A Pest Risk Assessment of *Phytophthora ramorum* In North America

This risk assessment follows the format used by the Exotic Forest Pest Information System for North America, a joint project of the member organizations of the Insect and Disease Study Group of the North American Forest Commission. For a description of the evaluation process used, see Participant's Guidelines at **http://www.spfnic.fs.fed.us/exfor/docs/guidelines.pdf**

IDENTITY

Name: *Phytophthora ramorum*

Pest Authorities: S. Werres, A.W.A.M. de Cock & W.A. Man in't Veld

Taxonomic Position: Oomycota:Pythiales:Pythiaceae
Sub-specific Taxon:

Pest Type: Fungus or fungus-like

Common Name(s): Sudden Oak Death (on tanoak and some oak species); ramorum leaf blight, ramorum shoot blight (on other hosts)

Synonym(s):

RISK RATING SUMMARY

Numerical Score: 9

Relative Risk Rating: Very High Risk

Uncertainty: Very Uncertain

Uncertainty in this assessment results from: Knowledge of the host range of this pathogen is incomplete. The susceptibility of North American or worldwide species of *Quercus*, *Lithocarpus*, *Abies*, *Acer*, *Aesculus*, *Arbutus*, *Arctosptaphlyos*, *Camellia*, *Corylus*, *Heteromeles*, *Kalmia*, *Lonicera*, *Pieris*, *Pseudotsuga*, *Rhamnus*, *Rhododendron*, *Sequoia*, *Taxus*, *Trientalis*, *Umbellularia*, *Vaccinium*, *Viburnum*, or other economically or environmentally significant genera is unknown. The etiology of the pathogen, including requirements for infection and means of spread, is mostly unknown. Ecological or other limits to its further distribution are largely unknown. The geographic origin of the pathogen is unknown.

RISK RATING DETAILS

Establishment Potential Is High Risk

The relevant criteria chosen for this organism are:

- Organism has successfully established in location(s) outside its native distribution.
- Suitable climatic conditions and suitable host material coincide with ports of entry or major destinations.
- Organism has demonstrated ability to utilize new hosts.
- Organism has high inoculum potential or high likelihood of reproducing after entry.

Justification: Potential hosts are abundant throughout much of North America and Eurasia, including regions that are climatically similar to the known disease range. The current known wildland distribution of the pathogen in North America is in coastal environments of California and southern Oregon, indicating possible environmental limitations to distribution.

Spread Potential Is High Risk

The relevant criteria chosen for this organism are:

- Organism is capable of dispersing more than several km per year through its own movement or by abiotic factors (such as wind, water or vectors).
- Organism has demonstrated the ability for redistribution through human-assisted transport.
- Organism has a high reproductive potential.
- Potential hosts have contiguous distribution.
- Eradication techniques are unknown, infeasible, or expected to be ineffective.
- Organism has broad host range.

Justification: The pathogen produces various dispersal structures, including resistant chlamydospores, motile zoospores, and deciduous sporangia. Pathways of long distance spread include movement of infected ornamental nursery stock and other infested plant materials. Species in about 17 plant families are known to be susceptible.

Economic Potential Is High Risk

The relevant criteria chosen for this organism are:

- Organism attacks hosts or products with significant commercial value (such as for timber, pulp, or wood products).
- Organism directly causes tree mortality or predisposes host to mortality by other organisms.
- Damage by organism causes a decrease in value of the host affected, for instance, by lowering its market price, increasing cost of production, maintenance, or mitigation, or reducing value of property where it is located.
- Organism may cause loss of markets (domestic or foreign) due to presence and quarantine significant status.
- No effective control measure exists.

Justification: This pathogen is capable of killing healthy mature California black oaks, coast live oaks, Shreve's oaks, canyon live oaks and tanoak. If other species of oaks were susceptible, the economic impact would be significantly increased. Two species of eastern oaks, northern red oak (*Quercus rubra*) and pin oak (*Quercus palustris*) developed stem cankers after inoculation of seedlings with the pathogen (Rizzo et al. 2002b). Some species of eastern oaks are commercially valuable in many locations. Pacific madrone and Rhododendron have also been seriously affected, with mortality reported in some areas. Oak and tanoak mortality and resulting fuel loading in urban areas would add to costs of fire prevention, and removal costs of hazardous and dead trees would be significant. Quarantine restrictions imposed on the horticultural industry could have significant economic consequences.

