Management and Control of Diseases Caused by *Phytophthora ramorum*, a Summary of the Literature Through 2006

Introduction

Although diseases caused by *Phytophthora ramorum* Werres, Cock, & Man in’t Veld have been studied only since about the year 2000, the literature abounds with results of numerous research and administrative study efforts to manage and control the pathogen. The existing literature is found in a wide array of publications (journals, popular articles, research summaries) and formats (printed articles, web-based articles, abstracts, posters). The objective here is to summarize the existing literature on management and control of *P. ramorum* so that it will be available to researchers, managers and publics concerned with the pathogen and the diseases it causes. The hope is that the increased availability of the literature will improve treatments and thus forest health.

Disease Management Principles

Basically, disease management involves **prevention** – any action taken before the host is infected to protect it from disease, or **suppression** – an action taken against the pathogen after the host is infected. Several different systems have been used to group and discuss prevention and suppression strategies. J.C. Walker (1968) divides control measures into two major groups, **protection**, and disease **resistance**; he then divides protection into three subgroups, **exclusion**, **eradication**, and **direct protection**. H.H. Whetzel (1929) described four general disease control principles, **exclusion**, **eradication**, **protection** and **immunization (resistance)**. Although these principles have been expanded or altered to some extent over the years, they remain valid. Whetzel’s (1929) breakdown is used here as a means of discussing the literature on management and control of *P. ramorum*. The first two principles, exclusion and eradication, involve control of the pathogen; the second two, protection and resistance, deal primarily with defense of the plant. Some actions may fall into more than one of the categories.

Early plant pathologists stated the principles of control in absolute terms, such as eliminate, exclude and prevent. Today, we realize that absolute **control** to eliminate a pathogen is often not possible, or even the goal, but that **management** of the disease to acceptable levels is the real goal.
The four principles can be summarized as follows:

**Exclusion:** Any strategy that attempts to prevent the introduction of a pathogen into an area where it is not yet present. Exclusion, via quarantine regulations and other means, is aimed at preventing the introduction of inoculum, or reducing the amount of initial inoculum introduced, from outside sources.

**Eradication:** The strategies are aimed at eliminating or reducing a pathogen after it is introduced into an area, but before it has become well established or widely spread. Eradication involves strategies that eliminate, destroy, or inactivate the inoculum through sanitation, removal of reservoirs of inoculum, removal of alternate hosts, and other methods.

**Protection:** Protection strategies assume that the pathogen is present and that infection will occur without the intervention of protective measures. Protection prevents or reduces infection by means of a toxicant or some other barrier to infection. It establishes a barrier between the pathogen and the host plant or the susceptible part of the host plant. It is usually thought of as a chemical barrier such as a fungicide, bactericide or nematicide, but it can also be a physical, spatial, or temporal barrier.

**Resistance:** Resistance strategies utilize a host or hosts that are resistant to or tolerant of infection. Plant cultivars or varieties that reduce the rate of inoculum production, the rate of infection, or the rate of pathogen development are deployed. Use of disease-resistant plants can be an effective and environmentally sound method to manage plant diseases, if plants of satisfactory quality and adapted to the growing region with adequate levels of durable resistance are available.

**Exclusion**

Exclusion involves a combination of quarantines or regulations and best management practices (BMPs) designed to prevent, or reduce the risk of pathogen introduction.

**Regulations**

Reducing or eliminating pathogen introduction is typically done by regulation. In order to limit *P. ramorum* spread, regulatory actions are being implemented and enforced worldwide.

**Federal regulations in the U.S.:** In the United States, the Animal and Plant Health Inspection Service (APHIS), a division of the U.S. Department of Agriculture (USDA), is responsible for promulgating and enforcing interstate and international plant quarantine measures. In addition,
state agencies deal with within state quarantines. In February 2002, the Plant Protection and Quarantine (PPQ) branch of APHIS issued an interim rule on *P. ramorum* governing interstate shipment of host plants and associated soil to prevent spread of *P. ramorum* from the known infested area. California and Oregon have similar regulations. These regulations, which continue to evolve, cover lumber, logs, mulch, wood chips, firewood, nursery plants, soil, yard waste, florist materials, and many other commodities. Land managers are charged with enforcing the regulations on public lands; private landowners must also comply.

Since January 2005 a new federal order (Emergency Federal Order Restricting Movement of Nursery Stock From California, Oregon, and Washington Nurseries December 21, 2004, USDA). The order (USDA APHIS 2005a) regulates interstate movement of nursery stock from uninfested areas in California, Oregon and Washington. Under the new federal order, all nurseries with host or associated host plants on site must be inspected and found free of *P. ramorum* before they can ship nursery stock interstate. If *P. ramorum* is detected at a nursery the Confirmed Nursery Protocol (USDA APHIS 2004a) is implemented requiring the destruction of the infested plants and all other host and associated host plants in the contiguous block as the infected plant. The block is considered contiguous until there is a 2 meter break of either no plants or no hosts or associated plants. The site is delimited and monitored for at least two years, for more details, see the protocol.

USDA APHIS has issued a national strategic plan (USDA APHIS 2005b) that addresses the control and management of *P. ramorum* in cultivated and natural environments. The strategy’s first defense is exclusion, to prevent pathogen introduction and disease development in new areas. The primary objective of the national strategy is to “prohibit introduction, or significantly reduce the rate of introduction or reintroduction, of *P. ramorum*, into presently non-infested regions of the United States, and to manage presently infested nursery systems, forests, and urban landscapes to minimize and mitigate damage.”

Wildland and residential protocols are provided by APHIS. The Forest and Wildland Protocol (USDA APHIS 2006) describes the notification procedures required by APHIS if *P. ramorum* is found in a forest or wildland environment, and provides guidance to deploying a rapid response to eradicate, suppress or otherwise contain the pathogen. The Residential Protocol (USDA APHIS 2004b) specifies actions to be taken when a positive *P. ramorum* infection is confirmed in nursery stock planted in residential or commercial landscape settings. The objective is eradication of the pathogen from the site.

**EU regulations:** In November 2002 the European Union (EU) adopted emergency measures to prevent the introduction and movement of *P. ramorum* into and within the EU nations. Legislation (2002/757/EC) to control the introduction of susceptible hosts into the European Commu-
nity, in particular, the import of susceptible plants and plant products from the U.S., was enacted. For export of susceptible plants from the U.S. to member countries in the EU, plants must originate from a *P. ramorum*-free area or from a place of production which has been inspected by U.S. authorities and found free from symptoms. The movement of *Rhododendron* and *Viburnum* (the main hosts of *P. ramorum* in Europe) within the EU are controlled via “plant passports”, certificates verifying that the plants have had the required statutory inspections and have been found free from quarantine pests (including *P. ramorum*). The legislation also calls for all EU member states to undertake surveys for *P. ramorum* and disseminate the results. If *P. ramorum* is found, then all susceptible plants within 2 meters (6.6 feet) are destroyed. Any additional plants in the lot are held for a period of 3 months, with at least two additional inspections before being released. The rest of the facility is intensively re-inspected before allowing plants to be moved. The legislation was amended in 2004 (Commission of European Communities 2004). As of December 2006, countries with regulations on the importation of *P. ramorum* host material include Canada, the UK, South Korea, New Zealand, Australia, the Czech Republic, Mexico, Taiwan, the U.S., and the EU.

Regulations and quarantines are continuously updated to reflect new findings, are subject to change, and vary from region to region. Consult the www.suddenoakdeath.org website for up-to-date information, or see the USDA APHIS PPQ (Plant Pest and Quarantine) *P. ramorum* website (USDA APHIS PPQ 2006) for regulations and regulatory updates in the U.S.

**Best Management Practices**

BMPs are methods, measures, practices, or procedures that have been determined to be effective means of preventing or reducing adverse effects. Through experience, research, and knowledge of the disease cycle of *P. ramorum*, BMPs to prevent or reduce the spread of the pathogen have been compiled. Many of the practices are exclusionary, meant to exclude *P. ramorum* from non-infested areas by preventing or reducing the risk of spread. They are usually most effective when applied as a system of practices rather than as individual practices.

**BMPs in wildlands and urban-interface zones:** Numerous publications outline BMPs to prevent or reduce the spread of *P. ramorum*. The California Oak Mortality Task Force (COMTF) at www.suddenoakdeath.org has compiled BMPs for a number of activities and user groups on wildlands and in urban-interface zones (Figure 1). They include guidelines for forestry (California Oak Mortality Task Force 2006a), recreational users (California Oak Mortality Task Force 2004a), forest collectors (California Oak Mortality Task Force 2004b), arborists (Califor-
nia Oak Mortality Task Force 2005), homeowners (California Oak Mortality Task Force 2006b),
firefighters (California Oak Mortality Task Force 2004c), tribal plant gatherers (California Oak
Mortality Task Force 2004d), and Christmas tree growers (to be posted on suddenoakdeath.org).
These BMPs provide guidelines to prevent or minimize the introduction and subsequent spread
of *P. ramorum* by limiting movement of host material or infested soil.

