Recovery Plan

for

Scots Pine Blister Rust

caused by

***Cronartium flaccidum* (Alb. & Schwein.) G. Winter and *Peridermium pini* (Pers.) Lév.**
[syn. *C. asclepiadeum* (Willd.) Fr., *Endocronartium pini* (Pers.) Y. Hiratsuka]

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This recovery plan is one of several disease-specific documents produced as part of the National Plant Disease Recovery System (NPDRS) called for in Homeland Security Presidential Directive Number 9 (HSPD-9). The purpose of the NPDRS is to insure that the tools, infrastructure, communication networks, and capacity required for mitigating impacts of high-consequence, plant-disease outbreaks are in place so that a reasonable level of crop production is maintained.

Each disease-specific plan is intended to provide a brief primer on the disease, assess the status of critical recovery components, and identify disease management research, extension, and education needs. These documents are not intended to be stand-alone documents that address all of the many and varied aspects of plant disease outbreak and all of the decisions that must be made and actions taken to achieve effective response and recovery. They are, however, documents that will help USDA guide further efforts directed toward plant disease recovery.

Executive Summary

Scots pine blister rust (caused by the fungi *Cronartium flaccidum* and *Peridermium pini*) infects many Eurasian pines including *Pinus sylvestris* (Scots pine), *Pinus pinaster*, *P. pinea*, *P. halepensis*, *P. mugo*, and *P. nigra* (Austrian pine). *Cronartium flaccidum* completes its life cycle alternating between pines and various kinds of seed plants; the related *P. pini* spreads directly from pine to pine. Scots pine blister rust is widely distributed across Eurasia. It is most severe on Scots pine and several Mediterranean pines.

Susceptibility of species and populations of native North American pines to Scots pine rust is mostly unknown at this time. *Pinus resinosa* (red pine), which is closely related to known hosts, should be considered a potential pine host. However, if this rust has or gains the capacity to infect North American pines, the economic and ecological impact would be incalculable. For example, it has cost over 1 billion in current US dollars to control white pine blister rust (caused by *C. ribicola*) since its introduction into North America in the 1900s, and this disease has caused much greater losses in forest productivity and ecological impacts.

Scots pine is one of the most widely distributed conifers in the world. It grows naturally from Scotland to the Pacific Ocean and from the Arctic Circle in Scandinavia to the Mediterranean Basin. Scots pine has been widely planted in colder regions of North America, and is naturalized in the US Northeast, Midwest, and Pacific Northwest. It is planted for erosion control and as an ornamental and is also harvested for pulp and timber. However, its current economic value is primarily as a Christmas tree crop. According to the United States House of Representatives records, the total value of the United States Christmas tree industry in 2005 was $1.4 billion, of which Scots pine is estimated to be between 20-30% of the Christmas tree market.

Trees of different ages and sizes can be affected by Scots pine blister rust. Symptoms of Scots pine blister rust (or resin-top disease) in pine include stem swelling, branch flagging, excessive pitch flow, and top-kill and, in alternate hosts, leaf spots and stem distortion. The rust is primarily spread by windborne spores and requires a live host for infection. However, infective spores may be carried on plant material and infected plants can be non-symptomatic. Early detection and diagnosis is difficult but can be improved by the use of molecular techniques.

Although Scots pine blister rust is widespread in Eurasia, it has not been found in North America. The disease has long been a major factor in reducing forest productivity in Europe. The safest policy would be to prohibit importation of the rust's pine and non-pine hosts into North America. If host plants were imported, a thorough visual inspection for signs and symptoms of Scots pine blister rust should be conducted. Early detection of Scots pine blister rust at port facilities can provide some defense against introduction. However, non-symptomatic

infections in this slow-developing disease could easily be overlooked by visual inspections, so out-plantings should be monitored for several years. Further diagnostic techniques, such as microscopy and DNA sequencing, can be used to confirm rust infection and identity in symptomatic plants.

Recommendations

- **Ban importation of Scots pine living trees/seedlings for nursery trade; allow importation of known angiosperm alternate hosts only if dormant and leafless.**
- **Determine potential susceptibility of pine hosts of Scots pine blister rust in North America.**
- **Establish a monitoring system for Scots pine blister rust and other invasive rust species, especially in tree nursery and Christmas tree farm settings at likely points of ingress.**
- **Develop more effective molecular diagnostic techniques to detect and identify *C. flaccidum* and *P. pini* at the species, subspecies, and population levels.**
- **Develop prediction models of potential spread of Scots pine blister rust based on distribution of suitable hosts combined with climate models.**
- **Improve education to raise awareness about potentially invasive rust pathogens among plant diagnosticians, extension agents, forest managers, nursery growers, Christmas tree growers, horticulturalists, and the general public.**
- **Conduct genetic analyses of Scots pine blister rust as well as known and potential hosts of Scots pine blister rust to predict potential invasive risk in North America.**

Scots Pine Blister Rust
Caused by
Cronartium flaccidum and *Peridermium pini*

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I. Introduction

Geographic distribution of Scots pine blister rust

The causal agent of Scots pine blister rust (or resin-top disease; top-dieback of pine) is *Cronartium flaccidum* (Alb. & Schwein.) G. Winter. The sexually reproducing form of Scots pine blister rust, *C. flaccidum,* completes its life cycle alternating between pines of the subgenus *Pinus* and seed-plants of various families. Scots pine blister rust is also caused by a form of the rust that spreads directly from pine to pine and is named, *Peridermium pini* (Pers.) Lév.