Environmental Potential Is High Risk

The relevant criteria chosen for this organism are:

- Organism is expected to cause significant direct environmental effects, such as extensive ecological disruption or large scale reduction of biodiversity.
- Organism is expected to have indirect impacts on species listed by Federal, Provincial, or State agencies as endangered, threatened, or candidate. This may include disruption of sensitive or critical habitat.
- Organism may attack host with small native range.
- Introduction of the organism would likely result in control/eradication programs that may have potential adverse environmental affects.

Justification: Oak species play an important ecological role in forests and woodlands as food and habitat for wildlife, and as soil cover in watersheds. The loss of oaks and tanoak would reduce biodiversity. Other susceptible species such as *Rhododendron* spp., *Vaccinium ovatum*, *Arbutus menziesii* and *Umbellularia californica* are unique components of several coastal and inland ecosystems in California. Some hosts have important cultural values to native Americans.

HOSTS

Known hosts of *Phytophthora ramorum* include numerous species in a wide range of plant families. Reported hosts as of August 2003 (Rizzo et al. 2001; McPherson et al. 2000; Werres 2001, Werres and Marwitz 1997, Davidson et al. 2003) are listed here in two tables, one with regulated species and the second with associated species. Regulated species are those for which Koch's postulates have been completed. Associated species are those from which *P. ramorum* has been cultured or detected using PCR (polymerase chain reaction), but Koch's postulates have not yet been completed. An updated list of regulated and associated host species is maintained by APHIS at www.aphis.usda.gov.ppq.ispm/sod. Following the host is geographic location (CA = California, OR = Oregon, WA = Washington, CAN = Canada, E = Europe) and typical symptoms. See www.suddenoakdeath.org for recent hosts. Numerous additional species are susceptible to infection following artificial inoculation (Davidson et al. 2003, Rizzo and Garbelotto 2003).

Plant Species Regulated for *Phytophthora ramorum*.				
Family	**Host**	**Common Name**	**Location**	**Typical Symptoms**
Aceraceae	*Acer macrophyllum*	Big leaf maple	CA	Foliar lesions
Caprifoliaceae	*Lonicera hispidula*	California honeysuckle	CA	Foliar lesions
	Viburnum x *bodnantaense*	Viburnum (Bodnant)	CA, OR, E	Stem lesions, wilting
	Viburnum tinus	Laurustinus	CA, E	Stem lesions, wilting
Ericaceae	*Arbutus menziesii*	Pacific madrone	CA	Foliar lesions, branch cankers, mortality

	Arctostaphylos manzanita	manzanita	CA	Foliar lesions, stem and branch cankers, branch dieback
	Pieris formosa	Andromeda	CA, OR, E	Foliar lesions, stem cankers
	Rhododendron spp.	Rhododendron	CA, OR, WA, CAN, E	Foliar lesions, stem and branch cankers, mortality
	Vaccinium ovatum	Evergreen huckleberry	CA, OR	Foliar lesions, stem and branch cankers, mortality
Fagaceae	*Lithocarpus densiflorus*	Tanoak	CA, OR	Foliar lesions, stem and branch cankers, mortality
	Quercus agrifolia	Coast live oak	CA	Stem cankers, mortality
	Quercus chrysolepsis	Canyon live oak	CA	Stem cankers, mortality
	Quercus kelloggii	California black oak	CA	Stem cankers, mortality
	Quercus parvula var. *shrevei*	Shreve oak	CA	Stem cankers, mortality
Hippocastanaceae	*Aesculus californica*	California buckeye	CA	Foliar lesions
Lauraceae	*Umbellularia californica*	California bay (Bay laurel)	CA	Foliar lesions
Pinaceae	*Pseudotsuga menziesii*	Douglas-fir	CA	Foliar lesions, branch dieback
Primulaceae	*Trientalis latifolia*	Western starflower	CA	Foliar lesions
Rhamnaceae	*Rhamnus californica*	California coffeeberry	CA	Foliar lesions
Rosaceae	*Heteromeles arbutifolia*	Toyon	CA	Foliar lesions, branch cankers, branch dieback
Taxaceae	*Taxus baccata*	English yew	E	Branch dieback
Taxodiaceae	*Sequoia sempervirens*	Coast redwood	CA	Foliar lesions, branch cankers
Theaceae	*Camellia japonica*	Camellia	CA, OR, E	Foliar lesions