In 2002, the Management Committee of the COMTF compiled BMPs in zone of infestation-regu-
lated areas (California Oak Mortality Task Force 2002); measures to prevent the spread of the
pathogen during tree removal or pruning in regulated areas, and measures to minimize the move-
ment of host material and soil from infested areas are presented.

**BMPs in nurseries:** Numerous BMPs or guidelines on *P. ramorum* in nurseries are available.
Guidelines developed in cooperation with the California Association of Nurseries and Garden
Centers, the Oregon Association of Nurseries, the Washington Nursery and Landscape Associa-
tion, Oregon State University, the Oregon Department of Agriculture, and the Washington De-
partment of Agriculture (Parke 2005), are designed to exclude *P. ramorum* from nurseries. These
guidelines, which incorporate actual regulations as well, include:

1) Notify your State Department of Agriculture of all incoming shipments of
tree and shrub nursery stock from out-of-state within two business days of shipment
arrival.

2) Purchase hosts and associated hosts only from certified sources when such purchases
originate in a federally quarantined or regulated area where official *P. ramorum*
certification programs acceptable to your State Department of Agriculture exist.

3) If purchasing from locations where no official certification program exists, have
nursery stock officially inspected and tested for *P. ramorum* upon receipt. Keep these
plants safeguarded and segregated from other hosts and associated host plants, and off
sale, until test results are completed.

4) Maintain records of all incoming and outgoing shipments of hosts and associated
hosts for a minimum of 24 months. Identify the host or associated host species, cultivar,
quantity, origin, date of shipment, and receiver. Landscapers should also keep records of
plant purchases and planting sites for hosts and associated hosts.

5) Off-load incoming shipments of host and/or associated host stock to an area that can
be cleaned of leafy debris. Collect the debris from the receiving pad and the delivery
truck and bag for disposal. Do not send this plant debris to your own plant dump or
composting facility.

6) Visually inspect all incoming plant material (not just hosts and associated hosts) for
symptoms of *P. ramorum* prior to it being incorporated into the production facility. See
guides to recognizing symptoms on nursery hosts. Report suspicious symptoms to your
state Nursery Inspector.
7) Wholesale production nurseries should keep all incoming hosts and associated hosts in separate blocks at least 2-m from other hosts in the nursery for a minimum of 3 months during the growing season.

8) If possible, avoid product returns of host and/or associate host stock from a receiver located in a regulated area. If unavoidable, contact your state Nursery Inspector prior to accepting the stock return.

9) If you visit known infested areas, wash your shoes, tools, or vehicles that may have contacted contaminated soil before traveling to disease-free areas. See APHIS protocols for disinfesting contaminated materials.

BMPs for California nurseries, developed by the Nursery Committee of the California Oak Mortality Task Force (Suslow and others 2005) are divided into the two categories of exclusion/prevention, and monitoring. Guidelines for Oregon nurseries (Parke and others 2003) and Washington nurseries (Parke and others 2004) have been developed.

The British Columbia Nursery and Landscape Association has developed a *P. ramorum* certification program for nursery growers, silviculture and floriculture industries (British Columbia Nursery and Landscape Association 2005). The objective is to minimize the risk of importing and moving the pathogen in the province. The program includes mandatory sampling and testing for *P. ramorum*, workshops for nursery staff, implementation of best management practices and an audit by an independent organization.

Education and outreach efforts to make available the BMPs that have been developed, such as those conducted by the California Oak Mortality Task Force and the website they developed, are an essential part of delivering information on the pathogen and its management to the publics.

**Research Studies**

Research studies have demonstrated the spread of *P. ramorum* in water and through movement of infested soil and wood, and the need for regulations and BMPs to reduce that spread.

**Pathogen spread in streams:** Tjosvold and others (2002b) recovered *P. ramorum* from stream water that could potentially be used for irrigation by nurseries and landowners situated along the streams. They sampled stream water for the presence of *P. ramorum* inoculum approximately weekly for 1 year, in seven rivers and creeks in Santa Cruz County, California. Five streams drained through woodland known to contain *P. ramorum* and two streams drained through woodland that contained hosts of *P. ramorum*, but no confirmed disease. Water samples were collected downstream from each watershed, taken to the laboratory, baited with pears, and pear tissue from
suspicious *P. ramorum* lesions transferred to PARP selective media for pathogen identification. *Phytophthora ramorum* was detected in the five streams draining through woodland known to contain the pathogen, but not from the two streams with hosts only. The pathogen was found almost entirely during the period following the beginning of winter rainfall and through early spring (January through March). *Phytophthora ramorum* was detected in streams during the dry months on one occasion, in September from one river following a short rain in the river’s drainage. Using rhododendron leaf baits, Davidson and others (2005) recovered *P. ramorum* from stream water in an unforested pasture site about 1 km downstream of a forested area with inoculum sources. The pathogen was recovered in one of two trials during the rainy season. Currently, extensive stream monitoring networks are in place at various locations in California and Oregon to determine the presence of the pathogen.

**Pathogen spread by humans:** Tjosvold and others (2002a) demonstrated that *P. ramorum* inoculum in soil along hiking trails could be picked up on shoes of recreational hikers. They sampled soil following rainy periods in March and May and then monthly through the dry summer and fall period in a California State Park. At each sampling date, soil was sampled from five locations along a 1.3 km (0.81 mile) loop trail and from the bottom of shoes of hikers who had hiked the trail. The soil samples were baited with pears in the laboratory, and pear tissues suspected to be infected transferred to a medium selective for *Phytophthora* (PARP) for pathogen identification. In the spring rainy periods, the incidence of successful pear baiting for *P. ramorum* varied from 40 to 60 percent success rate for trail soil and 40 to 95 percent success rate for soil removed from hiker’s shoes. The pathogen was not recovered from trail soil or shoe soil in the dry summer period. Davidson and others (2005) also demonstrated human spread of infested soil during the rainy season. When they baited soil taken from hikers’ shoes after they walked a preserve trail in Sonoma County California, the pathogen was recovered from 7 of 15 samples in one trial and from 5 of 15 samples in a second trial.

In studies conducted in Sonoma County California, symptom levels and spread of the pathogen were greater in areas with high human activity (Cooper and Cushman 2006; Cushman and Meentemeyer 2006a, 2006b). Cooper and Cushman (2006) demonstrated that recreation hikers and bikers can pick and carry the pathogen in moist soil. When they sampled soil collected from the shoes and tires of visitors entering and exiting protected wildlands, they found that 7 percent of visitors entered the site with viable pathogen on their shoes and tires, and 23 percent carried it out with them. Cushman and Meentemeyer (2006a, 2006b) demonstrated that humans disperse *P. ramorum* along hiking trails in natural landscapes and that areas visited intensively by humans have a greater proportion of foliar and terminal hosts (terminal hosts included coast live oak (*Quercus agrifolia*), California black oak (*Quercus kelloggi*), and tanoak (*Lithocarpus densiflorus*) (with trunk cankers and/or canopy dieback) showing symptoms of infection than areas visited less frequently. They assessed soil samples for the presence or absence of *P. ramorum* on
a trail surface and at adjacent locations 2 meters (6.6 feet) off trail in three habitat types that were hypothesized to differ greatly in the amount of pathogen inoculum present in the soil: woodlands dominated by infected California bay laurel (*Umbellularia californica*) and coast live oak, open grassland lacking any foliar or terminal hosts, and stands of white oak (*Quercus garryana*; a non-host species). They found *P. ramorum* equally common in soil on and off trail from infected bay/coast live oak woodlands. However, for grasslands and white oak woodlands – habitats that lack *P. ramorum* hosts – the pathogen was commonly found in soil samples collected on trail, while being virtually absent off trail. These data suggest that hikers can be important dispersal agents of *P. ramorum* and are able to transport the pathogen into areas that lack a local source of inoculum.

Cushman and Meentemeyer (2005) compared levels of host infection with levels of human activity on 202 plots in eastern Sonoma County. About half of the plots occurred in areas experiencing high visitation rates by humans, and about half occurred in areas that had low visitation rates. During the spring and early summer, they sampled all foliar and terminal hosts in these plots for symptoms of infection by *P. ramorum*. After taking into account the influence of elevation, precipitation, solar radiation and topography, they found that the proportion of symptomatic California bay laurel trees was significantly greater in plots experiencing high levels of human activity than those with low activity levels. In contrast, they did not find a significant relationship for terminal hosts. Their data suggest that high levels of recreational activity are associated with, and may lead to, increased levels of disease symptoms in California bay laurel trees, a foliar host that is thought to play a key role in the spread of the disease.

