistance. Further research will be required for the identification of superior live oak selections with reliable oak wilt resistance.

Key words: *Ceratocystis fagacearum*, *Quercus fusiformis*, resistance screening

The oak wilt epidemic in Texas, caused by *Ceratocystis fagacearum* (Bretz) Hunt, has taken a severe toll on urban and rural oak populations (Appel and Maggio 1984, Appel 1995). This epidemic is presently attenuated by applying a variety of management tools aimed at preventing pathogen spread and protecting high risk trees (Appel et al. 2003, Billings, this proceedings). These tools include cautious treatment of firewood, the elimination of inoculum sources and infection courts, trenching to destroy root connections between diseased and healthy trees, and intravascular injection with systemic fungicides. The worth of these measures has been proven and accepted, so they are routinely applied throughout Texas where warranted. They are not, however, infallible and they can sometimes be expensive and environmentally disruptive. Therefore, additional measures are needed to control oak wilt and preserve valuable trees and woodlands.

There are 26 *Quercus* species in Texas. Some are affected by oak wilt more so than others. The most susceptible oaks are members of the deciduous red oak group (genus *Quercus*, sub genus *Erythrobalanus*), such as *Q. buckleyi* and *Q marilandica*. These red oaks do not recover from infection (Figure 1). At the other extreme, deciduous white oaks (genus *Quercus*, sub genus *Leucobalanus*) are extremely resistant to oak wilt and rarely succumb to the disease. They are not, however, the most common component of the central Texas oak savannahs. Semi-deciduous live oaks, *Q. virginiana* and *Q. fusiformis*, are the most common tree in the central Texas rangelands and show variable tolerance to the oak wilt fungus (Appel 1986). The live oaks are classified as white oaks, but exhibit several anatomical characteristics inherent to the red oaks (Muller 1961). Fifteen to twenty percent of infected Texas live oaks survive infection, with the survivors ranging from no crown death to near total mortality (Figs. 2, 3) (Appel et al. 1989). This variable disease response presents a unique opportunity to search for the sources and causes of tolerance, or resistance, to *C. fagacearum* in the native live oak population.

Due to the ability of native live oaks to withstand site disturbances, and their extreme popularity as planted shade trees, live oak comprises a majority of urban trees in Central Texas cities and communities. Given the popularity of live oak in Texas, there is a sizeable potential market for an oak wilt resistant selection. The development of such a resistant selection will not be possible until there is further information on the heritability of resistance and whether live oak survival is the result of one or many resistance genes. Previous researchers presented evidence that the resistance of live oaks was genetic and heritable (Bellamy 1992, Greene and Appel 1994, McDonald et al. 1998). Half-sib groups of live oak seedlings were shown to differ in their resistance (Greene and Appel 1994). A post-epidemic population of live oaks had different allozyme allele frequencies than surrounding pre-epidemic trees by McDonald et al. (1998). Allozymes are different forms of enzymatic proteins that can be visualized by gel electrophoresis to infer different alleles of specific genes (Soltis and Soltis 1989). Differences in allele frequencies between the pre- and post-epidemic populations are evidence for natural selection being exerted on the host by the pathogen, perhaps indicating a shift toward greater resistance in the host.

The objectives of the present research project were designed to expand on the results of both Greene and Appel (1994) and McDonald et al. (1998). This was done by: 1) challenging large numbers of greenhouse-grown half-sib live oak seedling groups with *C. fagacearum* to look for differences in resistance, 2) creating and comparing clonal offspring from post-epidemic trees by screening them for response to challenge by *C. fagacearum*, and 3) evaluating the allozyme profiles of live oaks growing in additional disease centers to test for allele frequency changes in post-epidemic populations. One purpose of the project was to determine if allozymes can be used as markers to recognize trees containing resistance genes. If those efforts are reliable, then they may be selected for breeding and propagating future populations of resistant trees.

MATERIALS AND METHODS

Experiment 1

Seedlings grown for inoculation with *C. fagacearum* were collected from plateau live oaks (*Q. fusiformis*) in 1997 and 1998. One group of live oaks (post-epidemic trees) consisted of survivors in a disease center near Round Rock, TX. The post-epidemic trees exhibited a complete range of crown death (see Fig. 1), so that diseases responses of the artificially infected seedlings could be compared to that of their naturally infected parents. Progeny from these trees were compared to progeny derived from live oaks growing outside of, but adjacent to, the expanding disease center (pre-epidemic trees). Seedlings were grown for one year in pots with a 4:1 sand/bark mixture and slow release fertilizer and then inoculated with a suspension of *C. fagacearum* conidia (1 x 10^6 spores/ml). The seedlings from each tree were place in random blocks in a shade house and treated uniformly to minimize effects due to environmental variation. Typical disease symptoms were monitored regularly for a year, until disease progress ceased. Responses of seedling groups were compared for each crop using two measures: 1) percentage of group survivors after one year, and 2) percentage of group with less than 25 % crown stem death.

Clonal trees were grown from root spouts collected from post-epidemic tree in 1997. As with the seedlings, the parent trees for clonal sprouts were rated for disease response so that the responses of the clones under artificial inoculation with *C. fagacearum* could be compared to the response of the surviving parent in the infection center. Ramets were cut from live oak root systems, treated with the root stimulating hormone indole-3-butyric acid (Sigma, St. Louis, MO), and planted in "d" pots contain a 4:1 sand bark mixture (Wang and Rouse 1989). The plants were placed in a mist chamber until they grew substantial root systems (approximately 4 months), and then transferred into one gallon pots with the same mix supplemented with a slow release fertilizer. The clones were inoculated after two years growth using identical techniques as those for the seedlings and disease progress followed as previously stated. Clonal group disease responses were measured and compared using average stem death.

Experiment 2

Selected allozymes were analyzed in the leaves of live oaks growing in oak wilt centers at two separate locations in central Texas. One was approximately 10 ha., located in the Balcones Canyonlands Reserve (BCR) in western Travis County near Austin, TX. The other was a rural site north of Lampasas, TX, and was approximately 15 ha. The allozyme profiles of two distinct live oak populations were compared in each of the locations. The first population consisted of post-epidemic, surviving trees located on the interior of the disease center. The second consisted of healthy, pre-epidemic trees on the perimeters of the disease center. Trees from each site were chosen and marked with the limitation that no trees less than 10 m distant from another selected tree was included to avoid clonal individuals. Several leaves (10 - 20 per tree) were collected, transferred to the lab on ice, and processed to provide enzymatic proteins. The leaves were kept refrigerated in the laboratory at 4^{o} C and processed with 3 days of collection. Standard enzyme extraction, electrophoresis, and gel evaluation procedures were used for allozymes from four polymorphic loci (Stuber et al. 1988). The allozyme frequencies from pre-and post-epidemic populations were compared to determine such population history dynamics as selection, migration, and genetic drift (Ayala 1982, Nei 1978).

Allozymes were analyzed as alleles at individual loci. Therefore, the collection of allozymes at each tree represents its genotype. Allozyme data for all the trees at each site were entered into the software population genetics program "POPGENE-VERSION 1.31" (Yeh and Boyle 1997). The POPGENE program can be used to evaluate allele frequencies, genotype frequencies, genetic diversity, Hardy-Weinberg equilibrium, and a variety of other parameters reflecting the genetic structure and evolutionary background of a population. Details of these analyses will be discussed only in general terms during this presentation.

RESULTS

Experiment 1

Some groups of half-sib seedlings following inoculation had significantly greater average survival after one year than other groups from both the 1998 and 1999 seedling crops. Comparisons among 21 first year (1998) half-sib groups (seedlings surviving for one year after inoculation) resulted in five groups (numbers 1, 2, 3, 12 and 13) that had significantly higher percentages of survival than the five poorest groups (numbers 6, 7, 8, 10 and 15) ($p = 0.05$) (Fig. 4). The best performing seedling group (number 12) had a significantly higher percentage of successful seedlings than the poorest 15 groups. In the second year's crop, 1999, one group (number 13) had a significantly higher percentage of surviving seedlings than 11 out of the other 31 groups with the fewest survivors ($p = 0.05$) (Fig. 5).

When analyzing the proportions of the half sib seedlings with less than 25% stem death, group no. 20 from the 1999 crop was significantly more tolerant than 8 of the 30 other groups. Three of the groups were significantly more tolerant than nine of the least tolerant groups (Fig. 6).

In the comparisons of nine clonal groups with at least three members, one clonal group (number 6) was more tolerant than the three least tolerant groups (Fig. 7). The variances of tolerance within the clonal groups were surprisingly uniform.

The tolerances of half-sib seedling and clonal groups from post-epidemic trees were compared to their parent trees' performances in the field under natural infection by *C. fagacearum*. In general, the seedlings and clones that exhibited increased tolerance tended to have more tolerant parents as estimated by crown survival (Fig. 8). But, the correlation coefficients were all low.

Experiment 2

No specific data comparing the tree allozyme frequencies between pre- and post-epidemic areas of two disease site will be presented in this talk. There were no specific allozymes that had significant pre- to post-epidemic differences in both sites. These results will be discussed in general terms below.

DISCUSSION

These experiments were conducted to find potential sources of resistance to the oak wilt pathogen in native live oaks. Two general approaches were used. Both of these approaches were used in previous, preliminary studies to test for resistance in surviving live oaks growing in oak wilt centers in central Texas (Bellamy 1992, McDonald et al. 1998). The first was to test for unique enzyme profiles (allozymes) in surviving live oak populations to determine whether the pathogen is exerting natural selection for resistant host genotypes. If this was the case, then those survivors are potential sources of selection and breeding efforts to develop superior trees. The second was to collect acorns and root sprouts from those survivors as sources of seedlings and clones, respectively, for inoculation screenings (Green and Appel 1994). Results from the preliminary projects were sufficiently promising to extend them to a broader sample of trees growing over a wider geographic range in the present study.

In the screenings of seedlings, two responses were measured to evaluate potential resistance. The first was average group survival, for which there were differences among groups of seedlings derived from both the 1998 and 1999 acorn crops. Presumably, the best performing seedling groups would reflect some degree of resistance in their parents and point to those trees as candidates for further analyses. The second response measured in the seedlings was the proportions with less than 25% stem loss. Again, differences among the seedling groups for this criterion indicated there may be variability in resistance to *C. fagacearum* among the parents.

Since live oaks are open pollinated, out-crossing trees, variability in a population of seedlings grown from acorns from a maternal parent for any phenotype such as disease resistance may exist. For this reason, clones from the parental trees were developed to undergo similar screening. There was one clonal group with a significantly greater proportion of stems with less than 25% dieback. This tolerance in one of the groups lends further evidence for a genetic basis for resistance to oak wilt in the surviving native live oaks.

The methods used in the present study also have been used for identifying sources of resistance to a variety of diseases in other tree species. For example, clones have proven effective in testing for disease resistance in other species, such as elms for Dutch elm disease (Solla et al. 2005). In addition to the genetic basis for resistance, Solla et al. (2005) mentioned a wide number of other factors as being influential in the disease response. These included time of inoculation, environmental conditions, and even height of the inoculated elm saplings. These factors were probably influential in the present study on oak seedlings and saplings, adding to the variability in disease response and perhaps confounding the discovery of a clearly resistant selection. Nonetheless, the results are sufficiently encouraging and some useful materials have been found for continued propagation and testing.

An additional, useful measure of heritability for resistance is the relationship between the responses of progeny to artificial inoculation compared to the performance of the parents under natural infection in the field. Similar considerations are being made for other tree diseases, such as efforts to find disease resistance in native butternut (*Juglans cinerea*) to the exotic canker causing pathogen *Sirococcus clavigignenti-juglandacearum* (Michler et al. 2005). No significant trends were detected when the response of seedlings were compared to those of their parents, indicating a parent’s prior performance cannot be used to confidently predict the tolerance or resistance of the offspring toward the pathogen.

The two allozyme alleles that McDonald et al. (1998) found associated with survival were tested in this study and were not associated with survival in either disease center. We found no decrease in genetic diversity as was reported in that previous study. We did find that all live oak populations were in Hardy-Weinberg equilibrium which shows that these populations are maintaining genetic diversity through sexual reproduction instead of being only large populations of a few clones. Allozyme profiles of individual trees and GPS mapping did allow us to find several clonally propagated motts within the larger populations. The allozyme data also was used to show that the two disease sites, although separated by approximately 80 km, had nearly identical allele frequencies. This finding was evidence that gene flow is widespread and that natural populations of live oaks through out the Edward’s Plateau in central Texas should be expected to share similar genetic profiles.

CONCLUSIONS

A genetic basis for tolerance to oak wilt caused by *C. fagacearum* does exist in live oaks, and this tolerance is heritable. However, the level of crown loss in post-epidemic trees is a poor predictor of how offspring from those trees will perform when challenged with the fungus. Environment or chance plays a substantial role in the outcome of this disease in live oaks. Individual clonal groups show a more normal variation of response to the fungus. Two clonal groups have been found that showed consistent tolerance and may indicate a source of tolerant trees. The allozyme markers that were studied in this project are not useful marker to identify resistant live oaks. Future research should take advantage of artificially-created live oak clones and revisit environmental effects upon the disease process.

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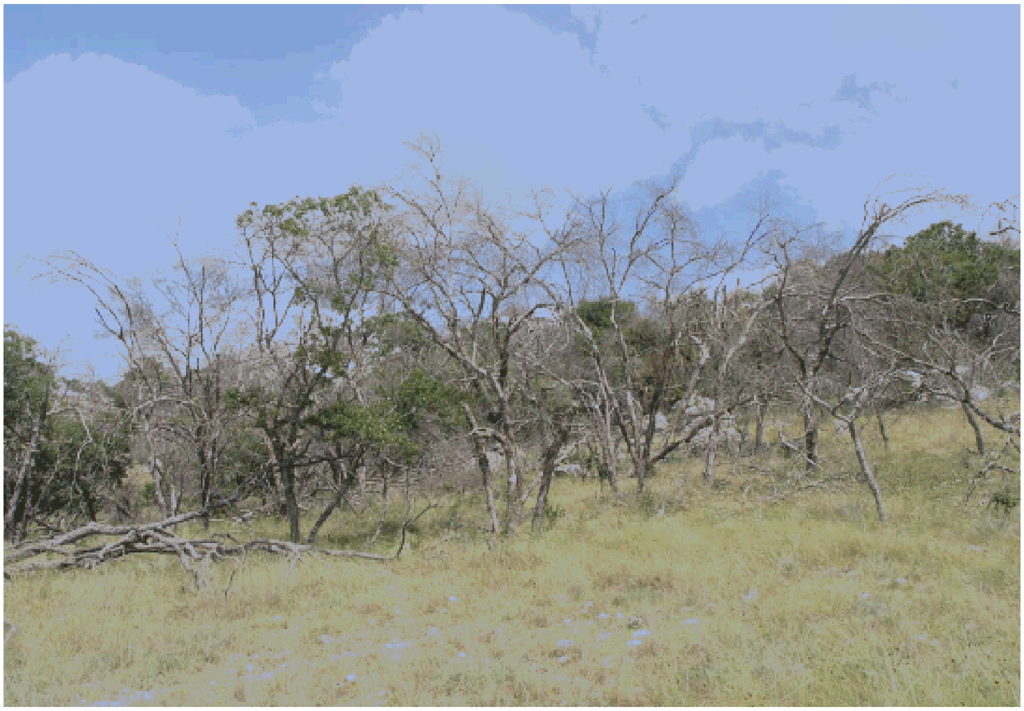

Figure 1. Red oaks in central Texas killed by *Ceratocystis fagacearum* exhibiting no survival.

Figure 2. Live oak within an oak wilt center in central Texas exhibiting partial survival following infection by *Ceratocystis fagacearum*.

Figure 3. Variable survival rates of live oaks within a typical central Texas oak wilt center.