Plant Species Associated with *Phytophthora ramorum*, not currently regulated				
Family	**Host**	**Common Name**	**Location**	**Typical Symptoms**
Anacardiaceae	*Toxicodendron diversilobum*	Poison oak	CA, OR	Stem canker
Betulaceae	*Corulus cornuta*	California hazelnut	CA	Foliar lesions
Caprifoliacae	*Viburnum plicatum* var. *tomentosum*	Viburnum (Doublefile)	E	Stem lesions, wilting
Ericaceae	*Arbutus unedo*	Strawberry tree	E	Foliar lesions
	Kalmia latifolia	Mountain laurel	E	Foliar lesions
	Pieris formosa x japonica	Andromeda (Forest Flame)	OR, E	Foliar lesions, stem cankers
	Pieris floribunda x japonica	Andromeda (Brouwer's Beauty)	OR, E	Foliar lesions, stem cankers
	Pieris japonica	Andromeda (Variegata and Flaming Silver)	OR, E	Foliar lesions, stem cankers
	Vaccinium vitis-idaea	lingonberry	E	Foliar lesions
Oleaceae	*Syringa* sp.	Lilac	E	Foliar lesions
Pinaceae	*Abies grandis*	Grand fir	CA	Foliar lesions, branch dieback
Pittosporaceae	*Pittosporum undulatum*	Victorian box	CA, E	Foliar lesions
Rhamnaceae	*Rhamnus purshiana*	Cascara	OR	Foliar lesions, branch dieback
Rosaceae	*Rubus spectabilis*	Salmonberry	OR	Foliar lesions
Theaceae	*Camellia sasanqua*	Camellia	CA, OR, E	Foliar lesions

GEOGRAPHICAL DISTRIBUTION (as of August 2003; see www.suddenoakdeath.org for the most recent distribution)

Europe:
Germany, the Netherlands (Werres et al. 2001), United Kingdom (Lane et al. 2003), Poland (Orlikowski and Szkuta 2002), Spain (Moralejo and Werres 2002), France (Delatour et al. 2002), Belgium (De Merlier et al. 2003), and Sweden (Jones et al. 2003).

North America:
Canada (British Columbia [Vancouver nursery]); United States (Washington [King County nursery], Oregon [Curry County, Clackamas County nursery, Jackson County nursery], California [12 coastal counties including Humboldt, Mendocino, Sonoma, Napa, Solano, Marin, Contra Costa, Alameda, San Mateo, Santa Clara, Santa Cruz, and Monterey, and a nursery in Stanislaus County) (Davidson et al. 2003). Known infected plants in the nursery infestations in British Columbia, Washington, Oregon and in Stanislaus County, California were destroyed.

BIOLOGY

Phytophthora ramorum, associated with Sudden Oak Death and other diseases on hardwood, coniferous, and herbaceous hosts in California and Oregon, was only recently described on Rhododendron and Viburnum in Europe (Werres et al. 2001). Based on sequences of the internal transcribed spacer (ITS) of nuclear ribosomal DNA, the closest species to *P. ramorum* is *P. lateralis* Tucker & Milbrath (Garbelotto et al. 2002a), which causes a root disease of *Chamaecyparis lawsoniana*.

Phytophthora ramorum is a cool temperature organism, with optimum growth at 20^{o}C. Numerous sporangia are produced in the laboratory on moistened leaves of *Umbellularia californica* and *Rhododendron* spp. within 72 hours (Davidson et al. 2002). The sporangia are deciduous, suggesting air-borne dispersal. Zoospores and chlamydospores of *P. ramorum* do not survive drying, but can survive in moist conditions for at least one month (Davidson et al. 2002). *Phytophthora ramorum* is heterothallic (Werres et al. 2001). Two mating types exist, the A1 mating type, found mostly in Europe, and the A2 type, found primarily in North America (Brazier et al. 2002, de Gruyter et al. 2002). The A1 type, until recently reported only from Europe, has been recovered from nursery stock in Washington and British Columbia (Everett Hansen, unpublished). The A2 mating type was recently detected in Belgium (Werres, personal communication). Two geographic strains, the European and the North American, are known.