A prototype scrubber for mountain bike users of public parks and recreation areas was developed by Thut and others (2006; Figure 2). The device reduced accumulated soil and mud, thus potentially decreasing the inoculum load on tires of mountain bikes before they leave an infested area. In preliminary tests, 75 percent of adhered sediment was removed from tire treads. The scrubber, which is essentially a trough of tough bristles through which the rider walks their bike, is suited for areas without electricity, pressurized water, or personnel; and is affordable, simple to operate, and easy to maintain at trailheads. Expanded studies to demonstrate effectiveness in the field need to be conducted.
**Pathogen survival in wood:** The pathogen may also be spread through movement of infested wood. Shelly and others (2006a) isolated *P. ramorum* from 8 of 49 freshly cut specimens and 1 of 30 specimens of tanoak and coast live oak that had air-dried for 6 months, demonstrating that *P. ramorum* could survive on firewood for at least 6 months.

Singh and Shelly (2006) analyzed the survival of *P. ramorum* in firewood as it was air-dried to a final moisture content of 15 percent. Split firewood selected from tanoak and coast live oak trees exhibiting *P. ramorum* infection was selected and stored at two locations: a commercial firewood operation, and at a University of California field station on an outside concrete pad with simulated rain exposure. Monthly samples of twenty specimens (10 with bark and 10 without bark) were selected from each of the two sites. Each specimen was tested twice, once for the presence of active *P. ramorum* zoospores and once for chlamydospore germination. They collected *P. ramorum* zoospores from infested wood up to 5 months after an infected tree was harvested, and from rainwater flowing over infested firewood. Survival rate in cut wood was higher under wetter conditions. Chlamydospore germination was difficult to obtain. The authors concluded from their results that there is a 12 percent chance that *P. ramorum* can be spread from an infested piece of firewood to a suitable host under favorable conditions as long as the wood moisture content remains high enough to support zoospore survival. They recommended that all firewood processed from trees infected with *P. ramorum* be air-dried to an average moisture content at least below 53 percent, but preferably below 50 percent. Their studies also suggest that firewood air-drying sites be constructed in locations where any rainwater runoff cannot flow to uninfected *P. ramorum* host plants.

**Pathogen spread through disposal and utilization activities:** Related studies (Shelly and others 2006b) determined the risk of spreading *P. ramorum*-infected wood through disposal and utilization activities. Two yards, one in Marin County and one in Santa Cruz County, were set up for the collection of wood suspected of being infected with *P. ramorum*. *Phytophthora ramorum* host material, most from hazard trees, has been processed through the collection yards. The material was converted into fuel for biomass power plants, firewood, and lumber. The authors monitored for *P. ramorum* spores during various stages of the processing and transportation, and monitored the host vegetation growing in and around the collection yards. They reported a small number of positive cultures of *P. ramorum* isolated from a variety of the unprocessed and processed materials (delivered chips, firewood, and grinder dust from a hammer milling operation). One of 45 chip samples at the Marin yard and one of 21 at the Santa Cruz yard were positive for *P. ramorum*. Eight of 76 samples of freshly split firewood and one of 30 samples of 6-month air dried firewood at the Marin yard also tested positive for *P. ramorum*. Grinder dust from the processing of diseased material tested positive in four of 26 samples at the Marin yard and one of 11 samples in the Santa Cruz yard. One of three rainwater runoff samples from the Marin yard tested
positive; firewood and runoff rainwater were not sampled at the Santa Cruz yard. Sampling of the host vegetation growing in and around the two yards confirmed the presence of *P. ramorum* at each site before operations began, but continued sampling did not find any significant increase in *P. ramorum* activity. Their data suggest that although *P. ramorum* can be isolated from various stages of processing at collection yards, the collection, sorting, and processing activities do not appear to influence infestation levels in host vegetation growing in and around the sites.

**Eradication**

Where appropriate, a response to verification of new occurrences of *P. ramorum* may be attempts to eradicate the pathogen. Eradication efforts may be applied to large geographic areas, to smaller areas such as forest stands or nurseries, or to individual host plants. Efforts to eliminate, destroy or reduce inoculum, including sanitation efforts, can be eradication strategies. Eradication of any disease can only be successful if the pathogen is detected early and its distribution is limited. If eradication is not appropriate, then attempts to control, manage, and mitigate impacts are considered.

**From Forests**

**Eradication efforts in Oregon:** In July 2001 *P. ramorum* was discovered at nine disease centers in mixed tanoak/Douglas-fir (*Pseudotsuga menziesii var. menziesii*) forests near Brookings, Oregon (Goheen and others 2002). Aerial photos of the area indicated that the pathogen was present at one of the sites since about 1997. The pathogen was isolated from stem cankers on tanoak and from foliage and shoots of native *Rhododendron* and *Vaccinium*. All lands within 1.6 km (1 mile) of the disease centers, an approximately 2331 hectare (9 square miles) area, were subjected to Oregon and APHIS quarantine that prohibited the transport of host materials. Since the fall of 2001, state and federal agencies have attempted to eradicate *P. ramorum* from those infested sites in Oregon by cutting and burning all infected host plants and adjacent apparently uninfected plants (Goheen and others 2004, Hansen and Sutton 2006, Kanaskie and others 2004; Figure 3). Following treatment, sites are monitored by baiting of streams and rainwater with leaves of tanoak and rhododendron, baiting of soils with pear fruits and tanoak and rhododendron leaves, and examining sprouting host plants for infection (Hansen and Sutton 2006). Although the monitoring indicated that the pathogen survived cutting and burning on more than 50 percent of the sites, the number of new infected trees discovered each year decreased (Kanaskie and others 2006b). More aggressive chemical sprout...
treatment in 2003 to 2005 dramatically decreased the recovery of *P. ramorum* within treated sites. The pathogen has been recovered from soils at several eradication sites, but with very low frequency. The eradication efforts have reduced inoculum levels and slowed the spread of the pathogen (Kanaskie and others 2006b). As of the end of 2005, eradication was in progress on approximately 51 sites, totaling 35.6 hectares (88 acres) (Nelson and others 2006).

Both the number of new infected trees and the number of new infested acres increased in 2005 compared to 2004. Of nine new sites detected in 2005, eight were within 0.4 km (1/4 mile) of previously known sites, and one was approximately 0.8 km (1/2 mile) away from a known site. The latter site was discovered during ground surveys triggered by the recovery of *P. ramorum* from rhododendron leaf baits in a nearby stream in October 2005, and was located just outside of the quarantine boundary. In addition to these nine new sites, nine existing eradication sites were expanded to include infected trees that were found near their perimeters in 2005. At the landscape level, the distribution of new infected trees suggests spread in a north to northeast direction, following the south to southwest winds that prevail during rainy periods (Nelson and others 2006).

The quarantine area in Oregon was expanded again in 2006 to accommodate 35 new infested sites. Two of the new infestations occurred outside of the quarantine area, one 1.6 km (1 mile) to the east and one 2.4 km (1.5 miles) to the west of the previously infested area. The new infested areas were added to quarantined portions of Curry County in Oregon, bringing the regulated area up to 5672 hectares (21.9 square miles). In addition to the new sites, six existing eradication sites were expanded to include infected trees found near their perimeters. The new infestations were attributed to two consecutive years of unusually wet spring and early summer weather favoring long distance spread of the pathogen. Eradication treatments – including herbicide treatment of tanoak, and cutting and burning of tanoak, myrtlewood (California bay laurel), huckleberry, and rhododendron – were completed on several acres of land in summer 2006.

**Slow the spread efforts in Humboldt County**: Because eradication is not feasible, efforts are being made to slow the spread of *P. ramorum* in coast redwood (*Sequoia sempervirens*) forests in Humboldt County, California (Figure 4). An infestation of *P. ramorum* in an about 518 hectare (2 square miles) area of redwood forests near the town of Redway in a residential setting in northern California was confirmed in July 2002. The area was treated in February 2004 by removing infested tanoaks (Valachovic and others 2006). Additional areas

![Figure 4. Suppression efforts in Humboldt County. Image: Yana Valchovic, University of California.](image-url)
of tanoak mortality in riparian forest settings near Redway and nearby Garberville were confirmed later in 2004. Because clear-cutting was not an option due to adverse environmental impacts, the residential setting and other considerations, removal of hosts, including California bay laurel and other foliar hosts, was considered. Possible suppression scenarios range from pruning of selected host branches on residential properties where landowners are unwilling to have trees removed, to felling and removal of infected tanoak, California bay laurel and madrone (Arbutus menziesii), as well as the pruning of coast redwood trees. Soil, plant parts, and new host sprouts from treatment sites will be monitored for at least two years after treatment. An integrated treatment and adaptive monitoring program including sampling of strategically located streams from central Mendocino County north to the Smith River near Oregon, and sampling of frequently visited national, state and county recreation areas from Mendocino County to the Oregon border is in place. Experimental silvicultural control efforts over 48.6 hectares (120 acres) were implemented in 2006. The treatments included California bay laurel and tanoak removal in combination with pile and broadcast burning.