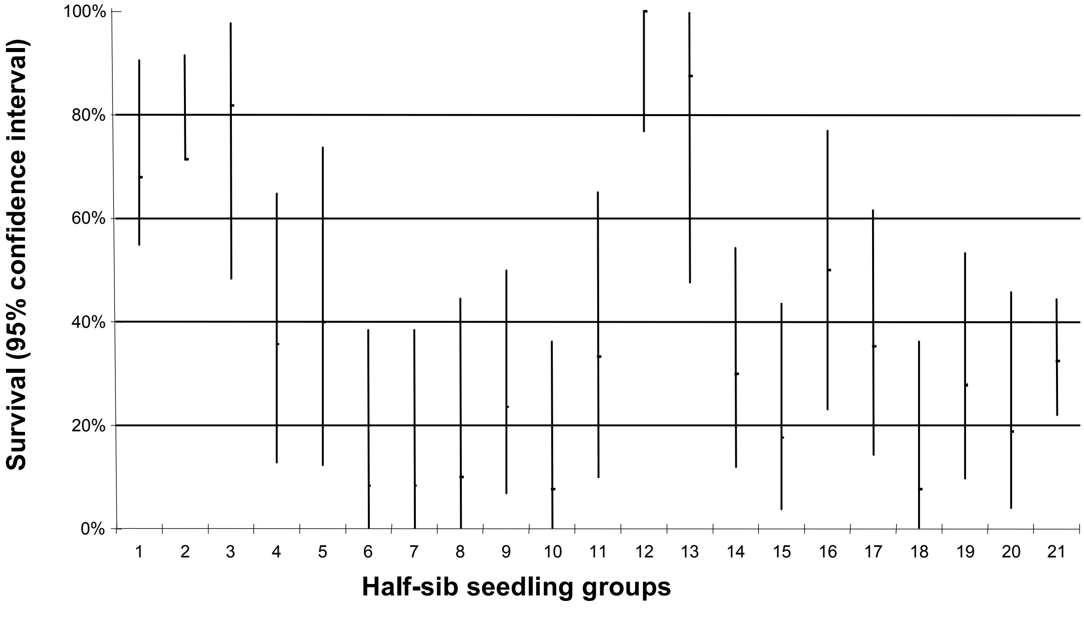

Figure 4. Comparison of survival (% alive) of 21 seedling groups grown from the 1998 acorn crop from live oaks in central Texas one year after inoculation with *Ceratocystis fagacearum*.

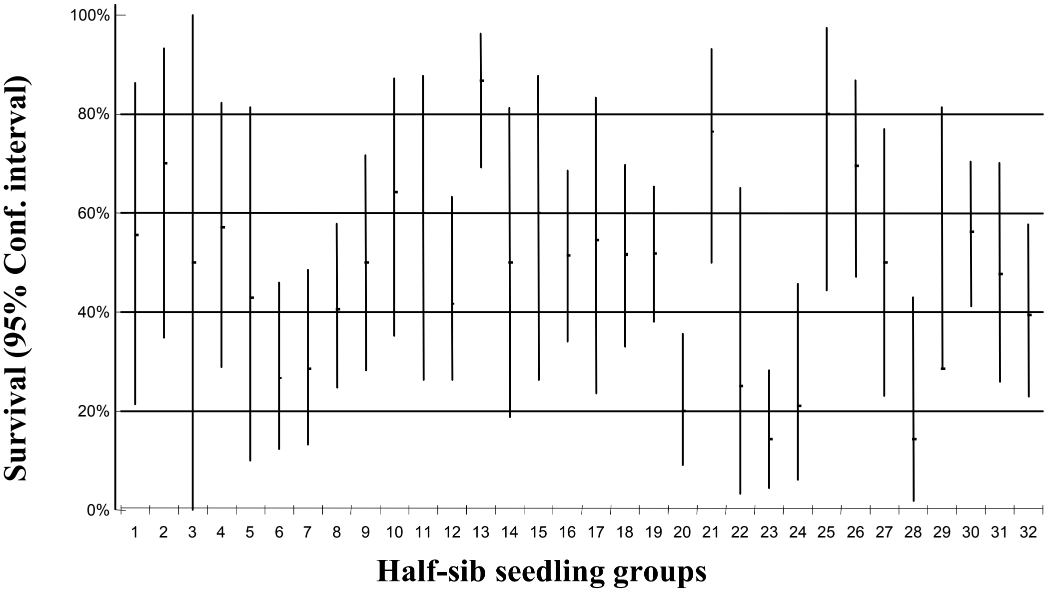

Figure 5. Comparison of survival of 32 seedling groups grown from the 1999 acorn crop from live oaks in central Texas one year after inoculation with the *Ceratocystis fagacearum*.

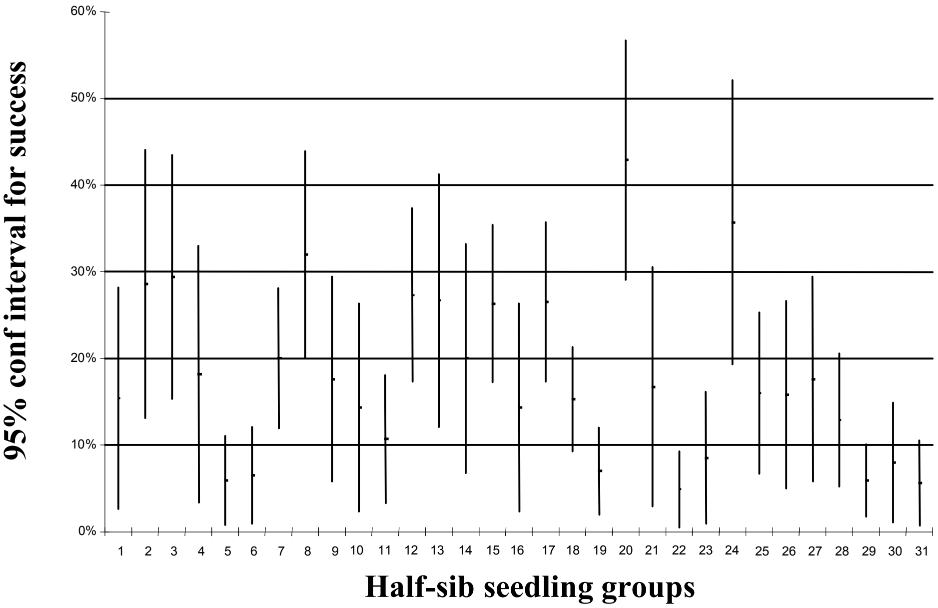

Figure 6. Tolerance, as defined by less than 25% stem loss, in groups of half sib seedlings one year following inoculation with *Ceratocystis fagacearum*.

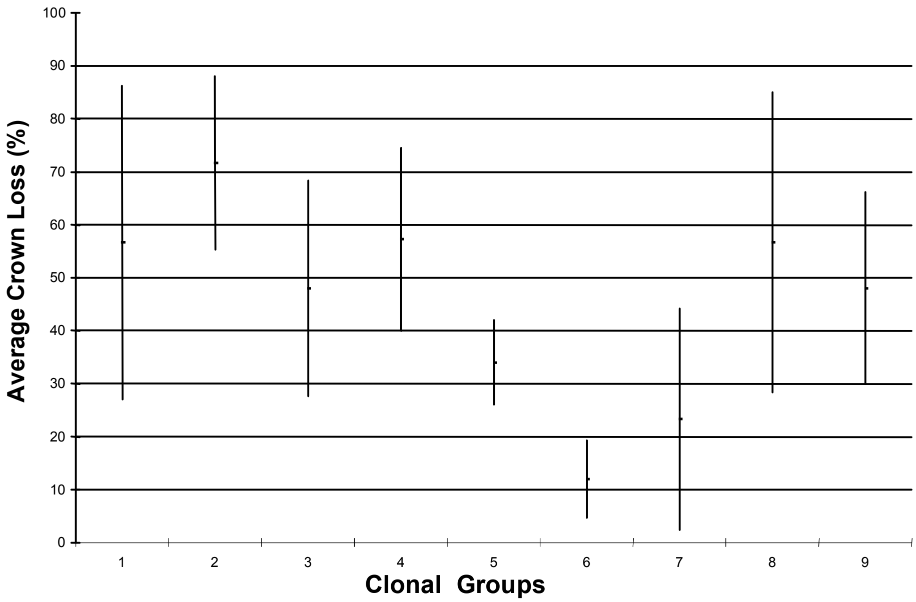

Figure 7. Average crown loss for groups of live oak clones inoculated with *Ceratocystis fagacearum.*

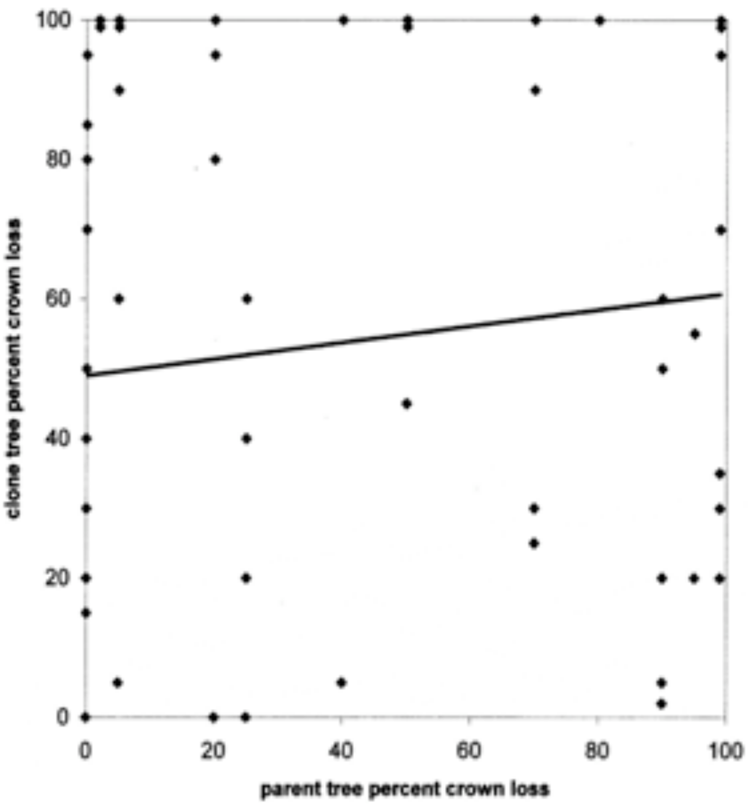

Figure 8. Correlation between the proportions (percent) of crown loss in clonal saplings artificially inoculated with *C. fagacearum* and the crown loss of their naturally-infected parents.

THE POTENTIAL OF TRENCH INSERTS FOR OAK WILT SUPPRESSION

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ABSTRACT

Trench inserts are physical barriers used to control root transmission of *Ceratocystis fagacearum* which provide a significant new strategy and technology for oak wilt suppression in the U.S. This cultural control method has been shown experimentally to significantly extend the effective life and utility of trenches in Texas. The utilization of trench inserts also has increased the effectiveness of trenches as physical barriers to root transmission. Water-permeable trench inserts are more effective barriers than trenches alone because they prevent new root graft formation in trench-backfill soil indefinitely. Trench inserts may provide greater insurance against future trench breakouts in backup trenches when original trenches fail. Water-impermeable trench inserts are not as effective because, in some cases, they tend to direct root growth around (usually above) the insert when inserts are buried too deeply. Trench inserts may be installed at a fraction of the costs of primary trenches and may not significantly increase total trenching costs. The use of trench inserts could potentially save millions of dollars through protection of uninfected trees, avoidance of tree removal costs, and reductions in property value depreciations for Texas landowners. This technology is equally applicable in other areas of the U.S. affected by this disease. Some potential problems associated with the installation of trench inserts are discussed.

Key words: *Ceratocystis fagacearum*, direct control, root barriers

Oak wilt, caused by *Ceratocystis fagacearum* (Bretz) Hunt, is probably the most destructive disease of oak species in the United States (Gibbs and French 1980, Appel 1995, Tainter 1995, Wilson 2001). The disease annually kills numerous oaks throughout the eastern half of the country, particularly those in the red/black oak group (subgenus *Quercus* section *Lobatae*) due to greater susceptibility to the disease and differences in physiology and microscopic anatomy of sapwood (Tillson and Muller 1942, Nixon 1993, Tainter 1995, Wilson, Lester and Oberle 2005). The semievergreen live oaks, including plateau live oak (*Q. fusiformis* = *Q. virginiana* var. *fusiformis*) and coastal live oak (*Q. virginiana*), are considered the most valuable woodland and urban tree species in central Texas (Appel et al. 1986, Martin, Maggio and Appel 1989). Although live oaks are intermediate in susceptibility to oak wilt, they are the most seriously affected oaks in terms of disease incidence and rate of spread. The natural growth tendencies of live oaks to form root sprouts from mother trees, giving rise to large clusters of clonal trees (motts) with extensive root grafts and interconnected common root systems, increase the predisposition of live oaks to root transmission (Muller 1951, Appel, Anderson and Lewis 1986, Davies 1992, Wilson 1995). Oak wilt disease incidence is often high in live oaks because of these growth-form predispositions, the formation of extensive shallow root systems, and the abundance and high density of live oaks in both urban and rural forest stands of central Texas.

Most live oaks defoliate and die within six months after the initial appearance of oak wilt symptoms. Consequently, there is very little time to initiate effective disease-control measures to save individual infected trees after symptoms first appear. Any tactics developed to halt disease spread must consider that disease development often occurs rapidly and the oak wilt fungus can move up to 50 m or more per year through grafted root systems at the edge of expanding oak wilt infections centers.

Trenching to cut root connections between healthy and diseased trees continues to be the principal means of controlling the spread of the oak wilt fungus through root transmission in the U.S. (Himelick and Fox 1961, Cameron and Billings 1995, Gehring 1995, Billings et al. 2001, Haugen et al., this proceedings). Trenching has been a particularly important tool for dealing with the disease in highly-valued live oak stands because root grafts and extensively interconnected root systems allow the disease to spread rapidly by root transmission. The Texas Oak Wilt Suppression Project (TOWSP), administered by the Texas Forest Service since 1988, has installed over 3.4 million linear feet of trench to combat the disease in 2,466 oak wilt infection centers found within 61 of 254 Texas counties (Billings, this proceedings). However, trenching is not totally effective in containing the disease, partly due to new root connections that form across the trench and allow disease centers to continue to expand beyond trench barriers. TOWSP post-suppression evaluations showed that about 33% of trenches installed prior to 1995 had at least one breakout (infected trees beyond the trench), although seldom is the entire trench a failure (Gehring 1995).

A 7-year study was initiated in 1993 to look at the feasibility of improving the effectiveness and longevity of trenches using trench inserts (Wilson and Lester 2002). A significant finding in this study was that small oak feeder roots, formed from roots severed by trenching, grew into the loose backfill soil within trenches allowing new root graft connections to form across the trench. The results showed favorable indications that trench inserts could provide significant improvements in the performance of trenches by preventing the formation of these new root grafts that allow inoculum (conidia and hyphal fragments) of the oak wilt fungus to move beyond the trench. Preliminary research demonstrated the efficacy of trench inserts in stopping the expansion of oak wilt infection centers beyond the trench up to six years after trenching (Wilson and Lester 1996a-c).

This paper explains why improvements in trenching technologies are needed to more effectively control root transmission of *C. fagacearum*, how trench inserts improve trench effectiveness and longevity, what additional expenses are associated with utilizing trench inserts, the comparative performance of different types of trench inserts, and some potential problems involved in the installation of trench inserts for oak wilt control. Recommendations also are provided that explain ways to more effectively and efficiently implement the use of trench inserts within existing oak wilt suppression programs.

TRENCHING EFFECTS ON SOIL STRUCTURE AND ROOT INTERATIONS

The first essential information needed for improving trenching technologies for oak wilt control is to determine why trenches fail or why trench breakouts occur. The principal reasons why trench breakouts occur usually vary with time after trench installation. Breakouts that occur within two years after trenching usually result from placing the trench too close to the infection center or not trenching deeply enough to sever all roots. Breakouts that occur after 2-3 years are likely the result of root regrafting across the trench. Trenching causes changes in the physical properties of soil structure and subsequent root interactions that occur in trench backfill soil after trenching. These effects of trenching on soil structure and oak-root interactions set into motion a dynamic process that ultimately increases the chances for trench breakouts over time following trenching.