The pathogen causes two different types of diseases – lethal stem infections on oaks and tanoak, and non-lethal foliar and twig infections on other hosts (Rizzo and Garbelotto 2003). Fruiting structures of *P. ramorum* (sporangia and chlamydospores) are produced on the foliage of non-oak hosts, but have not been observed on infected oak or tanoak wood. This suggests that multiple hosts are necessary in the disease cycle (Garbelotto et al. 2003, Rizzo and Garbelotto 2003).

In oaks and tanoak, the pathogen is typically found in phloem tissues, but commonly extends to the outer portion of the xylem. Means of entry through the bark are unknown. Infected phloem tissue is more or less uniformly discolored, while infected xylem tissues discoloration is typically in dark streaks. A dark brown to black line is usually evident at the margins of the infected areas in both xylem and phloem.

Phytophthora ramorum has been recovered from soil, soil litter, and rainwater collected adjacent to diseased coast live oaks and from wood of infected trees two months after they were cut down (Davidson et al. 2002).

Infection of foliar tissue apparently requires cool temperatures and free water. Infection of California bay leaves was highest at 18^{o}C, and required a minimum of 6 to 12 hours of free water (Garblotto et al. 2003).

PEST SIGNIFICANCE

Economic Impact: The pathogen causes a serious disease of tanoak and four species of oaks, resulting in crown dieback, stem bark lesions, and basal cankers (Rizzo et al. 2002a), typical of other *Phytophthora* species (Erwin and Ribeiro 1996, Mircetich et al. 1977). Infected trees die relatively quickly once crown symptoms develop. Disease severity (tree mortality) varies considerably from location to location.

In coastal central California, the value of oak woodland suitable for residential development has been estimated at $20,000 per acre; rangeland with at least 40 oaks per acre was worth 27 percent more than open land (Standiford 2000). Although coastal hardwoods have historically been treated as weeds, a hardwood timber products industry is emerging in California. The state's oak woodlands contain about 5 billion cubic feet of wood valued at over $275 million. The 5.8 billion cubic feet of oaks in nearby California timberlands are worth over $500 million for forest products alone. If the oaks and possibly other species in the Eastern deciduous forests prove susceptible to the pathogen, the potential threat to commercial timber production in the United States is in excess of $30 billion.

Foliar hosts are distributed among about 14 plant families. Some, such as Rhododendron and Camellia, are important in the horticultural industry. During 1997, about 14.2 million potted florist azaleas *(Rhododendron* spp.) valued at $48.3 million were produced in the United States. This does not include nursery azalea and rhododendron production (USDA National Agricultural Statistics Service, 1997 Floriculture Crops Summary; April 1998). Although *P. ramorum* does not always kill *Rhododendron* spp., the presence of the disease will significantly affect volume of movement in the trade. The coniferous foliar hosts, including coast redwood, Douglas-fir, and grand fir, have significant economic value.

Some other foliar hosts are also economically significant. The foliage of *Vaccinium ovatum*, used as browse by elk, is also harvested for use in floral arrangements. In the 1970s, an estimated $1 million worth of foliage was harvested annually in western Washington (Minore 1972). The genus includes the commercially important blueberries and cranberries.

Environmental Impact: Heavy loss of oaks, or of related susceptible genera, due to *P. ramorum* infection could result in significant ecological effects, including changes in forest composition, loss of wildlife food and habitat, increased soil erosion and a significant increase in fuel loads in heavily populated urban-forest interfaces. *Quercus* spp. are considered the most important and widespread of the hardwood trees in the North Temperate Zone, with about 300 species (Pavlik et al. 1991). Oaks are widespread across North America and Eurasia, extending south in tropical mountains to Cuba, Colombia, northern Africa, and Indonesia. In California, oak woodlands yield important benefits, including water and watershed protection, grazing, wildlife food and habitat, recreation, and wood products (Thomas 1997).

Many of the foliar hosts of *P. ramorum* have ecological significance. *Rhododendron* spp. occur worldwide, and some species in the United States are currently listed under the Endangered Species Act. *Vaccinium ovatum*, native to British Columbia, Washington, Oregon and California (Halverson 1986), is a prominent component of California and Oregon forests dominated by tanoak, canyon live oak and Pacific madrone (Sawyer et al. 1977). *Vaccinium* spp. are widely distributed throughout Europe, Asia, and North America; more than 40 species occur in North America.