**From Gardens**

In the Netherlands, eradication of *P. ramorum* from an infested garden was attempted by cutting back all infected rhododendron to 30 cm (11.8 inches). As an experiment, the remaining parts of the plants were treated with thiophanate–methyl, glyphosate, or left untreated, and the removal of plant debris and humus or plant debris only was tested. The regrowth and occurrence of new infections were monitored (Aveskamp and others 2006). The pathogen survived in the sandy soil for at least one year, and cutting back the rhododendron shrubs to 30 cm (11.8 inches) was not sufficient to eradicate *P. ramorum* from the infested garden.

**From Nurseries**

**U.S.:** Measures adopted to eradicate the pathogen from nurseries have met with limited success. In U.S. nurseries, eradication of the pathogen is the primary objective of the USDA APHIS strategic plan (USDA APHIS 2005). Through protocols for tracing infected plants and mitigating infested nurseries, *P. ramorum* may be eliminated from nursery stock. Successful eradication can be demonstrated through scientifically valid survey and sampling plans. The implementation of clean stock programs and best management practices for nurseries can ensure that nursery stock moving in commerce is free of *P. ramorum.*

The federal interim confirmed nursery protocol (USDA APHIS 2003), which outlined the destruction of infected nursery stock, safe disposal of contaminated containers and growing media, and subsequent testing of the remaining plants on-site, was used in an attempt to eradicate the pathogen in imported, infected nursery stock in Oregon (Osterbauer and others 2004).
Phytophthora ramorum was not detected in plants at the nurseries after the destruction of the originally infected plant material.

**UK and EU:** Eradication is being attempted in the UK and the EU by destroying all infected plants within a 2 m (6.6 ft) radius of a diseased plant and holding all susceptible plants within a 10 m (32.8 ft) radius plus any remaining plants from the same consignment as the diseased plants for further assessment (Sansford and others 2003, Slawson and others 2006). Release of these plants would be allowed following two negative visual inspections during three months of active growth.

The eradication and containment actions required against *P. ramorum* and *P. kernoviae* in the UK (United Kingdom Department for Environment, Food and Rural Affairs 2006a) are listed here:

### Nurseries and retail premises
- Destruction by burning or deep burial (infected plants, susceptible plants within a 2m radius of infected plants and associated plant debris).
- Disinfection of surfaces.
- Prohibition on movement of susceptible plants within a 10 m radius of infected plants and remaining plants in infected lot for at least 3 months.
- Prohibition on use of Phytophthora fungicides during the holding period.
- Advise the cessation of overhead irrigation
- Trace-back and trace-forward of related plant material.

### Parks, gardens and uncultivated land
- Prohibition on movement of the infected plant and parts of the plant (e.g. must not be used for propagation purposes or foliage purposes).
- Destruction by burning or deep burial (infected plants, susceptible plants within an appropriate cordon sanitaire and associated plant debris).
- Prevention of regrowth.
- For infected trees, felling or pruning will be required depending on the part of the tree infected and the extent of infection.
- Measures must be taken to prevent re-infection at the site (e.g. prohibition on planting susceptible plants in contaminated soil, removal or sterilisation of contaminated soil).
- In the case of two sites where infection is more widespread, it has been accepted that eradication is likely to be protracted, and so, a ‘Disease Management Zone’ approach has been implemented in which containment measures are imposed whilst the eradication is undertaken.

Slawson and others (2006) reported that the regulations on the movement of *Rhododendron*, *Viburnum* and *Camellia* within the EU have reduced the number of positive finds in nursery
and retail facilities. They also reported some success with eradication. Of 462 outbreaks (376 at nurseries and garden centers and 86 on managed and unmanaged land) recorded through December 2004, 82 percent were eradicated from nursery and retail facilities, and 27 percent were eradicated from managed and unmanaged lands. In the Netherlands, the EU actions to prevent the introduction and spread of *P. ramorum* appear to be successful in nurseries, but less so in woodland areas (Steeghs and de Gruyter 2006). Steeghs and de Gruyter (2006) suggest that because *P. ramorum* is known from about 25 to 30 field sites in the country, complete eradication would not be possible.

**Heat Treatments**

Various heat treatment experiments have been done and are underway to determine efficacy in eradicating *P. ramorum* from infested host material.

**Effects of composting on pathogen viability:** Composting is an effective treatment option for sanitization of *P. ramorum*-infected plant material (Garbelotto 2003). Swain and others (2002, 2006) demonstrated that composting effectively eliminates *P. ramorum* from green-waste. In laboratory heat treatment tests, wood chips and cankered stems from coast live oak and infected California bay laurel leaves were all non-infectious after a two week exposure at 55°C (131°F). These same types of infectious plant materials were also used in field composting trials, utilizing both windrow and forced-air methods. All plant material extracted from compost piles was free from *P. ramorum* after two weeks.

Studies by Swain and Garbelotto (2006) suggest that plant material infested with *P. ramorum* and brought into composting facilities may present a contamination risk to users of finished compost coming from the facility. Isolating sources of fresh plant material from curing and finished compost at facilities producing compost for commercial sale or transport out of quarantined areas would eliminate contamination.

**Effect of heat treatments on pathogen viability:** Harnik and others (2004) showed that *P. ramorum* is highly heat tolerant and could be re-isolated from artificially inoculated California bay laurel leaves placed at 55°C (131°F) for up to 1 week. The pathogen was not recovered after 2 weeks at 55°C (131°F). Because the prolonged heat treatments are impractical for bay leaves intended to be sold commercially as a spice, the authors developed a treatment involving a gradual and progressive heating process combined with the application of a moderate vacuum (0.133kPa) that could be completed in 22 hours; the treatment eliminated the recovery of *P. ramorum*, and had no negative effect on the quality of the bay leaves.

Aveskamp and Wingelaar (2006) demonstrated that the tunnel-composting process (heating plant
material to a minimum of 60°C (140°F) for at least 10 hours under controlled conditions, with hot air flowing through the plant debris during the process) eliminated *P. ramorum* from infected *Rhododendron* leaves and shoots among *Rhododendron* plant debris.

Moist, steam heat is more effective than dry heat. Linderman and Davis (2006) recovered *P. ramorum* sporangia or chlamydospores from soilless potting media up to 6 months after being added. Aerated steam pasteurization at 50°C (122°F) or higher for 30 minutes was an effective means of eradicating *P. ramorum* as well as other pathogens from the infested media and contaminated containers without destroying the containers.

**Protection**

Protection strategies – those that provide a chemical, physical, spatial or temporal barrier to infection – are used when the pathogen is present and infection will likely occur without the intervention of protective measures. Most barriers are chemical.

**Chemical**

**Treatment of oaks and tanoak:** It was recognized early on that although fungicidal treatment of host trees in the forest situation would likely not be practical, treatment of individual high value trees in the urban environment could be beneficial. In vitro tests (Garbelotto and Rizzo 2001, Garbelotto and others 2002b) determined that many of the standard chemicals used to control other *Phytophthora* spp. (Erwin and Ribeiro 1996, Hardy and others 2001) were effective against *P. ramorum*. Garbelotto and Rizzo (2001) found Al-fosetyl, metalaxyl, copper sulfate, copper hydroxide, and phosphonate effective against *P. ramorum* in vitro. They and Garbelotto and others (2002b) found three chemical compounds effective in reducing *P. ramorum* growth rate in potted coast live oak saplings. Saplings injected with phosphetyl-Al, metalaxyl, and phosphorous acid had significantly smaller cankers than untreated saplings or saplings injected with copper sulfate pentahydrate.

Field experiments conducted in Marin, Alameda, and Santa Cruz counties in California evaluated the effectiveness of chemical treatments for controlling *P. ramorum* on nursery-grown saplings and native populations of mature coast live oak and tanoak (Garbelotto and others 2003b). Trees were inoculated by placing *P. ramorum* mycelium under the bark. A variety of commercially available chemicals effective against other *Phytophthora* species were evaluated in at least 10 different trials. Application methods included trunk injections, soil drenches, topical applications, and foliar sprays. Treatments with phosphonate compounds significantly and consistently reduced lesion size in both oaks and tanoaks. Injecting the chemicals into the trunk of the tree
was the most effective method. Treatment of the tree prior to infection was significantly more effective at controlling the pathogen than treatment after infection. Phosphonate-treated trees remained resistant to new *P. ramorum* infections for at least three months. However, mature trees may require a longer period following chemical treatment to become resistant to infection. The currently recommended optimum treatment is for the first treatment to be done in fall or spring (when temperatures are mild), with a second treatment 6 months later, and then repeat treatment every 18 months thereafter (unpublished information, COMTF).

Additional field experiments evaluated the effectiveness of phosphonate chemical treatments for control of *P. ramorum* in tanoak and Shreve’s oak (*Q. parvula var. Shrevei*) (Schmidt and others 2006). Native stands of mature, uninfected trees were treated with Agrifos® systemic fungicide and subsequently inoculated with *P. ramorum*. Injections as well as topical applications of Agrifos® with Pentrabark® surfactant were evaluated. The injection and topical phosphonate treatments significantly reduced lesion size in tanoaks and Shreve’s oaks compared to untreated control trees. However, the extent of moss covering the tree trunk affected the efficacy of Shreve’s oaks topical treatment. A combined treatment of injection and topical application methods was most effective in Shreve’s oak. The range of resistance and susceptibility to *P. ramorum* that exists in native stands may affect the success of phosphonate treatments.