PROBLEMS WITH TRENCHING

One of the biggest problems associated with the mechanical cutting of trenches for oak wilt control involves the effects of trenching on soil structure and characteristics within the trench. Trenching creates a soil environment highly favorable for root growth. Farmers till the soil in their fields before planting for this very reason. Tilling the soil reduces the bulk density of soil by breaking up soil aggregates into smaller particles, rendering the soil friable and more favorable for root growth, penetration by rainfall, and infiltration by fertilizers and nutrients. For the same reason, no-till cultivation has been adopted as a farming practice in many areas of the U.S. to reduce soil erosion and weed growth stimulated by the loosening of soil structure that facilitates root growth of competitive weed plants. Trenching has the same effects on soil structure as tilling the soil. Backfill soil within the trench is loosened significantly (bulk density 1.22 g/cm^3) relative to the compacted surrounding soil (bulk density 1.62 g/cm^3) (Backhaus 2005).

There are several consequences that result from these changes in soil structure due to trenching. Roots from the surrounding compacted soil seek to grow in this loose backfill soil because it provides the path of least resistance for root growth, expansion, and branching. Consequently, roots proliferate and penetrate into this loose trench backfill soil much more rapidly than in the adjacent, compacted soil on either side of the trench. The loosened backfill soil within newly-cut trenches also is a natural sink for water and nutrient flow into the ground, again because it is the path of least resistance. Water and dissolved nutrients tend to collect and accumulate within the loosened trench soil, further enhancing and stimulating new root growth from roots adjacent to the trench. The natural influx of tree root growth into this more favorable trench soil is promoted by all of the improvements in soil conditions that result from the trenching process.

The cutting of oak roots by trenching induces the formation of fine (<5 mm-diameter), feeder roots in trench soil due to the loss of apical dominance. This same phenomenon occurs when apical meristems are cut in the upper parts of the tree resulting in the loss of apical dominance and the production of sucker sprouts on trunks and lateral epicormic branches. The production of lateral roots, due to the loss of apical root dominance in roots severed by trenching, leads to the proliferation of fine feeder roots in the loose backfill soil of newly-cut trenches. These feeder roots begin forming within a few inches of the severed ends of roots as soon as soil moisture becomes available. Trenches are generally backfilled immediately during the trenching process, allowing new root growth to begin forming usually after the next rain event. Most feeder roots are found within the top 18 inches (46 cm) of the soil surface where soil moisture is most available following a rain. Feeder roots also form from the cut ends of deeper roots severed by trenching, up to 6 feet (1.8 m) or more below the soil surface depending on soil depth.

The very high tendency of Texas live oaks to form root grafts and common root systems allows these species to utilize the ideal conditions within newly-cut trenches to initiate the formation of new fine feeder roots that readily graft with roots of other live oaks with which they come in contact. Because live oaks on both sides of the trench have roots severed by trenching, these trees send out an abundance of new feeder roots into trench soil creating conditions very favorable for the formation of new root grafts across the trench. It is for this reason that the

TOWSP recommends uprooting all trees and disrupting or extracting the root system inside the trench in rural areas.

TRENCH BREAKOUTS – WHY THEY OCCUR

The majority (60.1 %) of oak wilt breakouts from TOWSP trenches have occurred during the first two years after trench installation (Table 1), due to factors other than regrowth of roots across the trench (Gehring 1995). The rate of new trench breakouts decreases rapidly over time after two years resulting in negative slope curves for breakouts beyond two years after trenching. Nevertheless, up to 40% or more of all trench breakouts occur after two years following trenching. Even though trench breakout rates continue to decrease after two years, breakouts have been recorded to occur up to fifteen years or more after trench installation, far beyond the time normally expected for *C. fagacearum*-inoculum to move through existing root grafts across the trench. The expanding edges of oak wilt infection centers are known to move up to 80 feet (25 m) or more per year in Texas live oaks. Because trenches normally are installed within a 100-feet (30 m) buffer zone beyond the advancing front of the infection center, it usually takes a maximum of two or three years for *C. fagacearum*-inoculum to move through any preexisting root connections that were not severed by the trench.

Breakouts that occur after two years are increasingly more likely to be due to transmission of the fungus through new root grafts that formed after trenching (Table 2). The delayed timing of later breakouts is due to the time required for new root grafts to form and provide a route for inoculum in the roots to pass beyond the trench barrier. Most breakouts occurring within the first two years after trenching have been attributed to inoculum passing through pre-existing root grafts either due to 1) insufficient trench depth, 2) insufficient buffer distance set up between the visible (symptomatic) advancing edge of the infection center and the positions selected for trench placement, or 3) a discontinuous trench (Gehring 1995).

Trenches that are not cut to sufficient depth allow the fungus to pass through roots that were not severed under the trench. This occurrence is common where the soil depth to bedrock in localized areas is greater than the depth normally encountered in that area or when soil depth is greater than the depth recommended by suppression-operation criteria. Cutting the trench too close to the infection center, without leaving a sufficient buffer zone, can also be a problem. Trenches placed too closed to diseased trees fail because the fungus has already moved through roots by the time the trench is installed. Discontinuous trenches, often caused by the need to avoid buried utility lines, provides opportunities for inoculum to pass through gaps in the trench where roots were not severed. Obviously, the rates of trench breakouts, due to discontinuous trenches, tend to increase in urban areas.

The TOWSP does not cost-share continuous trenches unless the utility lines have been installed at least four feet deep with the past four years. Even though most trench breakouts occurring after two years following trenching occur due to new root graft formation, some breakouts occasionally may occur due to movement of *C. fagacearum*-inoculum across the trench by insects or other vectors (Table 2). The movement of red oak firewood from infected trees within infection centers to areas outside of the trench also may explain some jumps or gaps in infection patterns in the vicinity of trenches. There is also the possibility that unknown root-feeding or stem-feeding insect vectors may be carrying inoculum of *C. fagacearum* across trench barriers.

Problems of trenching associated with improper trench depth and buffer distance can be largely solved by increasing trench depth when possible and increasing the buffer zones used for determining trench placement. These adjustments have been made several times in the operational criteria used for trench installation in TOWSP operations. Unfortunately, modifications in trench designs and placements do not solve the problem of breakouts due to other causes, particularly the formation of new root grafts in the loose trench backfill soil. Trenches alone are not permanent by design. They cease to become a barrier as soon as new root grafts form across the trench. The very high tendency of live oaks to form root grafts, coupled with the greater incidence of root growth and root graft formation in trench backfill soil, increasingly favors the ability of *C. fagacearum*-inoculum to eventually move through a new root graft connection to the other side of the trench over time.

The actual likelihood that new root grafts will form in the trench backfill soil in any one location is dependent on a number of factors, including weather and rainfall patterns, the presence and density of trees on both sides of the trench, the amount of inoculum-pressure put on the trench (determined by the size of the infection center being contained), the rate of movement of the infection front, the depth of the soil and/or trench, soil texture and fertility, and slope of the terrain. However, the rate of new root graft formation in trench soil is probably most determined by available soil moisture in the trench, the density of live oaks on both sides of the trench, and the depth of the soil in the trench. These three factors probably have the greatest effect on feeder-root density, and thus determine the likelihood that new root grafts will form across the trench.

An alternative explanation has been proposed to explain breakouts that occur beyond two years after trenching. This explanation suggests that these breakouts may be due to insufficient trench depth instead of the formation of new root grafts in the trench soil. The theory implies that roots occur under the trench by which the oak wilt fungus eventually passes, but that the movement of *C. fagacearum*-inoculum in the roots is delayed by insufficient rainfall, inadequate tree transpiration, or other factors that somehow slow down the movement of inoculum in the root system and delay trench breakouts. The problem with this explanation is that the movement of water carrying *C. fagacearum*-inoculum in the transpiration stream of roots through root grafts is controlled mostly by the transpiration of healthy trees outside of the trench that pulls water from the root systems of diseased trees inside of the trench.

Transpiration rates in the stems of oak wilt-infected trees are slowed due to vascular plugging by the fungus. Consequently, transpiration rates are higher in healthy trees that have no vascular plugging. This is the reason why transpiration water tends to flow mostly away from diseased trees (at the expanding edge of the infection center) toward uninfected healthy trees (outside of the trench) that still have substantial transpiration occurring. This is the only reasonable explanation to account for the often rapid rates (75-150 feet or 23-46 m per year) of expansion observed in Texas oak wilt infection centers. Given this strong outflow of transpiration water through preexisting root grafts, that were not severed between diseased trees at the edge of infection centers and healthy trees outside of the trench, there should be a very low probability that *C. fagacearum*-inoculum would not pass through one of these preexisting root grafts within the first two years after trench installation.

The movement of transpiration water through root grafts to healthy trees can be slowed by drought conditions. However, if there is a root connection path (root graft) around or under the trench for inoculum to pass through, it should occur within two years because movement of transpiration water is analogous to water running downhill by gravity. Healthy trees cannot survive for very long without transpiration. Anything being carried by the water, whether it is dissolved nutrients or *C. fagacearum*-inoculum, is moved in the transpiration stream and taken up by the roots of healthy trees outside of the trench. Therefore, it is reasonable to assume that breakouts that occur beyond two years after trenching are due to newly formed root grafts in the trench because all old preexisting root connections were effectively severed by trenching. In the absence of an extended drought, the delay in trench breakouts beyond two years is increasingly more likely caused by the delay in formation of new root-connection paths across the trench by which inoculum can be carried to healthy trees outside of the trench. The only other appreciable factor that could lead to a delay in trench breakouts beyond two years after trenching is placement of the trench significantly more than 100 feet beyond the infection center. In this case, it would take longer for the fungus to traverse the greater distance through connected root systems to challenge the trench. The greater time required before the trench is challenged provides more time for new root grafts to form across the trench, increasing the chances for trench breakouts when inoculum of the fungus finally arrives at the trench. More evidence for trench breakouts due to new root graft formation is provided under the section Trenching Results in a Metropolitan Area.

EXPERIMENTAL EVIDENCE FOR TRENCH INSERT EFFECTIVENESS

A 7-year USDA-Forest Service research study was initiated in 1993 near Austin, TX to evaluate the efficacy for using trench inserts as a new cultural control method for the management of oak wilt in Texas (Wilson and Lester 2002). This study addressed the need to reduce the incidence of trench breakouts that occur beyond the first two years after trench installation due to causes other than improper trench placement or insufficient depth. The failure of primary trenches to prevent root transmission of *C. fagacearum* usually requires the installation of expensive backup trenches to attempt to contain further expansion of these unchecked oak wilt infection centers.

Sometimes even backup trenches fail, leading to additional costly trench breakouts that may be too large and expensive to contain. The larger an oak wilt infection center becomes, the more expensive it is to contain because approved trenching projects require installation of a suppression trench completely around the infection center. One of the key objectives of this 7-year trenching study was to determine why trench breakouts occur beyond the first two years after trenching when trench breakouts are normally expected to occur. A better understanding of trench breakouts and how they occur was needed in order to find new ways to extend trench utility and effectiveness beyond two years, and thus avoid costly trench breakouts.

The effects of trenching on soil structure in the trench and resulting root growth in trench backfill soil following trenching was evaluated with an experimental trench having different treatment segments set up along its length. Treatment segments consisted of four types of trench inserts, trench alone, and no trench controls to determine whether trench breakouts were affected by the presence or absence of trench inserts. The experimental hypothesis being tested was whether trench inserts affect the number and timing of trench breakouts relative to trench alone or no trench controls. If a difference in timing of breakouts could be detected between treatments, this would indicate that there must be a fundamental difference in the process or timing of root transmission events that explains the common delays in trench breakouts that are often observed with trenching treatments compared with no-trench controls.

PERFORMANCE OF WATER-PERMEABLE VS. WATER-IMPERMEABLE TRENCH INSERTS

The efficacy of trench inserts in preventing root transmission of *C. fagacearum* was tested in order to determine the effects of different types of trench inserts on trench performance. Four types of trench inserts, consisting of two water-permeable materials and two water-impermeable materials, were tested and compared to trenches alone and no trenching segments. These six treatments each were replicated three times in a random sequence along the full length of a continuous 0.75-mile (1.2 km) trench located 100 feet (30 m) beyond the expanding edge of a large oak wilt infection center.

The two water-permeable inserts consisted of 4 oz. (113 gm) (1×) Typar, a spun polypropylene landscape fabric, and Biobarrier which contains the same fabric as Typar, but also contains trifluralin-impregnated 10-mm diameter, controlled-release hemispherical pellets (54% polyethylene, 18% carbon black, and 28% trifluralin by weight) bonded to polypropylene fabric with uniform 3.8-cm spacing or 688 pellets per square meter (Reemay Inc., Old Hickory, TN). The water-impermeable insert materials consisted of polyethylene Rufco Geomembrane liners (Raven Industries, Springfield, OH) of two thicknesses (20 and 30 mil), namely Rufco 2000B, and Rufco 3000B, respectively. Trench inserts were placed into trenches in 15.2 or 30.5 m lengths, mounted with 15 cm steel or aluminum pins to the wall of the trench on the side closest to the infection center, and additionally supported by backfilling the trench with soil removed during construction of the trench, followed by leveling with a backhoe scoop blade (see Wilson and Lester 2002).

The occurrence of new trench breakouts of oak wilt disease by year for six years following trenching provides a comparison of performance of the six treatments (Table 3). The study was established during an extended period of drought which caused trench breakouts to be somewhat delayed as a result of reduced transpiration in test trees. The first appearance of oak wilt beyond a no-trench segment occurred the second year after trenching. A second appearance of oak wilt beyond a no-trench segment occurred the third year. One trench segment of Geomembrane 20 (Geo 20) also had a disease breakout the third year. Two trench breakouts occurred in Geo 20 segments the fourth year after trenching. Excavations of Geo 20 trench breakout segments indicated that small roots had grown across the trench in the soil above the trench inserts. Apparently, the Geo 20 trench inserts were buried too deeply in these segments allowing new root grafts to form between feeder roots across the trench above the insert material that resulted in trench breakouts.

One trench-only segment had a trench breakout the fourth year after trenching, also likely due to new root grafts forming across the trench in the loose backfill soil. The last trench breakout recorded in the study occurred the fifth year after trenching in the no-trench segment. However, none of the nine trench segments containing Typar, Biobarrier, or Geo 30 inserts had breakouts of oak wilt during the entire six years of this test. Based on these limited number of treatment replications, the water-permeable inserts (Typar and Biobarrier) appeared most effective in preventing the formation of new root grafts across the trench in trench backfill soil up to six years after trenching

The breakouts occurring in the water impermeable Geo 20 segments may have occurred as a result of the diversion of root growth around the trench insert (toward the surface) after roots came in contact with the material. This diversion of root growth tends to occur with water impermeable materials because the roots cannot obtain moisture through the insert material and continue to grow whereas the presence of moisture through the barrier (as in the water permeable inserts) causes the roots to branch dichotomously against the barrier instead of continuing to elongate in search for moisture. Consequently, water-permeable inserts generally are more effective barriers to root graft formation because they do not cause significant diversion of root growth after contact with the material.

TRENCHING RESULTS IN A METROPOLITAN AREA

The causes of oak wilt trench breakouts in urban and suburban trenching projects that did not install trench inserts were investigated further to see if more information could be deduced from the results of trenching at different depths using conventional trenching methods recommended by the TOWSP. A series of 24 trenches installed over a 17-year period (1989-2006) by the city of Lakeway, Texas was selected as a model system for this investigation. These trenching projects were placed into two categories, based on trench depth, for the purpose of data interpretation: 1) ten 30 to 36"-deep trenches installed from 1989-1999; and 2) fourteen 39 to 48"-deep trenches installed from 1997-2006. The relative effectiveness of trenches, within these two trench-depth categories, in preventing trench breakouts over time following trenching, is summarized based on observations as of May 2007 (Table 4).

Among trenches in the 30-36" category, 10% held up with no trench breakouts up to 8 years after trenching, 50% had trench breakouts within the first two years after trench installation, and 40% exhibited breakouts 5-14 years after trenching. By comparison, trenches in the 39 to 48" category had significantly higher percentage (42.9%) of trenches without breakouts up to five years after trenching than trenches in the shallower category over the same time interval. A significantly lower percentage (21.4%) of deeper trenches had breakouts within the first 2.5 years than the shallower trenches. However, there was no significant difference in the percentage of trench breakouts between shallow vs. deep trenches that occurred three or more years following trench installation. This surprising discovery indicates that increasing trench depth provides little benefit in reducing trench breakouts that occur more than two years after trenching when trench inserts are not used.