Control: No control measures are known. The efficacies of various fungicides are being tested (Garbelotto and Rizzo 2001, Garbelotto et al. 2002b). Some protective fungicides have provided control of dieback of ericaceous plants caused by other species of *Phytophthora* (Hoitink et al. 1999).

DETECTION AND IDENTIFICATION

Symptoms: The more common symptoms on known hosts are summarized in the Hosts section. On oaks and tanoak, infection results in cankers and tree mortality. On other hosts, infection typically results in leaf lesions and stem dieback. Diseased tanoaks and oaks exhibit symptoms that include crown dieback, stem bark lesions or cankers, and tarry, reddish to dark brown exudations characteristic of a Phytophthora root and collar rot. On tanoaks, infection of the terminal twigs can lead to tip dieback, leaf flagging, or the formation of shepard's crooks. The exudations do not always develop on tanoak, especially on smaller diameter branches. The cankers are typically found on the lower portion of the trunk, but may occur to 12 feet or higher. Cankers do not extend into the roots below the soil line (Davidson et al. 2003). Branch cankers, especially on tanoak, also occur. Infected hosts often appear to die suddenly, with crowns turning from apparently healthy green to yellow-green to brown within a few weeks (Swiecki 2000).

Symptoms on foliar hosts vary (Davidson et al. 2003, McPherson et al. 2000). See www.suddenoakdeath.org and Davidson et al. 2003 for illustrations of symptoms on various hosts. Symptoms on Rhododendron in Europe are similar to those caused by other species of *Phytophthora* associated with above ground shoot dieback (Benson and Hoitink 1986). On Pacific madrone, the pathogen causes leaf lesions and cankers on small branches. Infection of coast redwood, Douglas-fir, and grand fir results in leaf lesions and branch dieback. Epicormic sprouts of coast redwood die back and eventually are killed.

Morphology: Colony characteristics and gametangial morphology are described by Werres et al. (2001). Large (22 to 72 µm), mostly terminal, chlamydospores are distinctive. Sporangia are semi-papillate and deciduous. The molecular sequence at the ITS region is unique (Davidson et al. 2003).

Testing Methods for Identification: The pathogen can be isolated from bark lesions, and has been recovered from soil around symptomatic hosts using pear and young rhododendron leaves as baits (Davidson et al. 2000). Samples of inner bark (phloem) tissue from outer edges of necrotic lesions may be washed in running water and plated directly onto a selective medium (Erwin and Ribeiro 1996) and incubated at 18^{o}C in the dark (Davidson et al. 2003). Isolation from foliage and branches is similar, with pieces of tissue from margins of the lesion or canker being plated. Molecular diagnostic tests based on PCR technology have been used successfully in California and Oregon (Davidson et al. 2003).

MEANS OF MOVEMENT AND DISPERSAL

Nursery stock (coast live oak, tanoak, huckleberry, and cultivars of *Rhododendron* spp. and *Camellia* for example) and infested green waste are the most likely means of long-distance transport of the pathogen. The pathogen has been recovered from splashed rainwater, soil, and soil litter (Davidson et al. 2002) and thus is capable of local or long distance spread in soil and water. *Phytophthora ramorum* was recovered from soil carried on hikers shoes during spring rainy periods (Tjosvold et al. 2002). Oospores and chlamydospores of other *Phytophthora* species are long-lived and capable of survival in soil and dead host tissues under adverse conditions (Erwin and Ribeiro 1996). Little is known about survival of the pathogen in bark used as mulch. Preliminary trials (Garbelotto, unpublished) indicated that composting of wood chips, branches and California bay leaves for two weeks, with temperatures ranging from 45 to 60^{o}C, eliminated *P. ramorum*.

The current status of intra- and interstate movement of unprocessed oak and tanoak materials, and of nursery grown *Rhododendron* spp., *Vaccinium ovatum*, and species of *Camellia* from infested areas in California has been largely undocumented. State regulations of California and Oregon, and Federal regulations, restrict and limit intra- and interstate movement of infested material.

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