Kanaskie and others (2006a) also tested the efficacy of phosphonate (Agrifos®) injected into the sapwood and applied to the trunks (with Pentrabark® surfactant) of living tanoak trees on *P. ramorum* lesion development. Trees were treated in February and May at the highest label rates and at twice the highest label rates. A sample of treated trees and untreated controls were then harvested in May, June, and July, and a one-meter (3.3 ft) section of the lower boles collected. Each bole section was inoculated with mycelial plugs of a North American and a European isolate of *P. ramorum* and incubated for 4 weeks at constant temperature. At the end of the incubation period the bark was shaved, the longitudinal and radial extent of lesions associated with each inoculation point was measured, and re-isolation of the pathogen from the lesions was attempted. The European isolate caused larger lesions than the North American isolate, and lesion size was significantly smaller in the injected trees than in the bark-spray application or control trees.

Data from the above experiments were used to support the registration in California of Agrifos® (EPA Reg. No. 71962-1-54705; active ingredients, mono- and di-potassium salts of phosphorous acid) to prevent infection of oaks and tanoak. Agrifos® (systemic fungicide) and Pentrabark® (surfactant) were approved on 01 October 2003 by the California Department of Pesticide Regulation (DPR), under a FIFRA Section 24c Special Local Needs Label, as a treatment for oaks and tanoaks that are at high risk of contracting *P. ramorum*. The fungicide can be applied as a foliar spray, soil drench, soil incorporation, basal bark application (Figure 5) or bare root dip. The fungicide is currently being recommended for use on high-value trees and on trees around high-use
facilities. The phosphite is translocated systemically and broken down into phosphonic acid, which triggers a defense response in the plant. The host response prevents infection and slows down the growth of cankers. The optimal treatment routine calls for the first treatment in November-December (if temperatures are still mild), with a booster treatment 6 months later, and then repeated annually. Phosphite does not kill the pathogen and must be applied annually and every 6 months for the first year. Foliar treatment of oaks and tanoaks using phosphonates only provides short-lived protection and causes phytotoxicity (Garbelotto 2004).

Fungicide treatment of host trees for *P. ramorum* is not always appropriate. Copper hydroxide and other phosphorous acid compounds are most effective as preventives. Trees with advanced symptoms (such as multiple bleeding areas, extensive beetle attack, evidence of decay, and/or a sparse or brown canopy) will not benefit from treatment, and trees with *P. ramorum* well-established will not be cured. See the Sudden Oak Death Guidelines for Arborists (California Oak Mortality Task Force 2005a) for a summary of recommended fungicide treatments.

**Treatment of foliar hosts:** Chemicals to protect foliar hosts have also been tested. Harnik and Garbelotto (2006) tested the ability of three chemicals to inhibit hyphal growth, sporangia production and zoospore germination of *P. ramorum* in vitro. The chemicals metalaxyl (Subdue®), phosphorus acid (Agrifos400®) and copper hydroxide (Champ®) were tested at different concentrations against 12 North American *P. ramorum* isolates. In planta experiments on controlling the pathogen using foliar spray on California bay laurel were also conducted. Isolates varied in response to the treatment, but all three of the chemicals were effective in inhibiting all life cycle stages tested. In planta, copper hydroxide was very effective in controlling infection on California bay laurel leaves up to 6 weeks after treatment.

Goheen and others (2006b) tested the fungicides dimethomorph (Stature®) and phosphonate (Agrifos®) for their ability to protect *Rhododendron macrophyllum*, *Vaccinium ovatum*, California bay laurel and tanoak from foliar infection. The two fungicides were applied in the field at 1x and 2x their recommended rates in February and April. New foliage was treated in May. Detached leaves were taken to the laboratory, wounded, and inoculated with A1 (N11A) and A2 (4143) isolates of *P. ramorum*. No fungicide treatment provided complete protection.

In Poland, the efficacy of six fungicides (phosetyl Al, furalaxyl, fenamidone + phosetyl Al, propamocarb + phosetyl Al, oxadixyl + mancozeb, cymoxanil + famoxate) against *P. ramorum* twig blight of rhododendron was assessed (Orlikowski 2004). Laboratory studies and glasshouse
trials were conducted with artificially inoculated soils and plants, and the tested compounds were applied at a dose of 8 µg of a.i./cm². All of the fungicides tested significantly inhibited the development of twig blight; furalaxyl was the most effective.

Studies by Chastagner and Hansen (2003) and Chastagner and others (2003, 2005, 2006) found several fungicides and some surfactants with the potential to control *P. ramorum* infection of Douglas-fir seedlings. The authors evaluated 20 systemic and contact fungicides in protecting Douglas-fir seedlings from infection by the pathogen. Some systemic products were applied about a week prior to bud break, while most treatments were applied just after bud break. The only pre-bud break treatment that completely prevented infection was a drench application of mefenoxam (Subdue MAXX®). Pre-bud break drench applications of Stature®, Insignia®, and Terrazole® had no affect on the number of infected seedlings. The reduction in infection by the pre-bud break applications of Heritage® and Chipco Signature® was variable and applications of Phostrol™ reduced infections by 71 to 75 percent. Post-bud break applications of the contact fungicides Dithane®, Gavel®, Maneb®, and Polyram® provided 100 percent control. Applications of Champ Formula 2F®, Reason®, Daconil Ultrex®, Stature®, and IKF – 916® reduced the number of infected seedlings by 70 to 100 percent. Other fungicides included in the tests provided more limited or variable reductions in the number of infected seedlings. Post-bud break applications of the organosilicone surfactant Silwet L-77® had no effect on infection of seedlings. However, the post-bud break application of Latron CS-7® reduced infection by 67 to 100 percent. The systemic fungicides could suppress development of symptoms, but the protective contact fungicides would not.

Heungens and others (2006) evaluated metalaxyl, dimethomorf, cyazofamid, fosetyl Al, cy-moxanil and mancozeb for their effect against *P. ramorum* on Rhododendron plants. Fungicides that performed best were metalaxyl, dimethomorf, and cyazofamid, resulting in near-complete avoidance of stem infections. Fosetyl-Al and cymoxanil had intermediate effects. Mancozeb was the least effective of the products tested. Protective effects were best when the lower surface of the leaf was covered with the fungicide. This is consistent with the observation that zoospore infection of non-wounded leaves takes place mostly through the lower surface of the leaves. Fungicide treatments 2 days after zoospore inoculation were much less effective than protective treatments (1 day before zoospore inoculation), indicating that the fungicides were more successful as protectants and not very effective as curatives or eradicants.

Linderman and Davis (2005, 2006) evaluated fungicides labeled for Oomycete pathogens for their capacity to inhibit infection of *Rhododendron* (cv Nova Zembla) leaves by *P. ramorum* (both NA strain 2027 mating type A2 and European strain D12A mating type A1) compared to *P. cactorum*, *P. citricola*, *P. nicotianae*, and *P. citrophthora*. Most of the chemicals tested had some efficacy on some species of Phytophthora, but drench or foliar application of mefenoxam (Sub-
due Maxx®) and an unregistered compound SA 110201 (Sipcam Agro USA, Inc.) were most effective on the tested species, with the exception of *P. citrophthora*. The systemic or translaminar chemicals tested were effective in suppressing infections, but did not eradicate the pathogens.

The studies by Linderman and Davis (2005, 2006) demonstrated that inoculating detached leaves was comparable to inoculating intact plants to evaluate chemical and biological agents against *Phytophthora* species.

Tjosvold and others (2006) evaluated registered products for the prevention and eradication of *P. ramorum* on *Rhododendron* (‘Cunningham’s White’ and R. ‘Irish Lace’), *Camellia (C. japonica ‘Elena Nobile’), Pieris (P. japonica ‘Whitewater’),* and *Viburnum (V. tinus ‘Compacta’)*. Maximum rates were applied as foliar sprays on wounded and non-wounded leaves. These fungicides provided preventative activity for at least 2 weeks, but not 4 weeks following their application. For *Rhododendron*, mefenoxam (Subdue Maxx®), dimethomorph (Stature DM®), pyraclostrobin (Insignia®) and fenamidone applied as foliar sprays consistently provided preventive control as expressed by lesion development on wounded and nonwounded leaves using inoculum plugs. Post-infection treatments of leaf lesions with foliar and soil-applied fungicides were ineffective. The pathogen was recovered from lesions consistently for at least 6 weeks after fungicide application regardless of treatment.