The absence of a difference in breakouts with trenching depth after two years suggests that there is a fundamental different event that is occurring after three years and beyond that is the cause of breakouts which is different from those occurring within the first two years after trenching as indicated by Gehring (1995). The most probable explanation for this result is the formation of new root grafts across the trench which can occur regardless of trench depth in the trench backfill soil. Because most feeder roots are found in the top 18 inches below the soil surface, this is the area of the soil profile where most new root grafts likely form after trenching. Nevertheless, feeder roots are also found at the ends of deep roots that can form new root grafts across the trench following the installation of deeper trenches. Even though deeper trenches appear to be a benefit primarily within the first two years after trenching (when most breakouts occur), the installation of deeper trenches probably does provide greater long-term protection against trench breakouts when trench inserts are utilized. The greater trench depths with inserts will provide assurance that the deeper feeder roots will not form new root grafts across the trench beyond the second year after trenching.

Additional evidence to support the assertion that greater trench depth is an important factor in improving the long-term effectiveness of trenches with trench inserts is forthcoming from TOWSP trenches installed since 2004 by Texas landowners under the direction of TFS employees in Bandera and Kerr Counties. So far, over 20,000 linear feet of trench have been installed with the Typar insert material in trenches ranging from 5-14 feet (1.5-4.3 m). In the past three years, none of these trenches with Typar inserts have had trench breakouts of oak wilt. However, long-term observations will be required to fully assess the efficacy of trench inserts.

As the numbers and linear feet of trenches with Typar inserts expands, the TOWSP personnel will be able to better evaluate the effectiveness of these water-permeable inserts in actual oak wilt suppression trenches.

COSTS ASSOCIATED WITH TRENCH INSERTS

Any assessment of the efficacy of a new disease-control method must not only consider the effectiveness of the control method, but also the necessary additional costs that would be required to implement and utilize the new method. A full-scale economic assessment is not suggested here, but rather an examination of the probable costs of materials alone in the absence of variable costs such as additional labor and equipment modifications needed for implementation. The approximate costs of trench insert materials currently available for oak wilt suppression are provided and compared as a percentage of the average TOWSP trenching costs in urban ($16.85/linear foot) and suburban ($3.47/linear foot) environments since 2004 without trench inserts (Table 5). Trenching costs can be much higher in some cases. These estimated material costs are based on trenches that are at least 48 inches deep (with inserts at least 48 inches wide) at current prices.

The Typar and Geomembrane materials cost $1.20 or less per linear foot and represent only 2-7% of urban trenching costs and 11-34% of suburban trenching. The Biobarrier products with the slow-release trifluralin herbicide nodules cost $7-9 per linear foot representing 41-53% of urban trenching costs and twice as much as suburban trenching costs, significantly more than the other materials. Even though Biobarrier is more expensive than Typar alone, it does provide the additional protection of stopping root growth and elongation, precluding root contact with this material. Thus, Biobarrier provides a chemical barrier in addition to the physical barrier provided by the Typar fabric of which it is composed.

Theoretically, this integrated control with Biobarrier, utilizing two different strategies (chemical and physical), should be more effective than a physical barrier alone. As a statement of confidence, the manufacturer (Reemay Inc., Old Hickory TN 37138) guarantees this material will prevent root punctures up to 15 years. Another advantage is that trifluralin herbicide is water insoluble and will not contaminate groundwater aquifers. All of these trench insert materials have very similar puncture strengths, but the Typar material was the lightest (4 oz. per linear foot) among those tested, and performed as well as the Biobarrier products in experimental tests. The water permeable Typar material also was the cheapest material (only 40¢/linear foot) that was tested experimentally. As implied earlier, these costs do not include the additional labor costs required for installing the trench inserts or the additional costs associated with backfilling the trench by equipment other than the original trencher.

A more comprehensive list of commercially-available Typar products shows that this geotextile material comes in a wide range of weights, puncture strengths, and widths (Table 6). The landscape-grade Typar materials are most appropriate for trench-insert applications in oak wilt suppression, particularly Typar 3401 which comes in 48 and 60 inch widths, the most common trench depths used in oak wilt suppression. For deeper soils, trenches cut greater that 60 inches deep should utilize the Typar 3341 or a similar product because it is available at a width of 151 inches and may be cut down to appropriate widths at the factory if requested. Typar products in the 3500 and higher series are generally designed for more heavy-duty applications such as for road and storm drain construction, and are probably overkill for most oak wilt suppression applications, although some oak species under certain situations may be able to exert sufficient root puncture pressure to warrant use of these stronger materials.

PRECAUTIONS IN SELECTING AND USING TRENCH INSERTS

New roots forming from severed roots after trenching can grow both over and under the insert material, especially with water impermeable trench inserts which have a tendency to direct root growth along the face of the material and around the barrier. By contrast, water permeable inserts tend to cause these new roots to branch and form finer roots that stop elongating, once they come in contact with these inserts, because the roots are able to obtain moisture through the material. Consequently, water-permeable inserts tend to perform better than water-impermeable inserts. Trench inserts should be installed carefully so that the top edge of the material is even with the soil surface to prevent root growth over the top of the buried insert. Some insert materials such as polypropylene geotextile fabrics breakdown readily in the sunlight over a relatively short time. Consequently, materials such as Typar must be fully covered by soil to protect them against sunlight. Thus, it is equally important to not bury trench inserts so shallowly that the material is not covered and subject to degradation by sunlight or exposure to the elements, but extends as deeply as possible in the trench.

There are two major types of geotextile fabrics, spun and woven, that are available for landscape applications. Spun fabrics have greater stretching capacity, are more flexible, and have greater water permeability due to greater numbers of micropores. However, woven fabrics have greater total puncture strength (50%) than spun fabrics, but do not stretch appreciably and are less flexible than spun fabrics. Woven landscape fabrics have holes between the weave that sometime allow fine roots to penetrate. Thus, spun fabrics generally are more durable due to flexibility, and have are more effective in preventing root penetrations than woven landscape fabrics.

The utilization of untested trench insert materials should be considered with much caution because they may potentially lead to trench failures, poor results, and greater tree mortality than would have occurred without any trench inserts. Failures associated with the use of untested insert materials can reduce landowner confidence in trench inserts as an oak wilt suppression tool. Previously, untested landscape fabrics have been used that proved to be ineffective because they decomposed in the soil (lacked durability), had little root-puncture resistance, or were water-impermeable.

DIFFICULTIES IN APPLYING TRENCH INSERTS

The current foremost obstacle to utilizing trench inserts for the suppression of oak wilt root transmission is the fact that most rock saws commonly used in central Texas for trenching are designed to back fill the trench immediately after it is cut, precluding the installation of trench inserts. The trench must be left open temporarily after trenching to permit the installation of inserts along the wall of the trench. The cost of retrofitting a typical rock saw to leave the trench open can cost thousands of dollars. Thus, to be efficient, trenchers designed to leave the trench open must be used and dedicated for this purpose. Backhoes that are often used to dig trenches deeper than five feet favor the installation of trench inserts because the trench can be left open as long as needed.

Ultimately, the best solution would be to design a trencher that not only cuts the trench and leaves it open, but also contains a vertical post on the back for dispensing the insert material into the trench so that the insert can be secured to the wall of the trench, and the trenched backfilled immediately by a bulldozer with a grading blade that follows behind. The two pieces of equipment working together may be able to get the job done faster and perhaps more cheaply due to less rental time. If a bulldozer is used to dig the trench, it should also be used to refill it.

The additional labor, equipment, and fabric costs associated with the installation of trench inserts may be sufficiently large to impact the decision to install trench inserts. For example, the rising cost of urban trenching may, in some cases, prohibit the addition of any further expenses because additional costs may exceed the available budget of a trenching project. Other additional trenching costs may include the necessary removal of soil from trench sections that collapse or cave-in before the inserts can be installed. Many of these additional expenses sometimes can be handled more cheaply by landowners that have access to the proper equipment, such as a backhoe to cut the trench, and have the skill to operate rented or borrowed equipment for this purpose. Relatively little skill and effort is needed to manually install Typar inserts because they are lightweight and require the same skills used in the installation of common garden and landscape fabrics for weed control. The only difference is that trench inserts are secured vertically in the trench with pins inserted at the top of the wall of the trench, instead of perpendicular to the ground surface as with landscape fabric.

Most rocksaw trenchers used in residential neighborhoods or urban areas cut relatively narrow trenches that may be too narrow to allow easy installation of trench inserts. Rocksaws are the main trencher type used in cities because they are small enough to maneuver within the tight spaces found in neighborhoods and they do not tear up the ground and lawns as badly as the large, heavy chain trenchers or back hoes. One possible solution is to attach small clip-on weights to the bottom edge of the fabric (at intervals along the full length) to help the fabric fall to the bottom of the trench. Also, long lightweight poles such as bamboo, wooden dowels, or half-inch PVC pipes could be used to help push the fabric to the bottom of the trench. Keeping the fabric pulled tightly as it is being installed also helps in lowering it down into the trench. Trenches cut with a backhoe or the larger chain trenchers are much wider than those cut with rocksaws and allow a person to climb down into the trench to straighten and work the fabric to the bottom of the trench.

Another common problem in urban areas is the difficulty of installing trench inserts where there is an abundance of buried utility pipes. This problem involves the question of how to cut the insert material and then get a good seal around utility pipes to prevent roots from growing through these breaks in the fabric. A good approach is to assess whether the pipes are closest to the top or the bottom of the trench. The insert fabric should be cut from the edge of the material that is closest to the pipe to minimize the length of the cut required. The fabric at the cuts should then be overlapped a few inches and stapled, followed by taping with a very sticky wide tape after the insert material is secured with pins into the upper wall of the trench. If the utility pipes are concentrated in a short section of the trench, it may be easiest to just install the inserts in the long continuous sections of the trench that have no utility pipes. There is a low probability that a trench breakout will occur in a very short section of the trench with utility pipes compared with longer sections of the trench.

DISCUSSION AND CONCLUSIONS

Most oak wilt specialists acknowledge that the formation of new root grafts across an oak wilt suppression trench may eventually occur, leading to a breakout some years after a trench is installed. In the author's opinion, this phenomenon is not only common, but increasingly prevalent three or more years after trenching, even in dry sites, especially for live oaks that have such a strong propensity to form root grafts in the shallow soils of central Texas. Oak roots in this region on the Edwards Plateau commonly grow through layers of limestone permeated by pockets of soil. Soil usually fills holes in the rock formed by the percolation of ground water through the limestone. Nevertheless, the limestone bedrock layer tends to restrict and concentrate oak root growth above it, increasing the chances for root graft formation between the roots. In this situation, trenches alone are not intended to provide long-term protection against root transmission because new root grafts are expected to form over time between these concentrated roots that grow within trench backfill soil.

The current oak wilt breakout rate for TOWSP trenching projects ranges from 21-40% (on a whole-trench basis), depending on location and conditions, suggesting that there is still room for significant improvements in trenching technologies utilized for oak wilt suppression. These rates of trenching failures (breakouts) may not appear very high, but they are very significant for a highly-damaging necrotrophic fungal pathogen that is capable of killing living trees in a relatively short period of time (less than a year) after infection. The ability of *C. fagacearum* inoculum (spores and hyphal fragments) to travel within the transpiration water of oak roots up to 100 feet (30 m) or more per year, beyond the expanding edge of infection centers, further exacerbates the accumulation of damage and mortality to oaks caused by this disease.

Given the current rate of trench breakouts, the oak wilt pathogen has at least one chance in three (during the first two years) of passing beyond any one individual suppression trench installed in Texas using conventional TOWSP methods and trenching recommendations. This rate of disease breakout from trenches is sufficient to maintain the growth of *C. fagacearum* inoculum in oaks and keep the epidemic expanding, especially because numbers of trench breakouts continue to increase over time. For example, there are certain localized areas in Texas where the oak wilt epidemic has expanded to largely unmanageable proportions (Billings et al. 2001). In these areas of very high oak wilt density, the best chance for slowing the epidemic has been for the disease to simply burn itself out as a result of high oak mortality, leaving relatively few susceptible trees to maintain the expansion of the epidemic. Thus, new significant trenching methodologies are sorely needed to further decrease the failure rate of trenches and reduce the spread of individual oak wilt centers. The utilization of new integrated methods besides trenching, such as statewide restrictions on the intercounty transport of firewood from counties with oak wilt and the development of advanced epidemiological models to track movement of the pathogen, also would be useful to focus control implementations to help prevent the spread of oak wilt into other Texas counties and possibly other southern states.

Trench inserts provide a significant new method for improving trenches for oak wilt suppression in the U.S. The benefits of trench inserts could be substantial if they prove to be an effective means for reducing the rate of trench breakouts over long time periods. There are at least two possible strategies for utilizing trench inserts for oak wilt control. The first strategy could be used in situations where the additional costs of applying trench inserts would not pose a significant financial burden due to an abundance of available funds for the trenching project. In this case, trench inserts could be installed in every instance where the available funds for a trenching project are not limited, and the minimal extra expense for inserts could provide greater insurance against future trench breakouts. The second strategy takes into consideration that funds available for the trenching project are limited and the additional costs of trench inserts would pose a significant financial burden. In this case, trench inserts would not be used in the primary trench, but would only be considered if the primary trench failed in the future. Then, trench inserts could be installed in the new backup trench to enclose the breakout and improve long-term security against a secondary breakout. This approach is much more practical and feasible in the majority of oak wilt trenching projects where funding is limited.

Wilson and Lester (2002) reported some experimental evidence demonstrating the efficacy of trench inserts for increasing the effectiveness and longevity of trenches, and providing long-term oak wilt control beyond the first few years after trenching. This article was published at the completion of a 6-year trenching study during which preliminary results of the trench-insert tests were reported (Wilson and Lester 1996a-c, 1997, 1999). The utility of trench inserts has been shown to lie primarily in the prevention of oak wilt root transmission by precluding the formation of new root grafts across the trench within trench backfill soil, two or more years after trenching. The effectiveness of trench inserts in oak wilt suppression programs is being further evaluated by the TOWSP. Trench inserts have been installed in more than 20,000 linear feet (6,153 m) of oak wilt suppression trenches installed by TFS personnel, working within the TOWSP since 2004. Because more than two years are required for roots to grow across trenches and for inserts to show efficacy, the impact of these inserts has yet to be determined. Data from future post-suppression evaluations in the coming years hopefully will provide more conclusive evidence of the performance and effectiveness of trenches containing trench inserts compared with conventional TOWSP trenches without inserts.

The Typar trench insert material is recommended here as the best, most cost-effective material currently available as a water-permeable physical barrier for installation within oak wilt suppression trenches. This lightweight material is relatively easy to install (compared with the other trench-insert materials), comes in a variety of widths, is very cheap (only 40¢ per linear foot), and works as well as Biobarrier based on experimental tests (Wilson and Lester 2002). Typar is a spun fabric that probably performs better than woven fabrics due to the potential for root tips to penetrate holes between the weave in some woven fabrics. Other water-permeable insert materials may have utility as trench inserts, but no other materials besides Typar are currently recommended until they can be properly tested and evaluated both experimentally and in TOWSP field trials.

There are a number of advantages of utilizing water-permeable trench inserts over conventional methods of installing trenches without inserts. Trench inserts eliminate the need for expensive backup trenches, required when primary trenches fail and oak wilt breakouts occur beyond the trench. Trench inserts also provide greater security (insurance) against breakouts in high-hazard sites with large valuable trees, or where symptomatic trees are not removed inside the trench. The additional cost of the Typar water-permeable trench insert is low, on a percentage basis (2-11%), relative to conventional average TOWSP trenching costs in urban, suburban, and rural sites. Typar is available in a variety of thicknesses and prices, providing a range of root-puncture resistance for applications with various oak species, and varying levels of protection against root penetrations. The most expensive trench insert barrier, giving the greatest protection against oak wilt root transmission, is provided by Biobarrier (Typar with trifluralin nodules) which delivers both herbicide and physical barriers to root penetrations.