In the UK, a range of fungicides were tested for activity against *P. ramorum* (Turner and others 2006b). Seven fungicides/mancozeb (Invader®), cymoxanil/mancozeb (Curzate M68®), fenamidone/mancozeb (Sonata®), etridiazole (Standon Etridiazole 35®), azoxystrobin (Amistar®) and famoxadone/cymoxanil (Tanos®) – were tested for protectant and eradicant activity on containerized *Rhododendron* and *Viburnum*. All fungicides were applied as foliar sprays at the manufacturer’s recommended rate. On *Rhododendron*, metalaxyl-M, azoxystrobin and fenamidone/mancozeb completely inhibited symptom development when applied as protectant treatments either 4 or 7 days prior to inoculation. On *Viburnum*, only metalaxyl-M was completely effective at all protectant timings. Fenamidone/mancozeb was effective when applied 4 days prior to inoculation, but not when applied 3 days earlier. Fungicides were generally less effective when applied as eradicants. The most effective was metalaxyl-M, completely inhibiting disease development when applied 4 days after inoculation. None of the fungicides completely controlled disease development on *Viburnum* when applied after the same time period. Although metalaxyl-M was the most effective fungicide for control of *P. ramorum*, use of this fungicide has not been recommended due to the significant risk of the rapid development of fungicide resistance in the pathogen.

The results of the above fungicide efficacy tests are summarized in Table 1.
Table 1. Fungicides tested in planta and effective against *P. ramorum*.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Fungicide</th>
<th>Scientific Name</th>
<th>Common Name</th>
<th>Efficacy/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garbelotto and Rizzo (2001), Garbelotto and others (2002b)</td>
<td>phosetyl-Al, methalauxyl, phosphorous acid</td>
<td><em>Quercus agrifolia</em></td>
<td>Coast live oak</td>
<td>Injection of potted saplings resulted in significantly smaller cankers than untreated saplings or saplings injected with copper sulfate pentahydrate.</td>
</tr>
<tr>
<td>Schmidt and others 2006</td>
<td>phosphonate (Agri-fos®)</td>
<td><em>Lithocarpus densiflorus</em></td>
<td>tanoak</td>
<td>Injection and topical applications reduced lesion size.</td>
</tr>
<tr>
<td></td>
<td>phosphonate (Agri-fos®)</td>
<td><em>Quercus parvula var. Shrevei</em></td>
<td>Shreve’s oak</td>
<td>Combination of injection and topical was most effective.</td>
</tr>
<tr>
<td>Kanaskie and others 2006a</td>
<td>phosphonate with surfactant (Agrifos® with Pentrabark®)</td>
<td><em>Lithocarpus densiflorus</em></td>
<td>tanoak</td>
<td>Lesion size was significantly smaller in trees injected with phosphonate than in the bark-spray application (Agrifos® with Pentrabark®) or control trees.</td>
</tr>
<tr>
<td>Harnik and Garbelotto 2006</td>
<td>copper hydroxide (Champ®)</td>
<td><em>Umbellularia californica</em></td>
<td>California bay laurel</td>
<td>Foliar application prevented infection up to 6 weeks after treatment.</td>
</tr>
<tr>
<td>Orlikowski 2004</td>
<td>phosetyl Al, furaxyl, fenamidone + phosetyl Al, propamocarb + phosetyl Al, oxadixyl +mancozeb, cymoxanil + famoxate</td>
<td><em>Rhododendron</em></td>
<td>rhododendron</td>
<td>All the fungicides significantly inhibited the development of twig blight, with furaxyl the most effective.</td>
</tr>
<tr>
<td>Citation</td>
<td>Fungicide</td>
<td>Scientific Name</td>
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<td>------------------------------</td>
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</tr>
<tr>
<td>Dithane®, Gavel®, Maneb®, and Polyram®</td>
<td></td>
<td><em>Pseudotsuga menziesii var. menziesii</em></td>
<td>Douglas-fir</td>
<td>Post-bud break spray applications provided 100 percent control.</td>
</tr>
<tr>
<td>Champ Formula 2F®, Reason®, Daconil Ultrex®, Stature®, and IKF – 916®</td>
<td></td>
<td><em>Pseudotsuga menziesii var. menziesii</em></td>
<td>Douglas-fir</td>
<td>Post-bud break spray applications reduced infection by 70 to 100 percent.</td>
</tr>
<tr>
<td>Latron CS-7®</td>
<td></td>
<td><em>Pseudotsuga menziesii var. menziesii</em></td>
<td>Douglas-fir</td>
<td>Post-bud break spray applications reduced infection by 67 to 100 percent.</td>
</tr>
<tr>
<td>Phostrol™</td>
<td></td>
<td><em>Pseudotsuga menziesii var. menziesii</em></td>
<td>Douglas-fir</td>
<td>Post-bud break spray applications reduced infection by 71 to 75 percent.</td>
</tr>
<tr>
<td>Heungens and others 2006</td>
<td>metalaxyl, dimethomorff, cyazofamid, fosphetal Al, cy-moxanil and mancozeb</td>
<td><em>Rhododendron</em></td>
<td>rhododendron</td>
<td>Metalaxyl, dimethomorff, and cyazofamid, resulted in near-complete avoidance of stem infections; fosetyl-Al and cymoxanil had intermediate effects; mancozeb was the least effective. Protective effects best when lower leaf surface treated day before zoospore inoculation.</td>
</tr>
<tr>
<td>Linderman and Davis 2005, 2006b</td>
<td>menfenoxam (Subdue Maxx®), SA 110201 (Sipcam Agro USA, Inc.)</td>
<td><em>Rhododendron (cv Nova Zembla)</em></td>
<td>rhododendron</td>
<td>Drench and foliar applications were effective.</td>
</tr>
<tr>
<td>Citation</td>
<td>Fungicide</td>
<td>Scientific Name</td>
<td>Common Name</td>
<td>Efficacy/comments</td>
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</tr>
<tr>
<td>Tjosvold and others 2006</td>
<td>mefenoxam (Subdue Maxx®), dimethomorph (Stature DM®), pyraclostrobin Insignia®), fenamidone</td>
<td><em>Rhododendron</em></td>
<td>‘Cunningham’s White’ and R. ‘Irish Lace’</td>
<td>Foliar application provided preventive control; post-infection treatments were not effective.</td>
</tr>
<tr>
<td>Turner and others 2006b</td>
<td>metalaxyl-M (SL 567A), dimethomorph/mancozeb (Invader®), cymoxanil/mancozeb (Curzate M68®), fenamidone/mancozeb (Sonata®), etridiazole (Standon Etridiazole 35®), azoxystrobin (Amistar®) and famoxadone/cymoxanil (Tanos®)</td>
<td><em>Rhododendron</em>, <em>Viburnum</em></td>
<td></td>
<td>Foliar application of metalaxyl-M, azoxystrobin and fenamidone/mancozeb on <em>Rhododendron</em> completely inhibited symptom development when applied as protectants either 4 or 7 days prior to inoculation. On <em>Viburnum</em>, only metalaxyl-M was completely effective at all protectant timings. Fenamidone/mancozeb was effective when applied 4 days prior to inoculation, but not when applied 3 days earlier. Fungicides were generally less effective when applied as eradicants. The most effective was metalaxyl-M, completely inhibiting disease development when applied 4 days after inoculation. None of the fungicides completely controlled disease development on <em>Viburnum</em> when applied after the same time period.</td>
</tr>
</tbody>
</table>
In April 2006, the Washington State Department of Agriculture issued a special local need (SLN WA-06003) providing for the foliar application of Subdue MAXX® for the control of *P. ramorum* on container, greenhouse and field-grown nursery plants; landscape plants; forested areas associated or adjacent to nurseries; non-residential landscapes, commercial landscapes, botanical gardens; and Christmas trees. The fungicide also has a special local need for use against the pathogen in the state of Oregon.

Two fungicides, Fosetyl-Al (Chipco Aliette T&O®) and metalaxyl-M (Subdue MAXX®), were granted temporary emergency use registrations in 2006 by the Pest Management Regulatory Agency (PMRA) for ornamental host crops in Ontario to prevent the introduction and minimize the spread of *P. ramorum* (Ontario Ministry of Agriculture, Food and Rural Affairs 2006).

**Pathogen resistance to metalaxyl-M:** Some *Phytophthora* spp. have developed resistance to metalaxyl-M. Development of resistance to systemic fungicides has occurred with other *Phytophthora* spp. and is a concern with *P. ramorum*. Some *P. ramorum* isolates obtained from ornamental nursery plants in the UK have shown resistance to Metalaxyl-M (United Kingdom Department for Environment, Food and Rural Affairs 2006b). Heungens and others (2006) in Belgium identified a strain of *P. ramorum* with decreased sensitivity to metalaxyl.

**Masking of symptoms by systemic fungicides:** Shishkoff (2005) sprayed shoots of *Rhododendrons* infected by *P. ramorum* with fosetyl-Al (3 g/L), mefonoxam (0.08-0.15 mL/L), propanocarb (1.5 mL/L) or water alone to determine if systemic fungicides can mask the presence of the pathogen. The organism could be recovered from control, fosetyl-Al and propanocarb-treated lesions at high frequencies (64 to 100 percent) immediately after treatment, with recovery of the pathogen declining thereafter. The pathogen could not be recovered from mefonoxam-treated lesions until 3 to 5 weeks after treatment, when low frequencies (3 to 13 percent) were found. In no case were symptoms suppressed; lesions were easily visible in all treatments. The pathogen was easily recovered from stem tissue 3 to 5 weeks after treatment, and sometimes isolated from buds, fallen leaves and roots.

Effects of tree essential oils on the pathogen: Manter and others (2006) reported that 140 mg/kg of essential oil from the wood of yellow-cedar (*Chamaecyparis nootkatensis*), Port-Orford-cedar (*C. lawsoniana*), incense cedar (*Calocedrus decurrens*), or western juniper (*Juniperus occidentalis*) strongly inhibited zoospore germination and hyphal growth of *P. ramorum* in culture.

**Biological**

Biological agents are also being tested as protectants. The surfactant-producing bacterium *Pseudomonas fluorescens* strain SS101, know to cause lysing of zoospores, resulted in significantly
less infection of detached California bay laurel leaves by *P. ramorum* (Cohen and others 2006). Linderman and Davis (2005b) found that bacterial antagonists (*Bacillus brevis* and isolates of *Paenibacillus polymyxa*) significantly inhibited all *Phytophthora* species tested in vitro, but were ineffective in inoculation assays of leaves dipped in a cell suspension of each antagonist 24 hours prior to inoculation with *P. ramorum* or other species.

**Soil Amendments/Calcium**

Klinger and Zingaro (2006) suggest that symptoms associated with dying oaks in *P. ramorum*-infested areas are sometimes the same as those associated with an increase in soil acidity (reportedly due to mosses, industrial pollution such as acid rain, acid fog and other factors); and that the soil acidification weakens trees and disposes them to attack by secondary organisms. Thus soil amendments containing calcium and other ingredients to offset soil acidification have been recommended as treatment for *P. ramorum*-infected trees. Scientifically valid studies to support the recommendation are lacking. Increased soil acidity in infested areas has apparently not been demonstrated. The addition of calcium does have numerous effects on trees and on *Phytophthora* in vitro and in vivo, both positive and negative (Balci and Halmschlager 2003, Campanella and others 2002, Kim and others 1997, Messenger and others 2000, Simpfendorfer and Harden 2000, Von Broembsen and Deacon 1997). However, it does not appear that scientific studies have been done with calcium and *P. ramorum*.

**Compost Teas**

The use of a liquid tea made from compost to protect hosts of *P. ramorum* is gaining support among some organic growers and home gardeners. Compost tea, made by steeping compost in water with other natural ingredients for at least 24 hours, increases the growth of microbes which may inhibit harmful organisms. The tea is sprayed on leaves or used as a soil drench, depending on the part of the plant to be protected. The theory is that microbial compounds in the tea destroy harmful microbes that attempt to invade plants. Experimental evidence of efficacy in treating *P. ramorum* hosts is lacking. Linderman (R. Linderman, ARS, unpublished) treated rhododendron leaves with *Paenibacillus polymyxa* taken from compost, and then exposed the plant to *P. ramorum*. The *P. polymyxa* did not protect the plant from damage. Additional tests are in progress.

**Resistance**

If they were available, the use of host plants that are genetically resistant to *P. ramorum* would be an additional, long range method to manage the diseases caused by the pathogen. With other host-pathogen systems, the development of resistance has met with some success with annual
and biennial plants, but has proven more difficult with wood perennials, especially forest trees. A program to develop trees genetically resistant to a pathogen is long-term and expensive, and has been undertaken in North America for only a few forest tree species (Sniezko, in press). One successful example is the resistance program developed for the related Phytophthora species, *P. lateralis* and its host Port-Orford-cedar. A genetics white paper developed by the COMTF (Dodd and others 2006) points out the commitment and resources needed to develop a tree resistance program.

Information on the variation in virulence/aggressiveness of *P. ramorum* and the types of genetic resistance in the various host species is limited.

**Resistance in California Bay Laurel and Coast Live Oak**

Preliminary studies (Dodd and others 2005, Garbelotto and others 2003a, Hüberli and others 2002) indicated that individuals of California bay laurel and coast live oak display differential levels of resistance to *P. ramorum*. Hüberli and others (2002) found a range of resistance, as measured by leaf lesions, following inoculation with *P. ramorum* zoospores of California bay laurel leaves collected from throughout the geographic range of the pathogen. Dodd and others (2005), using molecular markers to study within- and among-population variation in host susceptibility to *P. ramorum*, reported variable susceptibility within populations of coast live oak and suggested that the variability was controlled by several gene loci. Beals and Dodd (2006) found a fairly uniform genetic structure in coast live oak throughout its range, with 96 percent of the molecular variance occurring within populations. Results suggest that searches for *Phytophthora*-resistant genotypes could be limited to smaller areas of the species’ distribution.

The ability of *P. ramorum* isolates to cause disease in California bay laurel varies. Meshriy and others (2006) reported differences in susceptibility to *P. ramorum* within populations of California bay laurel, with trees from Oregon being less susceptible, as exhibited by smaller lesions following zoospore inoculation of detached leaves, than those from California. They found only slight variation among populations from California. The genotypes of the two California bay laurel populations appear to differ, and there are physiological differences in the leaf surfaces of California bay laurel and Oregon myrtlewood (the common name used in Oregon for California bay laurel). The thicker cuticles of Oregon myrtlewood may reduce the potential for leaf infection.

Based on data from lab susceptibility trials and field infection data collected from 97 trees from 12 populations in northern California, Anacker and others (2006) found that lab lesion size and field infection levels varied significantly among both California bay laurel trees and populations. The phenotypic trait of leaf area was significantly related to lab lesion size, where bigger leaves produced bigger lesions. Variability in lesion size produced in the lab and infection levels in the field were significantly related to AFLP markers, suggesting a genetic basis to resistance. They
also identified markers associated with phenotypic traits putatively involved in conferring susceptibility, including leaf toughness and leaf water content. At the population level, they found that environmental variability significantly explained susceptibility to *P. ramorum*.

**Resistance in Tanoak**

Hayden and Garbelotto (2006) demonstrated differences in resistance among tanoak individuals and populations, suggesting the existence of quantitative resistance to *P. ramorum* in tanoak populations and individuals. Bark and wounded leaf-inoculated tanoak saplings grown from acorns collected in the Six Rivers National Forest showed significant variability in lesion size among individuals, with stem lesion area positively correlated with leaf lesion area. In their study, growing conditions also had an effect with trees in south-facing rows of the lath house having smaller lesions than those in north-facing rows.

**Resistance in Viburnum**

Grünwald and others (2006a) found a considerable range of resistance, from high susceptibility to resistance, among phenotypes in the genus *Viburnum*. They evaluated nine species of field-grown Viburnum (23 cultivars) for resistance to *P. ramorum* in detached leaf tests. They obtained significant differences for levels of resistance based on percentages of leaf areas affected (*P* < 0.001) and no significant differences for isolates and interactions between isolates and cultivars. The percentages of lesion areas affected ranged from 95% (cvs. *V. burkwoodii* cv. unknown, *V. plicatum* var. *tomentosum* cv. Mariesii, and *V. trilobium* cvs. Alfredo and Bailey), to intermediate responses between 25 and 90% (cvs. *V. burkwoodii* cv. Mohawk, *V. lantana* cv. Mohican, *V. opulus* cvs. Compacta and Hanum, *V. lentago* cv. unknown, *V. sargentii* cv. Onandaga, *V. trilobium* cv. Redwing) to less than 15% infection (*V. dentatum* cvs. Autumn Jazz, Blue Muffin, Chicago Lustre, and Burgundy; *V. opulus* cv. Sterile, *V. plicatum* cv. Newport, Popcorn, Shasta, and Shoshon; *V. nudum* cv. Winterthur, *V. trilobium* cv. Wentworth).

**Resistance in Lilac**

Grünwald and others (2006b) evaluated the relative susceptibility of 25 species and cultivars of lilac to *P. ramorum* using detached leaf assays. The cultivar tested had a significant effect on percent lesion area. Cultivars *Syringa vulgaris* cv. Ellen Willmott, *S. x prestoniae* cv. Minuet, and *S. vulgaris* cv. Katherine Havemeyer had less than 20 percent lesion area and were the most resistant.
Resistance in Rhododendron

Tooley and others (2002) found that leaves of Rhododendron ‘P.J.M.’, R. maximum, and R. carolinianum dipped in suspensions of P. ramorum sporangia developed lesions on less than 10 percent of the leaf area compared to a highly susceptible cultivar like Cunningham’s White that developed up to 50 percent leaf lesion area with the most virulent isolate tested.