There is also a strong advantage of having trench inserts installed when trenches must be placed (because of land-access constraints and multiple property lines) far out in front of the infection center; over 150 feet beyond symptomatic trees (not recommended or approved by TOWSP). The longer the time it takes for the trench to be challenged, as inoculum of the fungus approaches the trench in the root system, the more advanced new root grafts will be developed when the fungus finally arrives at the trench. This is the reason why it is not normally recommended to have buffer zones greater than 100 feet from the infection center to conventional trenches without trench inserts.

The ultimate success of integrating trench inserts into the trenching process for oak wilt suppression depends on whether progress can be made in overcoming logistic hurdles such as achieving public awareness of this new disease control strategy, communicating cogent explanations of trench-insert applications and effectiveness, and resolving problems associated with effective implementation (such as trenchers that backfill the trench immediately). First, increasing public awareness and education on trench-insert alternatives and the large potential for improved performance of trenches provided by trench inserts are essential. The inclusion of discussions on trench-insert installations within oak wilt suppression training courses and seminars is needed. Continued expanded field testing of trench inserts within the TOWSP as opportunities arise will facilitate the evaluation of efficacy vs. conventional trenching methods. Also, greater utilization of trench inserts by private oak wilt suppression businesses, and familiarity by trenching contractors will be necessary to streamline the integration of trench insert installation methods into mainstream suppression practices as much as is possible in urban and rural settings.

Ultimately, the development of new trenchers designed to cut trenches and dispense trench insert materials into the trench in one simultaneous operation would be most beneficial. It should be possible to design a trencher system that contains a lightweight, detachable trailer (in tandem) with a vertical post containing a bolt of trench insert material that could be dispensed as the trench is being cut. The trailer could be detached from the trencher when the trencher is serviced or moved to a new location. The advantages of simultaneous installation of trench inserts during the trenching operation include the avoidance of trench cave-in problems and hazards associated with leaving the trench open for extended periods of time.

Trenching as a disease-control strategy continues to be the easiest and most effective option for reducing oak wilt root transmission and tree mortality in localized areas. The direct control of insects or other potential vectors that carry the pathogen, presumably involved in the creation of new oak wilt infection centers, is not readily feasible other than to avoid the wounding of trees when vectors are active. Applying chemical or biological agents to reduce contact between potential vectors and inoculum sources such as fungal mats also is not feasible because of the very large number of red oaks that must be treated. Some currently unknown vectors may have the potential to directly penetrate bark and transmit the pathogen (Wilson, Lester and Edmonson 2000). If this is occurring randomly in forest and urban stands, then there is no feasible means of protecting trees from primary infections. The best opportunities for control in such cases would be to eliminate the sources of *C. fagacearum*-inoculum from which vectors acquire the fungus. However, this may not be feasible if there are too many sources of infected trees in a localized area, but it should be feasible in areas where oak wilt-infected trees are rare in the landscape.

I previously proposed the implementation of state quarantines to prevent the intercounty transport of *C. fagacearum*-infested firewood into counties not affected by the disease (Wilson 1995). This strategy, if implemented, would help eliminate the dispersal of inoculum by human means and reduce the incidence of inoculum transport and vector transmission by natural causes. Although there have been some research efforts to identify oak wilt resistance in live oaks (Greene 1995, McDonald et al. 1998, Gray, this proceedings), none has led to the development of oak wilt resistant lines because no resistance genes have been identified. Host resistance generally is a good long-term disease-control strategy, but in the case of oak wilt, sufficient time does not exist to regenerate resistant or tolerant mature oaks because current rates of oak mortality probably are eliminating mature susceptible trees from the landscape at a rate faster than mature oak wilt-resistant or tolerant oaks could be generated – ranging from 50 to 80 years

(Jacobs 2006). Planting fast-growing native hardwood species immune to oak wilt is a better strategy.

Trenching will likely continue to be the most important and effective oak wilt suppression method used in the foreseeable future as oak wilt incidence continues to increase and become more important in urban areas (Wilson et al. 2004). The continuous development and implementation of new, more effective tools to monitor and control oak wilt are essential for improving our success in managing this devastating disease (Appel and Maggio 1984, Appel et al. 1989, Appel 1995, Wilson and Forse 1997, Wilson and Lester 2002, Wilson, Lester and Oberle 2004, Wilson 2005, Wilson, Lester and Oberle 2005).

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Table 1. Incidence of oak wilt disease breakouts from Texas Oak Wilt Suppression Project (TOWSP) trenches relative to time following trench installation without trench inserts.

Years after trenching	**Oak wilt breakouts[1]**	**Breakout % of total**	**Cumulative % of total**	**% change in slope**
0.5	17	6.85	6.85	–
1.0	35	14.11	20.96	105.9
1.5	47	18.95	39.91	34.3
2.0	50	20.16	60.07	6.4
2.5	33	13.31	73.38	-34.0
3.0	29	11.69	85.07	-12.1
3.5	17	6.85	91.92	-41.4
4.0	8	3.23	95.15	-52.9
4.5	4	1.61	96.76	-50.0
5.0	6	2.42	99.18	50.0
>5.0	2	0.82	100.00	-66.7
	total 248			

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[1] Data are derived from TOWSP post-suppression reports on 248 trenches installed from 1988-1992 when trench depth was 32-36” deep (TOWSP, personal communication).

Table 2. Most probably causes of oak wilt disease breakouts from trenches over time following trench installation.

Trench breakouts occurring within 2 years (60 % of trench breakouts)[1]	**Trench breakouts occurring after 2 years (40% of trench breakouts)**
Improper trench placement (fungus already past; insufficient buffer zone)	Newly-formed root grafts in backfill soil (due to new root growth in trenches)
Insufficient trench depth (fungus passes under trench)	Movement across trench by vectors (above-ground transmission)
Discontinuous trench (fungus passes through gaps in the trench)	Movement across trench by other means (e.g. firewood cut from infected dead trees)

[1] Trench breakout rates are based on trench installations determined from TOWSP post-suppression data and trench-failures indicated by trench breakouts.

Table 3. Experimental incidence of oak wilt disease breakouts from trench barriers over time following trench installation with and without trench inserts.

	New oak wilt disease outbreaks beyond trench barriers					
	Years after trench installation[1]					
Trenching treatment[2]	**1**	**2**	**3**	**4**	**5**	**6**
Trench + Typar	0	0	0	0	0	0
Trench + Biobarrier	0	0	0	0	0	0
Trench + Geo 30 mil	0	0	0	0	0	0
Trench + Geo 20 mil	0	0	**1**	**2**	0	0
Trench only control	0	0	0	**1**	0	0
No trench control	0	**1**	**1**	0	**1**	0

[1] Data are derived with modifications from research publication (A.D. Wilson and D. G. Lester, 2002. Plant Dis. 86:1067-1074). The values above indicate **new** oak wilt disease outbreaks from trenches by year whereas the values in the paper indicate **cumulative** outbreaks by year that charted disease progress over time.

[2] Three replicate trench segments (320-meter mean length) were prepared for each trenching treatment.

Table 4. Oak wilt trenching project results and summary for Lakeway, TX from 1989-2006.

Years installed	Linear feet range	Trench depth	% of trenches	Post-installation result[1]
1989-1999	600-2314	30-36" deep	10.0	holding up to 8 years
		(10 trenches)	50.0	failed within 1-2 years
			40.0	failed after 5-14 years
1997-2006	465-4610	39-48" deep	42.9	holding up to 5 years
		(14 trenches)	21.4	failed within 1-2.5 years
			35.7	failed after 3-9 years

[1] Trenches that failed are defined as those that had at least one oak wilt breakout that occurred somewhere along the total length of the trench within the time periods indicated.

Table 5. Physical characteristics and costs of trench insert materials per linear foot relative to trenching costs.

Trench barrier	Mean costs \$/ l.f.[1]	% of trenching costs urban	% of trenching costs suburban	Puncture strength lbs	Weight oz/yd^2
Typar 3401	0.40	2.4	11.5	40	4.0
Geomembrane 20 mil	0.91	5.4	26.2	44	14.4
Geomembrane 30 mil	1.20	7.1	34.6	60	21.2
Biobarrier II (weed)	6.90	41.0	198.9	40	13.3
Biobarrier I (root)	8.84	52.5	254.8	40	13.3
Trenching only (suburban)	10.00	59.4	100.0	–	–
Trenching only (urban)	16.85	100.0	485.6	–	–

[1] Costs values per linear foot for trench inserts do not include additional labor costs, and are based on trench insert materials that are 60 inches wide and trenches that are 60 inches deep. Cheaper prices are possible through volume discounts when insert materials are purchased on bulk rolls and when the total linear feet of trench is increased.

Table 6. Availability and physical characteristics of Typar trench insert materials useful for oak wilt suppression.

Product type and grade	**Weight oz/yd^2**	**Puncture strength lbs (N)**	**Fabric width available (inches)[1]**				
			36	**48**	**60**	**75**	**other widths**
Landscape							
Typar 3201	1.9	18	+	+	–	+	–
Typar 3301	3.0	25	+	+	–	+	–
Typar 3341	3.4	34	–	–	–	–	151
Typar 3401	4.0	41	–	+	+	–	–
Heavy duty							
Typar 3501	5.0	56	–	–	–	–	151
Typar 3601	6.0	67	–	–	–	–	151
Typar 3631	6.3	81	–	–	–	–	151
Typar 3801	8.0	93	–	–	–	–	151

[1] Fabric width availability: (+) indicates this width of Typar fabric is available, (-) indicates this width of fabric is not available. Numerical values indicate the fabric widths available beyond 75 inches.

THE TEXAS COOPERATIVE OAK WILT SUPPRESSION PROJECT: LESSONS LEARNED IN THE FIRST TWENTY YEARS

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ABSTRACT

Live oaks (*Quercus virginiana* and *Q. fusiformis*), prized in central Texas for their stately beauty and welcomed shade, are being threatened by a destructive disease – oak wilt, caused by *Ceratocystis fagacearum*. In 1988, the Texas Forest Service (TFS), the USDA Forest Service, Forest Health Protection (USFS/FHP) and others initiated the Texas Cooperative Oak Wilt Suppression Project. For twenty years, this project has been managing the oak wilt problem through unique partnerships and local cooperation. Goals of the Suppression Project have focused on increasing public awareness about oak wilt, identifying and mapping active oak wilt infection centers, and partnering with landowners to contain oak wilt spread. More than 2 million dollars of federal cost shares have been delivered to participating landowners since 1988 as an incentive to treat expanding oak wilt centers. To date, the Suppression Project has installed more than 3.4 million feet (648 miles) of trenches to control 2,466 oak wilt centers. Of these , 2,156 centers (87%) were cost shared with $2.1 million of federal funds. An economic analysis has documented that the $9.2 million of federal, state, city, and private funds invested in the Suppression Project have yielded an average benefit:cost ratio of 6:1 and saved Texas communities an estimated $55 million in tree removal, replanting, and fungicide costs. Achievements in public awareness also have been substantial. An Internet web page devoted to oak wilt management in Texas (www.texasoakwilt.org) has been developed, representing a partnership among various stakeholders. In an on-going effort, specialists with TFS and Texas AgriLife Extension Service have trained various groups of Master Gardeners/Master Naturalists and International Society of Arboriculture-certified arborists on the basics of oak wilt identification and management. These accomplishments and lessons learned in the last 20 years concerning operational management of oak wilt in Texas are summarized.

Key words: *Ceratocystis fagacearum,* disease management, propiconazole

Live oak trees *(Quercus virginiana* and *Q. fusiformis*) comprise a major component of rural and urban landscapes in central Texas and are highly regarded for their beauty, shade, and forage for wildlife. Widespread mortality of live oaks in central Texas has been recognized for many years (Taubenhaus 1934, Dunlap and Harrison 1949) and oak wilt, caused by *Ceratocystis fagacearum* (Bretz) Hunt, was officially diagnosed in Dallas in 1961 (Dooling 1961). But it was not until the late 1970s that this widespread mortality of oaks in central Texas was attributed to the oak wilt pathogen (Lewis and Oliveria 1979, Appel 1995). This realization sparked interest in research on this disease in Texas (Appel and Maggio 1984, Appel and Lewis 1985, Appel et al. 1989, Appel and Kurdyla 1992) and provided the impetus for two important cooperative projects initiated in the 1980s: the Texas Oak Wilt Demonstration Project (1982-1987) and the Texas Oak Wilt Suppression Project (1988-present) (Cameron and Billings 1995, Billings et al. 2001).

Conditions in central Texas have changed since the Suppression Project began. An increasing number of large ranches are being subdivided into 5-100 acre “ranchettes” as more people take up residence in this region of the state. Their presence not only increases property values but also increases the incidence and economic impact of oak wilt (see Rooni, this proceedings). Some 25 years of experience combating oak wilt in Texas have given the Texas Forest Service (TFS) a unique perspective on how to effectively manage this destructive pest problem.

DEVELOPMENT OF THE TEXAS OAK WILT SUPPRESSION PROJECT

Project Proposal

During the final year of the Texas Oak Wilt Demonstration Project, the TFS Forest Pest Control Section (now Forest Pest Management) developed an Oak Wilt Suppression Project proposal and submitted it to the USDA Forest Service, Forest Pest Management (now Forest Health Protection (USFS/FHP)) in September 1987 (see Cameron and Billings 1995 for details). The Suppression Project was initiated in June, 1988.

Technical Advisory Board

To provide project guidance and direction, a Technical Advisory Board was formed, consisting of key administrators and specialists with the USFS/FHP, TFS, Texas Agricultural Experiment Station (now Texas AgriLife Research), Texas Agricultural Extension Service (now Texas AgriLife Extension Service), the cities of Austin, Lakeway, Cedar Park and Round Rock, and a private tree care company. This advisory board first met in December 1987 to discuss the Project proposal and implementation process. Since then, membership has increased from 10 to 16 members and the board has met annually to review Project accomplishments and provide long-term direction.

Objectives

The primary goal of the Texas Oak Wilt Suppression Project is to minimize the spread of oak wilt in rural and urban areas of central Texas. Initially, objectives of the Project were to: 1) initiate and accelerate public awareness campaigns to educate urban and rural landowners of the oak wilt threat as well as prevention and suppression alternatives, 2) identify oak wilt centers in selected suppression areas using aerial surveys and contacts with local landowners, 3) assist with implementation of control treatments by providing technical assistance and federal cost-share funds for approved treatments, 4) conduct post-suppression evaluations to record the frequency of re-infections (breakouts) and assist with retreatments if necessary, and 5) develop and refine a computerized record-keeping system for cataloguing and summarizing detection, ground evaluation, and control information (Cameron and Billings 1995).

In recent years, additional objectives have been added. These include an economic analysis of SuppressionProject benefits and costs, conducting systematic aerial detection surveys over the most severely-infected counties, organizing and conducting the first National Oak Wilt Symposium (Appel and Billings 1995), offering field tours to highlight the economic impact of oak wilt and showcase Project accomplishments, initiating a webpage devoted to oak wilt management in Texas, and developing a long-range strategic plan for oak wilt management in Texas. During the last decade, in response to increasing public demands, Suppression Project efforts have been expanded from three initially-targeted counties (Hood, Travis, Kendall) to more than 40 counties covering most of central Texas.

Organization

Cameron and Billings (1995) described the development and initial organizational structure of the Texas Oak Wilt Suppression Project. The Suppression Project currently is led by a project director at the Texas Forest Service headquarters in College Station, Texas. He is assisted by an administrative coordinator with TFS Forest Pest Management in College Station and a technical coordinator based in Austin. Field personnel gradually have been added to the project to carry out specific project objectives and to address increasing numbers of requests for assistance in key counties.

The seven oak wilt foresters currently involved in the Project devote 40-80% of their time to oak wilt and the remainder to coordinating and implementing other federal and state programs (forest stewardship, urban forestry, fire suppression). Four TFS urban foresters contribute 5 to 10% of their time toward implementing the Suppression Project. TFS secretarial staff members in Lufkin and College Station provide administrative support to field personnel. In addition, the city of Austin has one full-time oak wilt forester and two technicians to implement project objectives within the city limits and the city of Lakeway has employed an oak wilt forester since 2001. Both positions were initiated with support from Suppression Project partnership grants.