De Dobbelaere and others (2005) screened 63 Rhododendron species (21 species and 42 hybrids) for their susceptibility to P. ramorum. Four inoculation methods (wounded or non-wounded detached leaves and wounded or non-wounded branches) were used. Methods involving non-wounded tissue were used to estimate the ability of the hosts to resist tissue penetration. Methods involving wounded tissue evaluated the resistance to pathogen growth inside leaf tissue. Significant differences in disease susceptibility were observed between species as well as between hybrids with all methods used. Inoculation of wounded leaves and stems showed that most species and hybrids were susceptible to some extent. Inoculation of non-wounded leaves and/or stems resulted in a large degree of variation in susceptibility with little to no infection occurring in a few hybrids. The results suggested that if significant resistance is present, it probably occurs at the level of tissue penetration.

Linderman and others (2006c) reported significant differences in species or isolate virulence when detached leaves of ’Nova Zembla’ rhododendron, lilac (Syringa vulgaris), or doublefile viburnum (Viburnum plicatum var. tomentosum) were inoculated under controlled conditions with different species of Phytophthora or isolates of P. ramorum (both mating types).

Resistance in Vaccinium

Parke and others (2002a, 2002b) compared the potential susceptibility of wild Vaccinium species and of commercial Vaccinium crops such as blueberry, cranberry, and lingonberry in detached leaf assays. A wide range of disease responses, from resistant (cranberry) to highly susceptible (lingonberry), was observed among the Vaccinium species and among cultivars.

Survey and Monitoring

For the disease management strategies discussed here to be implemented correctly and efficaciously, it is essential to know the distribution and incidence of the pathogen. Detection efforts are done through surveys and monitoring. Monitoring to detect P. ramorum presence is a critical component of the USDA national P. ramorum management strategy (USDA APHIS 2005). The national strategic plan strives to prevent artificial spread of P. ramorum through prevention,
detection and monitoring, and control and management. The objective of the detection and monitoring component of the strategy is to rapidly and accurately determine where the pathogen and disease are located and to be able to reliably verify pathogen presence or absence in areas considered to be uninfested. The plan discusses detection and monitoring needs to include port inspections, nursery surveys, aerial and roadside surveys in wildland and urban forest settings, forest inventory and monitoring plots, and public employees trained to look for the disease.

Aerial and ground-based surveys and image analysis are used in California and Oregon forests and woodlands containing affected host species to determine the distribution and incidence of *P. ramorum*. In addition, research information on hosts, likely pathways of pathogen movement, and favorable climatic conditions is being used in a risk-based analysis to plan surveys to detect *P. ramorum* where it may appear in the future (Goheen 2003). For information on specific image analysis projects, see the website http://kellylab.berkeley.edu/SODmonitoring (University of California Berkeley 2003).

### Forest Survey and Monitoring in Oregon

Several *P. ramorum* detection surveys are conducted each year in at-risk forest areas by the Oregon Department of Forestry and the USDA Forest Service (Goheen and others 2006a). The forest range of tanoak is systematically surveyed from a fixed wing aerial survey plane, and suspicious trees are mapped. Follow-up helicopter surveys provide a closer look for systematic trees and enable more precise map coordinates. All suspected trees are checked from the ground and samples collected for confirmation as appropriate. In addition, annual ground surveys check the perimeters of previously treated areas for newly infected trees. Oregon nurseries, Christmas tree plantations, and other sites have been surveyed for the federally regulated *P. ramorum* (Osterbauer and others 2004).

### Forest Survey and Monitoring in California

California’s *P. ramorum* monitoring program focuses on early detection. Aerial and ground-based surveys of uninfested areas within minimally infested counties or counties with no known occurrence of *P. ramorum* but sharing a common border with regulated (infested) counties, are conducted, and ground-based early detection surveys in high-risk uninfested areas are done (Mai and others 2006, Mark and Jirka 2002, Meentemeyer and others 2006). Early detection efforts include monitoring of perennial streams in coastal areas of California at high risk of infestation (Murphy and others 2006).

A Web-based GIS (WebGIS) was developed (http://kellylab.berkeley.edu/SODmonitoring/OakMapper.htm) as part of the monitoring strategy of the monitoring committee of the California Oak Mortality Task Force (COMTF). WebGIS has been used to map the spread of *P. ramorum*
within California. OakMapper websites provide up-to-date static maps (local, county and state) and supporting spatial data on the currently confirmed locations of *P. ramorum* as collected from data provided by state and university laboratories (Kearns and others 2003, Kelly and Tuxen 2003, Kelly and others 2004). The database is the statewide repository for all positive *P. ramorum* confirmations in California. The WebGIS includes a public participation geographic information system (PPGIS) that collects information from various publics about trees suspected of having sudden oak death. Users may submit personal inquires and, to a limited extent input potential data of interest.

**National Surveys**

A national survey of forests at risk is conducted by the USDA Forest Service Forest Health Monitoring program and its partners to determine whether the pathogen occurs outside the quarantined areas of California and Oregon. As a first step, Forest Health Monitoring produced a risk-based U.S. map identifying sampling polygons. Factors used to assign risk and develop the sampling polygons were a) presence of known host species, host genera, and closely related genera, b) locations of nurseries receiving *Rhododendron* spp. stock, c) length of yearly mesic/moist weather period, and d) area outside limiting temperature extremes currently associated with *P. ramorum*. Based on these criteria, much of the southern Appalachian and the Pacific coastal regions are currently rated high risk. Additional information on the National Survey, including the methods used and a copy of the national risk map, are available on the internet (USDA Forest Service, Forest Health Protection 2006)

APHIS-PPQ conducts a national survey of nurseries throughout the United States to determine the risk of spread and establishment of the pathogen through nursery plants. The USDA Forest Service and states conducted nursery perimeter and general forest detection surveys in 38 states during 2005 (USDA APHIS 2005c).

**Canadian and UK Surveys**

A national *P. ramorum* survey was conducted in Canada from June to September 2003. The survey targeted importing nurseries, botanical and public gardens, and collections of rhododendron societies. In the UK, the progress of existing infections and the development of new infections have been monitored in three managed gardens since October 2003 (Turner and others 2006a).

Efforts to model the potential habitat for *P. ramorum* are also important for disease regulation and management. Those modeling efforts will be discussed in a later chapter.
Additional Management Actions

Rizzo and others (2005) discuss what they consider to be the necessary components of a management program for *P. ramorum* in California and Oregon forests. In addition to components that have been summarized here (monitoring, eradication, fungicides, and prevention of human spread), they add diagnosis, restoration, stand manipulation, and fire. Diagnosis will be covered in a future chapter. Restoration efforts involving revegetation will be dependent on results of host resistance studies. A brief summary of stand manipulation and fire in relation to *P. ramorum* management follows here.

**Stand Manipulation**

Efforts to manipulate forest stands by pruning, host removal, thinning and other actions to reduce incidence and impact of *P. ramorum* are underway in several California locations. The slow the spread efforts in the Redway area have been discussed here under Eradication. Similar efforts are being planned in the Big Sur area of central coastal California.

**Fire**

Prescribed fire has been used as a tool to restore and maintain natural ecosystems and control tree diseases elsewhere (Brennan and Hermann 1994, Harvey 1994). Because the first reports of *P. ramorum* impact in California forests were in urban areas with a history of fire suppression, some have suggested that the absence of fire may have created stand conditions favoring the pathogen (Moritz and Odion 2005, Rizzo and others 2002). Moritz and Odion (2005) found a strong negative relationship between *P. ramorum* infections across northern California and the locations of fires since 1950. Their data analysis supported the hypothesis that past fire occurrence is somehow important in the spread of the disease. However, in a more detailed study of Sonoma county only, evidence for a negative relationship between the disease and fire history was not as strong (Moritz and Odion 2006), pointing out the complex interactions involved among fire, the disease, and its management at the landscape level. A relationship between fire suppression and disease incidence does not necessarily mean that prescribed fire would be an effective management option, especially in the heavily populated areas of central coastal California. The effects of prescribed fire on *P. ramorum* are being studied in the slow the spread efforts in the Redway area.
Summary

An attempt was made here to compile and summarize the existing literature on management and control of the diseases caused by \textit{P. ramorum}. The pitfalls involved with attempting to summarize the literature associated with an active and evolving area of research such as \textit{P. ramorum} are many. A synthesis of that literature is difficult, as new findings and ongoing projects take time to become public or are published. The reader should make use of the various websites available to obtain the most current information. Useful websites on regulations and quarantine include several APHIS sites (http://www.aphis.usda.gov/ppq/ispm/pramorum/; and (http://www.aphis.usda.gov/ppq/ispm/pramorum/regulations.html) for U.S. regulations; the various state regulatory sites such as http://www.cdfa.ca.gov/phpps/pe/sod_survey/ and http://egov.oregon.gov/ODA/PLANT/sod_free.shtml ; and the U.K. site http://www.defra.gov.uk/planth/pramorum.htm for international information.

Information on recently completed and on-going studies on eradication, protection and resistance can be found in monthly reports issued by the California Oak Mortality Task Force at www.suddenoakdeath.org.
References