Funding

The USFS/FHP, Atlanta, GA provides federal funding (40% since 2006) for this cooperative suppression project while TFS (37%), city partners (3%), and private landowners in central Texas (20%) provide required matching funds. Federal suppression funds allocated annually for this project have ranged from $168,000 in FY 1988 to a high of $595,000 in FY 1995. In recent years, federal funds have leveled off at $400,000 to $500,000 per year. Each federal dollar is matched by cooperating agencies or private landowners. Thus, the total expenditure for this suppression project currently averages $1 MM to $1. 2 MM per year, including the State, City of Austin, and private landowner contributions. In recent years, federal suppression dollars for oak wilt have become increasingly difficult to capture, due to the longevity of the project (federal suppression projects seldom are funded for more than five consecutive years) and to competition for shrinking funds to address oak wilt in other regions and other major forest pests (e.g., southern pine beetle, gypsy moth, Asian longhorned beetle, emerald ash borer, etc.).

Control Tactics

The Texas Oak Wilt Suppression Project has a two-faceted approach to oak wilt management - prevention and direct control. Prevention is promoted through public education on proper timing of pruning and treating wounds on oak trees (Appel, Anderson and Lewis 1986, Camilli, Appel and Watson, this proceedings), elimination of potential fungal inoculum by destroying diseased red oaks, proper handling of firewood, use of propiconazole fungicide, and planting diverse and resistant tree species. Direct control procedures include detection, field evaluation, and control of expanding oak wilt centers (Cameron and Billings 1995). Project foresters work with individual landowners or neighborhood groups to identify the location of oak wilt center boundaries. If the infection center is well defined and considered containable, and the landowner is willing to implement the suggested control treatment, the Project forester conducts a cultural resource survey (Billings et al. 2001) and prepares a written oak wilt suppression plan. The plan, together with an estimate of costs and a request for cost shares, is submitted for approval to the Project Director. Upon approval, the treatment is installed under supervision of the Project forester. After the treatment is completed, the landowner or neighborhood organization is reimbursed with federal funds for up to 40% of the treatment costs, not to exceed $1000 per single landowner or $5,000 per oak wilt center with multiple landowners.

Currently, the primary cost-shared control procedure involves installation of trenches, at least 4 feet deep, to prevent continual tree-to-tree spread of the fungus through interconnected live oak root systems. A variety of equipment has been used to install trenches, including rotary rock saws, belt trenchers, back hoes, and ripper bars. Rock saws and back hoes are most often used in urban areas. Ripper bars pulled by bulldozers were commonly used in rural areas prior to 1999, but were replaced by rock saws when the depth requirements were increased from 3 to 4 feet. Trenches should completely encircle the center or tie into natural barriers or recently-dug utility trenches. The trench is placed 100 feet in front of symptomatic trees; at least one apparently healthy "buffer" tree should be included between symptomatic trees and the trench. Trenches are refilled with soil immediately after installation. Trench inserts (Wilson, this proceedings) are available, but are not recommended due to the additional expense nor are they cost shared.

Whenever practical, especially in rural areas, it is recommended to up-root and dispose of diseased and apparently healthy trees inside the trenched area. This practice is seldom applied in residential areas, where fungicide injection of trees within the trench is a preferred option. Cost-share funds also can be used for the removal and disposal of symptomatic red oak trees to prevent fungal mat formation and to remove diseased live oaks in urban areas.

Root-flare injections with the fungicide propiconazole prevents many trees from developing severe disease symptoms, but this treatment does not prevent the oak wilt fungus from moving through the untreated root systems and spreading the disease through a stand of live oaks (Appel and Kurdyla 1992). Also, retreatments may be necessary because the effectiveness of the fungicide apparently does not last for more than two years. Therefore, the primary justification for incorporating propiconazole treatments in the Texas Oak Wilt Suppression Project from FY 1990 to 1996 was to provide landowners an incentive to incorporate fungicides in trenching operations designed to stop the spread of the disease. Cost-share funds or donations of free propiconazole (Alamo®) were applied solely to high-value non-symptomatic trees inside cost-shared trenches. Beginning in FY 1997, fungicides were no longer cost-shared by the Project or provided free by the manufacturer.

Oak Wilt Information System

To track Project activities and accomplishments, TFS designed and implemented a computerized record-keeping system (Texas Oak Wilt Information System or TOWIS) in 1988 (Cameron and Billings 1995). This record-keeping system was written in D-Base III for IBM-compatible microcomputers. Project personnel entered data on personal computers at each field station. They could access their records at any time to keep track of landowner names and addresses, treatment status, and detailed treatment information on individual infection centers. Current data were periodically sent from each field station via electronic mail or diskette to the TFS headquarters in College Station where the master records are maintained.

In 2003, TFS staff members created the new database Central Texas Geographic Information System (CTexGIS*)* which has replaced TOWIS. CTexGIS now houses the databases for oak wilt, the Forest Stewardship Program (FSP) and the Forest Land Enhancement Program (FLEP). This database is linked to the geographic information system ArcGIS® 9.2 to provide a seamless integration of the temporal and spatial data. All staff foresters in central Texas were given training in use of both CTexGIS and ArcGIS® 9.2. Oak wilt data sets for a given forester are "checked out" periodically by the forester, added to or updated and "checked in" to the general database housed on a server in College Station. Through a series of queries or pre-programmed reports, project administrators and field foresters alike have ready access to data summaries for use in periodic reports, post-suppression and personnel performance evaluations, and economic analyses.

Digital Orthophoto Imagery

In FY 1997, implementation of Suppression Project objectives was greatly facilitated by purchase of digital color infra-red imagery (scale 1:40,000) of much of central Texas from EISYS, Austin, Texas. The imagery is provided on compact discs covering individual USGS 7 ½ minute quadrangles. The CDs will operate on microcomputers running Microsoft Windows 3.1, MS Windows 95, or MS Windows NT. With this resource, Project foresters have access to fairly recent (1995/1996) imagery with 1 m resolution. This digital imagery allows them to generate accurate treatment maps and to delineate the spatial distribution and abundance of available hosts in the treatment area. The CIR treatment maps are prepared with Arc-View software to highlight location of infected trees, planned trenches, existing roads and barriers, etc. These maps also are useful during post-suppression revisits to treatment sites as a means to accurately relocate old trenches. This imagery, now more than ten years old, is to be updated at the first available opportunity.

PROJECT IMPLEMENTATION AND ACCOMPLISHMENTS

Public Awareness of Oak Wilt

Suppression Project personnel are continually involved in efforts to make central Texas landowners aware of the oak wilt problem and available methods of diagnosis, control, and prevention. These efforts can be categorized as public presentations on oak wilt, media events, responses to daily telephone calls from concerned property owners, and individual on-site assists (Billings et al. 2001). Recently, a webpage specific to oak wilt in Texas (www.texasoakwilt.org) was initiated. This web page has been developed and is maintained as a partnership among the TFS, USFS/FHP (Region 8), Lady Bird Johnson Wildflower Center, National Biological Information Infrastructure, Houston Advanced Research Center and the International Society of Arboriculture, Texas Chapter (ISAT). This web page is becoming increasingly popular as a source of oak wilt information. For example, in a single month (March 2007), the web site received 79,000 hits and 19,000 page views. With success of the oak wilt webpage, the oak wilt telephone hot line, established in 1990 with support of the Lower Colorado River Authority (Billings et al. 2001), was discontinued in 2005.

To further promote public awareness of oak wilt and the Suppression Project, three illustrated circulars were published and widely distributed to interested landowners and neighborhood groups. These are titled *How to Identify and Manage Oak Wilt in Texas* (Appel, Filer and Cameron 1990, Appel et al. 2005), *Save Our Shade - A Guide to Cost-Sharing for Oak Wilt Control in Texas* (Texas Forest Service 1990), and *Partnerships and Cooperation Combat Oak Wilt in Texas* (Texas Forest Service 1999). A fourth circular entitled *Oak Wilt: A Guide to Identification and Management* (City of Austin 1994) was published by the City of Austin and distributed by Project personnel. Also, a MS Power Point presentation and a portable photo display describing oak wilt and Project activities have been prepared for public presentations.

Project personnel, in cooperation with Dr. David Appel, Texas A&M University, organized and hosted the 1992 National Oak Wilt Symposium in Austin (Appel and Billings 1995) and the 1996 North American Forest Insect Work Conference in San Antonio (Billings and Nebeker 1996). In 2007, Project personnel assisted the ISAT with organizing and hosting the 2nd National Oak Wilt Symposium. The impact of oak wilt and Project accomplishments were highlighted in Symposium and Conference presentations and field trips.

Identification and Confirmation of Oak Wilt Centers

To date, oak wilt has been confirmed in six counties in west Texas and 55 counties in central Texas. The latter are located primarily along the Interstate-35 corridor from Dallas-Fort Worth to San Antonio (see Rooni, these proceedings). Detection of oak wilt centers by Project personnel is achieved by conducting aerial survey flights over predetermined areas or by responding to landowner inquiries (see Billings et al. 2001).

Control Accomplishments

Since the Suppression Project began in 1988, a total of 2,466 oak wilt centers have been treated with trenches extending for 3.42 million feet (648 miles or 1,037 km). Of these, 2156 centers (87%) involving 3.22 million feet of trench have been cost shared with federal funds; the remainder involved technical assistance from Project staff without cost shares. Based on feet of trench installed with Project cost shares since 1988, the top 10 counties receiving federal assistance to halt oak wilt spread have been Bosque, Gillespie, Travis, Bandera, Kendall, Williamson, Hays, Hood, Bell, and Kerr County (Table 1). Average cost per foot of trench over this 20-year period among these ten counties ranged from $0.50/foot in Bosque County (mostly rural centers) to $4.13/foot in Travis County (mostly suburban and urban centers). Interestingly, the average cost to install trenches has tripled since 1990, increasing from $1.34/foot for the period 1988-1990 up to $4.11/foot in 2007 for all land-use categories combined.

The cost of installing trenches to suppress oak wilt continues to increase (see McKinney and Billings (1995) for initial treatment costs) and varies markedly with land use classification. In FY 1998, for example, trenching costs ranged from an average of $0.60/ft in rural non-residential sites to $10/ft in urban sites. In suburban and rural residential sites, average trench costs were $2.68/ft and $1.11/ft, respectively (Billings et al. 2001). In comparison, the cost of installing trenches to suppress oak wilt in FY 2006 ranged from an average of $1.65/ft in rural non-residential sites to $22.45/ft in urban sites. In suburban and rural residential sites, average trench costs were $3.32/ft and $4.14/ft, respectively. The average cost of trench installation has increased in all land use categories but particularly in urban areas, where trench costs increased by more than $12/foot. The high cost to trench in urban sites reflects the inherent expenses and liability associated with underground utilities and street repairs.

Much of this increased cost was borne by participating urban landowners, since maximum cost shares paid per center were capped at $1,000 for single landowners and $5,000 for four or more landowners and the federal match was reduced to 40% to cover a state-mandated increase from 10.5% to 26% for indirect costs in FY 2005.

Annual accomplishments, based solely on centers treated and amount of trench installed, steadily increased through the first eight years as the Suppression Project grew in personnel and experience (Fig. 1). Since 1995, the annual amount of trenches installed by the Project has declined to ca. 150,000 feet/yr (46,154 m/yr), due to various factors. These include reduced levels of cost share funds, increasing costs per foot of trench, increased government restrictions (i.e., cultural resources), shifting of Project emphasis to other objectives (post-suppression evaluations, aerial detection surveys, public awareness), and other demands on Project personnel (stewardship, fire suppression, urban forestry). Also, many of the small, accessible, and easily controlled centers have already been treated.

Through September 30, 2007, $2.5 million of federal cost shares had been reimbursed to participating landowners, representing 40% of the total costs of oak wilt treatments. The majority (80%) of these funds have been used for trenching, the primary means of halting the local spread of individual oak wilt centers in live oak stands. Other treatments receiving cost share funds include tree cutting (6%), uprooting trenches within the trenched area (4%), infected tree removal (6%), and fungicide treatments (4%).

Efficacy of Project Trenches

Procedures for conducting the post-suppression evaluation of Project trenches have been described previously (Gehring 1995). This evaluation has become an annual event to document efficacy of trenches, but is now limited primarily to those installed during the previous 3 years. In the fall of 1998, for example, Project personnel revisited oak wilt sites treated with cost-share funds from 1995 through 1997. The occurrence and frequency of breakouts on 571 oak wilt centers were evaluated in relation to feet of trench, month of installation, equipment type, and months since trench installation.

Results reveal that, on average, 76% of all trenches installed from 1994 to 1997 had no breakouts. Of 690 trenches installed between 1991 and 1994, 67% have had no breakouts. Breakouts, when they do occur, are most likely to become visible within 18-30 months after installation. Interestingly, frequency of breakouts did not seem to be related to month of installation or to equipment type. Breakouts were most often attributed to insufficient trench depth (e.g., roots present beneath the trench), rather than to roots reattaching or growing back across the trench. In the winter of 2008, a random sample of 121 trenches out of 356 trenches (34% sample) installed from 2002 – 2005 were revisited. Twenty-six breakouts were observed for a success rate of 79%. This is the first PSE where all trenches visited were at least 48” in depth and the increase in success is attributable to this increased depth (up to 5 feet (1.5 m) with rock saws and 12 feet (3.7 m) with back hoes) and the experience gained over the years in correct trench placement.

Partnerships

The Suppression Project has promoted and benefited from various partnerships. The City of Austin was a major partner in the Project from its initiation in 1988 until 2000, when city budget reductions caused the city to end its participation. In FY 1998, the council converted two temporary oak wilt positions to permanent ones, increasing the oak wilt staff to four persons. In 2006, the city hired an oak wilt forester and resumed participation in the Suppression Project. During the years the City of Austin served as a partner, the Project reimbursed Austin's Parks and Recreation Department (PARD) $25,000-30,000 for their staff's participation in the Project. Also, Austin's neighborhood associations and citizens were reimbursed up to 50% of their suppression costs for approved trenching projects and diseased tree removal. In 2007, the city opted to finance their oak wilt program entirely with city funds.

From 1989 through 2005, the City of Lakeway and Texas Forest Service personnel worked with 170 Lakeway property owners to install over 34,000 feet (10,462 m) of urban trenches. The city hired its first forester in February 2001, with a partnership grant from the Suppression Project. During the five years that the city was a partner, nine trenches were installed with 95 cooperators totaling almost 18,000 feet (5,538 m). The grants gave Lakeway officials incentive to tackle the oak wilt problem head-on. The city council stepped up to the plate by increasing funding for oak wilt suppression every year despite rapidly rising costs. Feedback on the oak wilt program has been overwhelmingly positive. Many citizens have expressed the belief that they benefit directly from Lakeway's forestry program. After FY 2005, the city declined further partnership grants, opting to continue funding their oak wilt program entirely with city funds.

As described above, partnership grants also have been provided to the Lady Bird Johnson Wildflower Center and the Houston Advanced Research Center primarily to develop the Texas oak wilt web page (www.texasoakwilt.org).

Master Gardener/Master Naturalist/ISA Certified Arborist Training

In recent years, TFS Project foresters in central Texas have become overwhelmed with phone calls and inquiries concerning oak wilt, many of which do not result in cost-shared treatments. In recognition of this fact, a new approach was taken beginning in FY 2005 to increase the availability of volunteers trained in oak wilt detection, prevention, and control. Training sessions were offered to interested Master Gardeners and Master Naturalists as a means to increase public awareness and to serve as an interface between the public and TFS foresters. In FY 2006 and 2007, TFS staff foresters, in cooperation with Dr. David N. Appel, a recognized authority on oak wilt in Texas, continued these training sessions various locations throughout central Texas.

In other training sessions, several dozen certified arborists with the International Society of Arboriculture were trained in oak wilt diagnosis, prevention, and suppression procedures. Again, Dr. Appel, with the Texas AgriLife Extension Service, and various TFS Project foresters served as instructors for classroom and field training sessions for the certified arborist training. Upon successful completion of this intensive 2-day course, each participant is certified as a "Specialist in Oak Wilt."

It is anticipated that these volunteers will assist TFS Project foresters in screening oak wilt-related phone calls and verifying the presence of oak wilt via on-site visits. It is envisioned that such a cooperative partnership with Master Gardeners, Master Naturalists, and ISA Certified Arborists will facilitate the suppression project by reducing the time TFS foresters now spend responding to inquiries from the general public and local property owners.

Economic Analysis of the Project

In FY 1997, an economic analysis of the Texas Oak Wilt Suppresion Project was independently conducted by J. T. Gunter, previously a forest economist from Mississippi State University. Input information consisted of Project accomplishments (specifically trenching, tree removal, and fungicide injection treatments) and Project costs (salaries, benefits, operating expenses, contracts, cost shares, administrative expenses, and indirect costs) for the period FY 1990 through 1996. Rates and extent of spread, host densities, and average tree diameter data were taken from a previous economic analysis of the Project (McKinney and Billings 1995). Project efforts were divided into four different land use categories (urban, suburban, rural residential, and rural non-residential) as previously defined (McKinney and Billings 1995).

Benefits were computed based solely and conservatively on the basis of those dead tree removal and replanting costs avoided when oak wilt spread was halted in individual centers for 5 years by 1) trenching and diseased tree removal or 2) trenching, fungicide injection of trees within the trench, and diseased tree removal. For each treated center, benefits were defined as the monies saved by a landowner by cooperating with the TFS to suppress the spread of oak wilt. In turn, costs were defined as the actual cost incurred by the Suppression Project to prevent further spread of the disease center, and incorporated Project operating and administrative costs.

No attempt was made to assess or include the value of the trees saved, as was done in an earlier analysis (McKinney and Billings 1995) or additional benefits (protecting real estate values, reducing air conditioning costs, etc.). Assumptions were that, if no trench was installed, oak wilt would continue to spread at 75 feet per year for 5 years, killing 85% of the oaks in the direction of spread (defined for purposes of this analysis as 50% (urban sites) to 75% (rural sites) of the circumference of the oak wilt center).

Based solely on dead tree removal and replanting costs avoided by halting oak wilt spread for 5 years, the average benefit cost ratios were 6, 14, 8 and 4:1 for urban, suburban, rural residential, and rural-non-residential sites, respectively. Based on fungicide injection, dead tree removal, and replanting costs avoided for five years with Project activities, benefit:cost ratios averaged 6, 16, 8 and 4 :1 for the same land use categories. The average benefit cost ratio for both scenarios was 6:1. This suggests that the Texas Oak Wilt Suppression Project is economically efficient. In other words, the $9.2 million of federal, state, local, and private funds invested in oak wilt suppression since 1988 has saved Texas landowners over $55 million in tree removal and replacement costs, exclusive of the many other benefits derived from keeping existing live oaks alive in the central Texas landscape.

LESSONS LEARNED

The Texas Cooperative Oak Wilt Suppression Project is unique among pest suppression projects in that it was initiated by the USFSW/FHP and the TFS in a region where neither agency previously had a strong presence. In the 20 years since the Project began, a professional staff has been established to assist private landowners over an extensive and expanding area in central Texas with education on oak wilt, detection and evaluation of infection centers, and implementation of control treatments with the assistance of cost-share funds. Through the dedicated efforts of numerous cooperating agencies, communities and individual landowners, central Texans are gradually learning to cope with this devastating disease. Furthermore, lessons the TFS and its cooperators have learned about managing oak wilt should benefit other states faced with this disease or other destructive pests affecting multiple ownerships.

Among the lessons the TFS has learned, both about the disease as it expresses itself in central Texas and about its management, are the following. Despite increased suppression, oak wilt may well be having a greater impact now in central Texas than it was having twenty years ago. This is due to the rapid increase in human population, property fragmentation, urban sprawl, increasing property values, and heightened value property owners now place on live oaks (see Rooni, this proceedings). Foresters working with the disease have learned that there is no typical oak wilt center. Each is unique, involves a different set of landowners with different values and resources, and may spread at widely different rates, thus complicating suppression.

Trench depth, placement, and tree removal within the trenched area are keys to successful suppression. Experience has shown that properly-placed trenches dug at least 4-feet (1.2 m) deep are usually effective for halting oak wilt spread, although failure (breakouts) somewhere along the trench is always a possibility and can be expected to occur in a third of the trenches. Most breakouts occur within two years, indicating poor placement or insufficient depth rather than root grafting across the trench. Seldom do breakouts signify a complete trench failure – just a weak point that can be addressed with a follow-up trench around the breakout area.

Management of oak wilt is equivalent to management of people, since oak wilt is as much a people problem as it is a disease problem. Public education is essential and never ending. New residents, unfamiliar with oak wilt, continually move to the area and their activities often incite the disease (i.e., pruning in the spring, not painting pruning wounds, storing infected red oaks, not diagnosing the disease in early stages, etc.). The loss of prized shade trees to oak wilt often elicits the standard grief steps in affected property owners: shock, denial, guilt, anger, depression, resignation, acceptance, and finally, hope. TFS foresters have learned to help clients through these various stages, offering reforestation with diverse tree species as hope. A holistic stewardship approach to land management has proven most successful.

The Texas Forest Service, in cooperation with the USDA Forest Service and the Texas AgriLife Extension Service, has learned that partnerships are the key to addressing this forest health problem, be it through the oak wilt web page, Master Gardner/Master Naturalist training, or cooperation with arborists and oak wilt venders. Once enlightened about oak wilt, neighborhoods have taken amazing and myriad steps to seek cooperation, fund suppression, and address the problem.

Finally, sufficient and sustained program funding has been critical. Indeed, oak wilt suppression without money is just conversation. With the proper staff, dedication, resources, partnerships, knowledge, and long-term commitment, anything is possible. The Texas Cooperative Oak Wilt Suppression Project is proof of that.

ACKNOWLEDGEMENTS

The author expresses his gratitude to the many people and organizations which have generously contributed their time, energies, and resources toward making this suppression project a success. I especially thank the USDA Forest Service, the cities of Austin and Lakeway, and the Texas Forest Service for their continued support in obtaining and providing funding for this project; the USDA Agriculture Research Service for providing office facilities; the Texas AgriLife Extension Service and Texas AgriLife Research for their continued technical support, and the Lady Bird Johnson Wildflower Center, National Biological Information Infrastructure/Houston Advanced Research Center, and the International Society of Arboriculture, Texas Chapter for supporting the oak wilt web page. The highly qualified and motivated field and office staffs of the Texas Forest Service and the cities of Austin and Lakeway deserve special recognition and thanks. Finally, I wish to acknowledge the many private individuals who have contributed countless hours and personal resources toward extending public education efforts and establishing the numerous control treatments credited to the Suppression Project.

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Table 1: Summary of oak wilt cost-shared trenches by county in central Texas: 1988 – 2007.

County	Centers	Feet	Cost shares	Total costs	Cost/foot
Bandera	197	272,942	$82,260	$211,285	$0.77
Bell	67	102,265	$66,110	$147,309	$1.44
Bexar	22	36,068	$54,431	$165,676	$4.59
Blanco	39	63,432	$45,419	$113,303	$1.79
Bosque	291	368,951	$88,753	$185,313	$0.50
Burnet	34	75,677	$57,592	$154,104	$2.04
Caldwell	1	3,000	$2,500	$5,000	$1.67
Colorado	8	23,835	$14,301	$34,843	$1.46
Comal	12	32,912	$11,539	$20,613	$0.63
Comanche	15	23,625	$14,178	$31,070	$1.32
Coryell	67	81,560	$32,917	$69,034	$0.85
Dallas	1	675	$1,753	$3,505	$5.19
Erath	69	99,015	$23,638	$48,784	$0.49
Falls	3	4,900	$5,400	$12,200	$2.49
Fayette	12	22,310	$18,692	$38,769	$1.74
Gillespie	216	342,929	$132,694	$342,675	$1.00
Guadalupe	1	3,000	$4,500	$9,000	$3.00
Hamilton	42	48,740	$23,720	$48,823	$1.00
Hays	121	217,948	$246,949	$599,255	$2.75
Hill	1	500	$330	$826	$1.65
Hood	96	158,961	$59,609	$130,477	$0.82
Johnson	1	1,000	$675	$1,350	$1.35
Karnes	1	5,300	$2,500	$10,600	$2.00
Kendall	178	257,690	$165,207	$457,391	$1.77
Kerr	67	100,872	$51,749	$155,841	$1.54
Kimble	6	10,675	$7,350	$20,725	$1.94
Lampasas	30	44,785	$27,662	$64,302	$1.44
Lavaca	5	17,130	$7,709	$15,419	$0.90
Llano	1	1,000	$1,165	$2,330	$2.33
McClennan	37	30,095	$31,104	$58,175	$1.93
Mason	3	5,312	$5,236	$10,472	$1.97
Medina	10	15,898	$5,968	$13,782	$0.87
Mills	38	67,509	$21,207	$45,808	$0.68
Palo Pinto	2	2,800	$580	$1,160	$0.41
Parker	26	36,470	$14,755	$30,208	$0.83
Parmer	20	14,131	$19,304	$40,734	$2.88
Somervell	75	90,505	$25,629	$54,908	$0.61
Tarrant	5	5,840	$2,775	$4,450	$0.76
Travis	187	287,320	$455,416	$1,185,942	$4.13

Uvalde	2	6,000	$5,255	$20,075	$3.35
Washington	1	4,678	$2,500	$5,000	$1.07
Williamson	145	234,626	$273,883	$598,888	$2.55
Wise	1	800	$300	$713	$0.89
Total (43 counties)	2156	3,223,681	$2,115,214	$5,170,137	$1.60

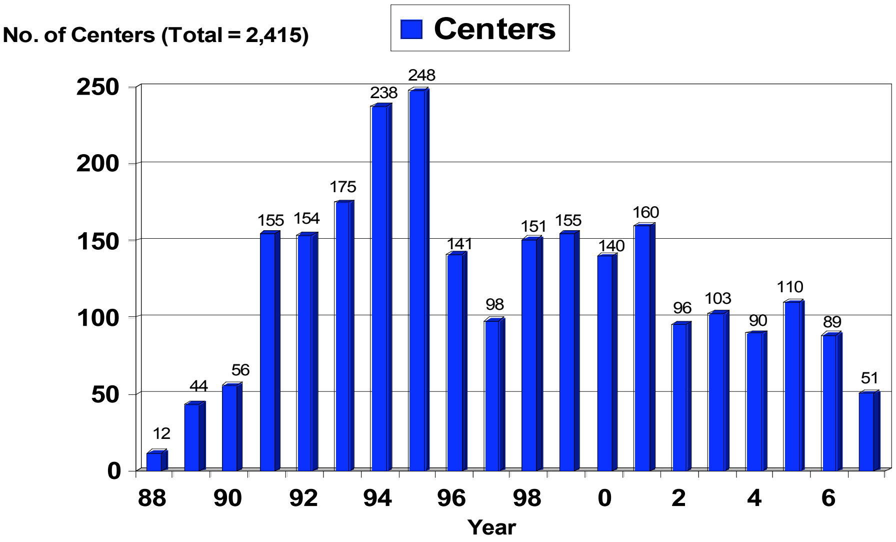

Figure 1A

Oak Wilt Centers Controlled with Trenches

Texas Oak Wilt Suppression Project

(includes non -cost shared trenches)

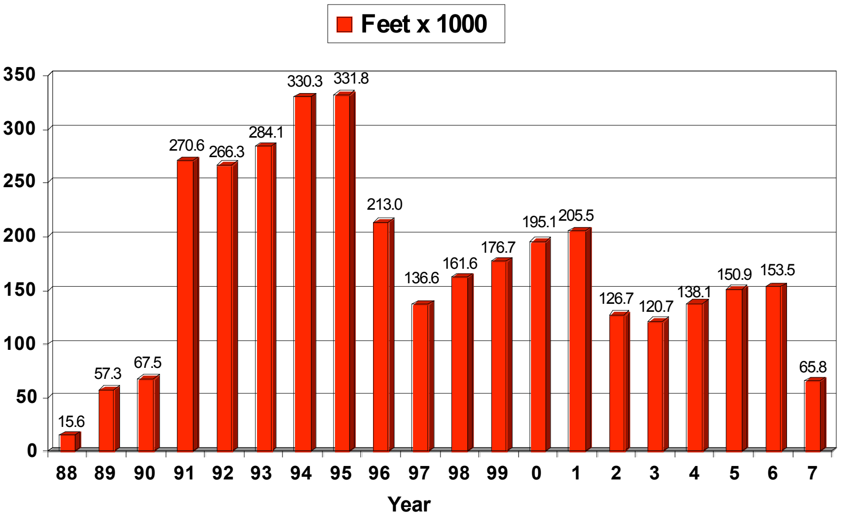

Figure 1B

Total Feet of Trench Installed

Texas Oak Wilt Suppression Project

Total = 3.42 million feet or 648 miles

Figure 1: Trenching accomplishments of the Texas Oak Wilt Suppression Project showing oak wilt centers treated (1A) and feet of trench installed (1B) with federal cost shares and/or technical assistance of Project personnel by federal fiscal year.

USDA FOREST SERVICE PERSPECTIVE ON OAK WILT SUPPRESSION

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ABSTRACT

For many years, insect and disease suppression has been a part of the efforts of the USDA Forest Service and its state and federal cooperators in fulfilling our mission to the nation. Various enabling laws have provided authority to cooperatively fund suppression projects. Disease suppression efforts in the U.S. began with the discovery of the introduction of several non-native and virulent tree pathogens which cause such diseases as chestnut blight and white pine blister rust. Both federal and state governments have supported suppression efforts against such diseases. Other diseases have also received attention such as oak wilt and dwarf mistletoes. Cooperative oak wilt suppression programs began in the early 1950s in Pennsylvania, West Virginia, and other eastern states; but by the 1970s they were deemed largely ineffective and unnecessary. More recently, outbreaks of oak wilt in central Texas and southeastern Minnesota have precipitated suppression projects that have had better success and continue at the present time. Funding of cooperative pest suppression projects is provided where a pest presents a significant threat to a major forest resource and the likelihood of success is reasonably high. Availability of funds, competition with other significant pest threats, and politics can often influence funding availability and decisions. Oak wilt suppression projects, like all projects, are considered within this context. While suppression projects remain a fundamental component of the overall USDA Forest Service mission (and that of state agencies, too), prevention activities and early detection/rapid response efforts are being increasingly employed in an effort to minimize the introduction, spread, and effects of insect and disease pests at an early date, before major epidemics can occur.

Key words: *Ceratocystis fagaceaum*, disease management

For many years insect and disease suppression has been a part of the efforts of the USDA Forest Service and its state and federal cooperators in fulfilling our mission to the nation. Various acts of legislation have authorized funding of suppression projects over the years. Our current authority resides primarily in the "Cooperative Forestry Assistance Act of 1978, As Amended Through 2002" (USDA Forest Service 2005). The Forest Health Protection Section (Section 8, 16 U.S.C. 2104) authorizes many activities related to forest health including suppression. Suppression funding is applied directly on federal lands of all types, but on state and private lands, project funding is cooperative, with states or other entities providing about 50 percent of the funds as a "match" to federal funds.

Matching expenditures can be direct cash outlays or indirect costs such as salary supporting an employee's time, institutional overhead charges, or labor and equipment used in lieu of contracted work, etc. However, matching cannot be made using funds from other federal grants. Most suppression funding is provided to state agencies, although occasionally non-profit, non-governmental organizations are also funded. Historically, insect suppression projects have probably dominated in size and financial scope, but disease projects have been funded as well. And most recently, non-native invasive plant suppression projects have been added to the spectrum.

EARLY DISEASE SUPPRESSION

Forest disease suppression efforts in the U.S. began with the introduction and discovery of several non-native, virulent tree pathogens which caused serious diseases and threatened major forest resources. The first of these was the chestnut blight (Beattie and Diller 1954, Hepting 1976). The fungal pathogen that causes the blight, *Cryphonectria parasitica,* (Murrill) Barr, was first discovered in the New York area in 1904, although it was probably introduced prior to that. It is now known to be of Asian origin. As the blight spread into the native chestnut population in eastern forests, the first suppression efforts came via a state program, not a federal one. The state of Pennsylvania created the Chestnut Blight Commission in 1911 and over a 4-year period allocated over $500,000 to the work. The federal government did play a role, though, and provided funds for research on the disease - $5,000 dollars in 1911 and $80,000 in 1912 and 1913.

The suppression effort in Pennsylvania was attended by much controversy over the potential for success. The skepticism turned out to be well-founded as the blight spread too fast for operational activities to keep up and by 1914, suppression efforts were abandoned. The blight spread mostly unabated and by about 1940 was found throughout the host range of American chestnut. Early interest in disease resistance to the blight was generated by the observation that Japanese and Chinese chestnuts were resistant. Experimental plantings of oriental trees and crosses with American chestnuts began a long-term effort to develop and deploy a resistant replacement to the native tree. This work continues today and test plantings of resistant trees from the American Chestnut Foundation are currently being made on some national forest sites.

White pine blister rust was the second introduced disease to threaten a major North American forest resource (Pack 1934, Hirt 1956, Maloy 1997, Kinloch 2003). This disease is caused by a fungus, *Cronartium ribicola* Fish. and is also of Asian origin. It was introduced first to Europe and then the New York area. The fungus requires an alternate host, *Ribes* spp. (currents, gooseberries), and it was on these that it was first found in 1906. It was later found on planted white pine in 1909 and on natural white pine in 1915. Coming so closely on the heels of the chestnut blight, concern was immediate and control efforts quickly considered. The earliest control efforts, about 1910, were aimed at nursery production in an effort to keep diseased seedlings from being widely outplanted. To make matters worse, the disease was also found introduced to Vancouver, Canada in 1921, adding a threat to the western 5-needle pines.

The threat from this disease was the genesis of one of our earliest forest disease legislative efforts in 1912, the "Plant Quarantine Act". Under this act, Quarantine #1 prohibited the importation of 5-needle pines to the U.S. The Act also enabled states to regulate the movement and cultivation of certain plants—this became the basis for the *Ribes* eradication efforts which were the focus of white pine blister rust suppression efforts for many years. The theory was that eliminating *Ribes* bushes in and around white pine stands would break up the complicated life cycle of this fungus and reduce or eliminate infection. Federal funds were initially provided in the amount of $20,000 in 1916, matching a $21,974 multi-state allocation. *Ribes* eradication grew into probably the biggest, most expensive forest disease suppression effort ever.

Efforts in one or more areas of the U.S. were active for about 50 years, ending in the 1960s with an estimated total expenditure of about $150 million. During the depression years, and the years after, the Civilian Conservation Corps was used as well as groups of men from other work relief programs. An estimated 20 million acres (8 million ha) were treated for white pine blister rust amelioration, a truly stunning amount. Unfortunately, the effect of all this effort was considered only minimally beneficial in the East and mostly unsuccessful in the West where the disease was more severe. As with the chestnut blight, difficulty in controlling blister rust engendered an interest in disease resistance, especially in the western white pines and breeding and research continues today. This disease continues to be a threat to valuable forest resources, especially in the western U.S.

OAK WILT SUPPRESSION

Other diseases such as oak wilt, the subject of this symposium, have also received attention. Oak wilt, caused by the fungus *Ceratocystis fagacearum* (Bretz) Hunt, was first recognized as a threat in the 1940s and 1950s (MacDonald 1995). Early suppression efforts began in the 1950s with programs in Pennsylvania, West Virginia, Kentucky, North Carolina, and Tennessee. Most of these received some federal funding although documentation is scant or difficult to locate. West Virginia and Pennsylvania apparently had the biggest, most active programs. For example, in 1957 West Virginia received about $30,000 as a 33.3% share of a $90,000 project. Federal funding continued for at least these two states for nearly 20 years until the suppression efforts were discontinued, being deemed either ineffective, uneconomical, or both. These programs were summarized at the 1st National Oak Wilt Symposium in 1992 (Haynes 1995, Merrill 1995). U.S. Forest Service research and monitoring of suppression methods was very active at this time and various state programs were intensively studied for effectiveness (Jones 1965, Jones 1971).

Renewed interest in oak wilt suppression surfaced in the 1980s when the disease became widely diagnosed in central Texas live oaks and research efforts began to test and demonstrate effective control tactics. A 5-year cooperative federal-state demonstration project during 1982-1987 in central Texas showed the extent of oak wilt distribution and the likelihood of a successful suppression project (Cameron and Billings 1995). A cooperative federal-state suppression project was initially funded in 1988 with $168,600 federal and matched by state and local expenditures. Since then, the project has been continuously operated by the Texas Forest Service with federal funding increasing to about $500,000 per year (Fig. 1) and is summarized elsewhere in this symposium (Billings, this proceedings). A similar project was also initiated in southeastern Minnesota in 1990 which ran for about 7 years (Fig. 2). After a period without federal funding, cooperative funding resumed in 2002, and continues to the present. These two projects have experienced success in controlling oak wilt due mostly to the uniformity of the host type being damaged. Spread in both areas is primarily by root contacts or grafts and trenching or plowing to sever these grafts does a good job of stopping infection center expansion.

Another disease problem which has received a good bit of suppression funding over quite a number of years is dwarf mistletoe (*Arceuthobium* spp). Most projects have been in the western regions and data on expenditures and locations are scattered and difficult to summarize. But, as an example, one summary of work in the Pacific Northwest documents suppression activities beginning about 1959 and peaking in the 1970s with expenditures of about $400,000 in one year (Hadfield and Russell 1978). Mistletoe control programs remain active and are still being funded.

This year, over $49 million has been allocated for forest pest suppression efforts. Pests include gypsy moth, southern pine beetle, dwarf mistletoes, emerald ash borer, hemlock woolly adelgid, oak wilt, and others. About $600,000 of this has been dedicated to cooperative oak wilt projects. Some of these are listed in Table 1. Other oak wilt projects which are receiving funds (although from a different source of federal funds) are listed in Table 2.

SUPPRESSION PERSPECTIVES

Federal funding of forest pest suppression projects is driven by a number of issues. But, to generalize, projects which successfully receive federal funds usually address a significant threat to a major economic or ecological resource and have a reasonable potential for biological and operational success. Project selection is also affected by (1) the amount of funding available in a given year, (2) the differing pest threats that loom in a given year, and (3) the ever-present wild card of politics (as then State Forester Bruce Miles said in his welcoming address to the 1st National Oak Wilt Symposium, sometimes a project gets funding when a senator or congressman "…explains it better…"; Miles 2005).

When funding levels are adequate, decision-making on federal funding requests by Forest Health Protection is relatively uncomplicated. Our specialists verify the need and potential success of proposed projects and, as long as sufficient funds are available, most projects are approved. When budgets are tight or when huge, expensive suppression needs arise, some projects must be left un-funded and others must do with less-than-requested amounts. Occasionally, federal funding exigencies, such as a disastrous wildfire season, have diverted suppression dollars away from legitimate, worthwhile pest suppression projects.

NON-SUPPRESSION EFFORTS

As a counterpoint to suppression, the U.S. Forest Service also is active in funding, operating, and supporting a number of prevention and early detection programs aimed at minimizing the introduction, spread, and detrimental effects of insect and disease pests at an early date, before major epidemics develop. Some examples of these are the (1) Southern Pine Beetle Prevention and Restoration Program, (2) the Sudden Oak Death Survey Program, and (3) the Early Detection/Rapid Response Program for exotic bark beetles.

The Southern Pine Beetle (*Dendroctonus frontalis* Zimm.) Prevention Program has been funded since 2003 as a cooperative effort with southern states. Nearly $60 million has been allocated to date and all 13 southern states as well as 12 national forests currently have active programs. Efforts are aimed at thinning pine stands early in their life cycle, including pre-commercially, to reduce the hazard to southern pine beetle. Many states are using cost-share incentives to encourage landowner participation. Hundreds of thousands of acres have been treated so far.

The sudden oak death surveys have been a response to the potential introduction of this disease-causing organism (*Phytophthora ramorum* S. Werres, A.W.A.M. de Cock and W.A. Man in't Veld) to other states from California, Oregon and Washington on infected nursery stock (Todd undated, USDA Forest Service 2004). The disease was discovered in California in 1995 killing oaks (*Quercus* spp.) and tanoaks (*Lithocarpus densiflorus*) in coastal and central counties. As the disease problem grew there, it was discovered in 2003 and 2004 that the causal agent was also infecting a large number of nursery plant species in commercial container nurseries and that these potentially-infected plants had been shipped unawares to 49 of the 50 states. Many of these plants were sold before the USDA and state agricultural agencies could get the nurseries inspected and destroy infected plants. The potential for the organism to escape into the natural environment outside of California was instantly huge. The Forest Service in conjunction with state cooperators quickly implemented a large-scale detection survey program looking at the perimeters of nurseries that received infected or potentially-infected nursery stock. Nearby forested areas with potential hosts or forest areas with suitable hosts and climate were also surveyed.

Detection survey work began with 7 states in 2003 and has increased to 38 states in 2006 (Oak et al. 2008). Funding levels have been between $300,000 and $1.3 million annually. To date, no introductions of the pathogen to new wildland areas have been discovered. Since distribution of infected nursery stock has been substantially reduced, the survey efforts are now being reduced in size, scope, and funding although this reduced effort will continue for some time. Since survey results have been negative for 4 years, an alternative detection technique is being used to sample larger areas with less effort. Stream baiting is being used in 2007 to detect the presence of the pathogen in waterways downstream of nurseries or forest areas worthy of survey.

The early detection and rapid response program for exotic bark beetles began in about 2001 with $30,000 in funding and has grown to a $750,000 program in 2007. Bark beetle trapping is currently being done in 17 states in about 120 locations. Traps are placed in proximity to ports of entry, shipping, storage or manufacturing facilities that represent pathways for the introduction of exotic beetles in wood products or shipping materials. A number of exotic beetles have been trapped and identified. One of particular interest was trapped in 2002 at Port Wentworth near Savannah, Georgia (Mayfield and Thomas 2006, Johnson et al. 2007). It was identified as an ambrosia beetle of Asian origin, *Xyleborus glabratus* Eichoff.

Unfortunately, in spite of this “early detection” the beetle has established itself in local populations of red bay (*Persea borbonia*) and sassafrass (*Sassafras albidum*) trees. This beetle, as with other ambrosia beetles, carries a fungus which colonizes the attacked trees and provides food for the beetles. The one carried here is a pathogenic fungus of the genus *Raffaelea* which acts as a vascular wilt, quickly killing infected trees. The pair of pests has rapidly expanded their range into 31 counties in Georgia, South Carolina, and Florida. The host range has also expanded with attacks and infections now known in pondberry (*Lindera melissafolium*), pondspice (*Litsea aestivalis*), and avocado (*Persea americana*) (Hanula et al. 2008).

CONCLUSIONS

In the future, suppression funding and projects will still be needed and will continue to play a significant role in the increasingly complex arena of forest health management and oak wilt projects will probably remain among those funded. However, prevention and aggressive detection programs may play an increasingly important role in a world of fast-paced, global commerce.

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Table 1. Fiscal year 2007 funds (USDA Forest Service) allocated to cooperative oak wilt suppression projects.

Cooperator	**Allocation**
Texas *($300,000 + $200,000 Southern Region funds)*	$500,000
Minnesota	$200,000
Michigan	$50,000
Wisconsin	$50,000
Chequamegon-Nicolet NF	$25,000

Table 2. Fiscal year 2007 funds (USDA Forest Service) allocated to other federal installations for oak wilt suppression projects.

Federal Installation	**Allocation**
Fort Hood, Texas	$70,000
Balcones National Wildlife Refuge, TX	$24,000
Army Corps Engineers, St. Paul District	$1,330
Fort McCoy, WI	$40,000

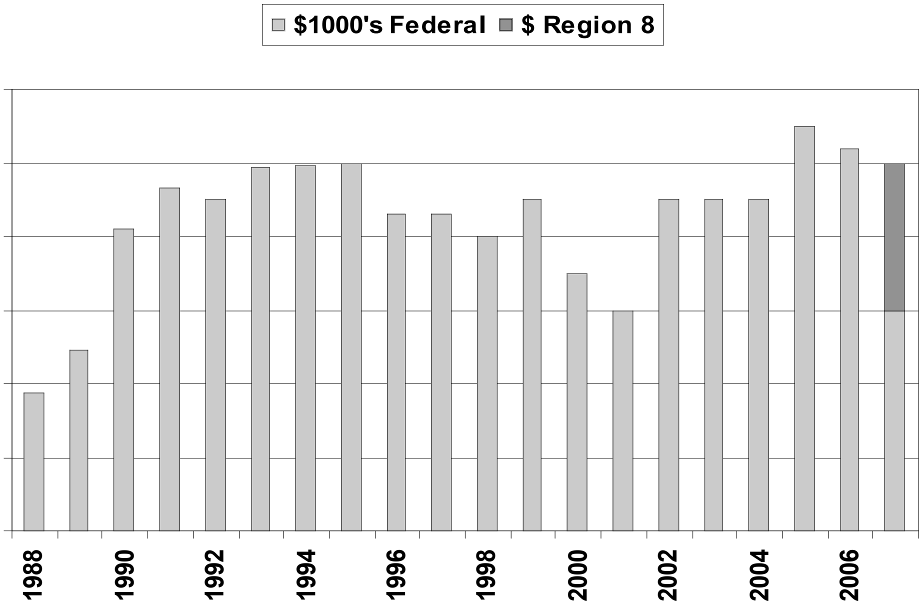

Figure 1. Federal (USDA Forest Service) dollars allocated to the Texas Cooperative Oak Wilt Suppression Project.

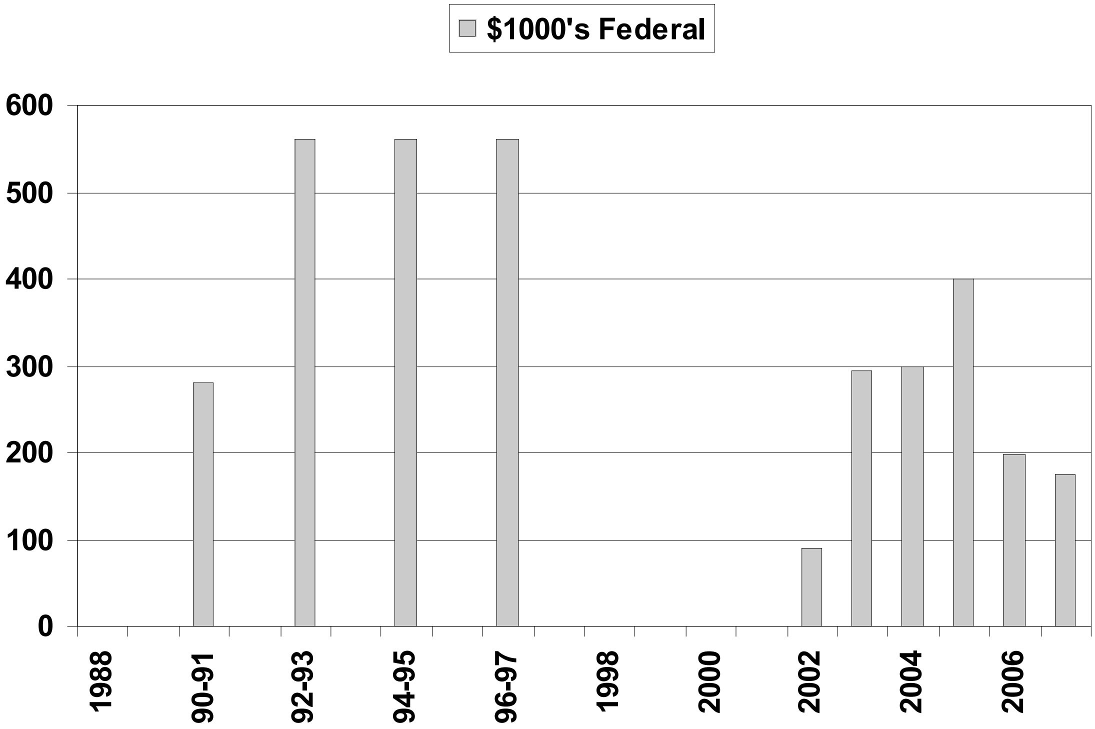

Figure 2. Federal (USDA Forest Service) dollars allocated to the Minnesota Cooperative Oak Wilt Suppression Project.