Scots pine blister rust infects many *Pinus* species in Europe and Asia. *Cronartium flaccidum* causes sever damage on *P. sylvestris* (Scots pine) in northern Finland while in southern Europe *C. flaccidum* is reported on Scots pine, *Pinus pinaster* Ait., *P. pinea* L., *P. halepensis* Mill., *P. mugo* Turra, *P. pumila* Reg. and *P. nigra* Arn. (Austrian pine) in natural forests. Scots pine and Austrian pine are commonly planted in North America and needle symptoms have been reported on other two needle pines that occur in United States after artificial inoculations or exposure to natural inoculum (Raddi and Fagnani 1978). *Cronartium flaccidum* alternate (telial) hosts are in the angiosperm families Gentianaceae, Balsaminaceae, Loasaceae, Paeoniaceae, Tropaeolaceae, Verbenaceae, Apocynaceae, Orobanchaceae and Acanthaceae.

Scots pine blister rust is widely distributed across Europe and Asia. It is most severe on Scots pine and several Mediterranean pines. Infested countries include Austria, Armenia, Azerbaijan, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Great Britain, Greece, Hungary, Italy, Kosovo, Lithuania, Macedonia, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russia (European to Far East), Serbia, Slovakia, Slovenia Spain, Sweden, Switzerland, and Ukraine. In eastern Asia, a rust referred to as Scots pine blister rust is found in China (Heilongjiang,

Jiangsu, Jilin, Liaoning, Sichuan, Yunnan, and Zhejiang provinces), Japan, and Korea.

Geographic distribution of Scots pine

Scots pine (sometimes called Scotch pine) is one of the most widely distributed conifers in the world. Its native range extends from Great Britain and Spain east through Siberia, south to the Caucasus region and north to Lapland. Scots pine has been widely planted in New Zealand and the colder regions of North America. It is naturalized in the US Northeast, Midwest, and Pacific Northwest. Scots pine is the only pine native to northern Europe and once formed much of the Caledonian Forest of the Scottish Highlands. In its northern distribution, it ranges from sea level to 3000 ft; in its southern distribution, Scots pine is a high-elevation tree growing at altitudes from 4000 to 8500 ft.

Trees can typically attain a height of 80 ft, diameter in excess of 3 ft, and age of 200 years or, exceptionally, a height of 150 ft, diameter of 5½ ft, and age of 700 years. Scots pine requires full sun to establish from seed and quickly invades disturbed areas.

In the United States, Scots pine has been planted for erosion control and as an ornamental and also harvested for pulp and timber; however, its primary economic value is currently for Christmas trees (Agricultural Marketing Resource Center 2008), although other conifers are more recently favored.

Nomenclature/Taxonomy of Scots pine blister rust

The rust fungi (Basidiomycetes: Uredinales) are a large, diverse group of fungi that reproduce only in living plant tissue. Among the many important plant pathogens in this group are the pine stem rusts *Cronartium* and *Peridermium*. The taxonomy of Scots pine blister rust has been particularly confusing, owing to a relationship between the host-alternating *C. flaccidum* and pine-to-pine *P. pini*. Foresters and mycologists have long recognized the similarity of the diseases caused by these fungi and the morphology of their spore production on infected pine stems. The chief difference between the pine-borne spores of the two fungi is their infection of seed-plants vs. pines. Hiratsuka (1968) reported developmental differences in spore germination (and life cycle) which prompted him to name the pine-to-pine form as *Endocronartium pini*. However, molecular evidence points to a very close evolutionary relationship between these rusts (e.g., Vogler and Bruns 1998). Hantula et al. (2002) provides morphological and molecular evidence demonstrating Scots pine blister rust as a single species with alternative life cycles. In this review, we refer to the rust without distinction for life cycles as Scots pine blister rust, as *C. flaccidum* for the host-alternating form, and as *P. pini* for the pine-to-pine form.

II. Symptoms

Scots pine blister rust infects a host pine through needle stomata, but symptoms only become apparent later in development in the branch and main stem. In the

pine, the fungus produces several kinds of reproductive structures seen as either tiny sacs of a sugary "nectar" with spermatia or small, white bladders (Figure 1) filled with powdery, orange-colored spores, aeciospores. Diseased branches become swollen; and after release of the aeciospores, the bark cracks, darkens, and the end of the branch is killed (Figure 1). The fungus in a main stem can also produce spermatia and aeciospores, but the disease appears first as a diamond-shaped, resinous canker that eventually girdles the stem and kills the upper crown. Insects carry the spermatia to other diseased pines and aid in fertilization; the aeciospores develop several years later, released in summer, and carried by the wind for long-distances to infect a suitable host. The fungus grows downward in a pine stem several inches per year. Small trees are killed within several years of infection; larger trees are often infected in the middle of the crown so if not killed by a girdling, resinous canker, an infected tree may persist for many years with a dead top (hence "resin-top disease").

Figure 1. Symptoms of *Cronartium flaccidum* on Scots pine (*Pinus sylvestris*) (Photo by Risto Jalkanen)

III. Spread

Although natural spread of Scots pine blister rust is principally by aerial dispersal, there are important differences for the two rust forms which infect either directly pine-to-pine or through an alternate host. Infection of a pine by *C. flaccidum* results eventually in production of a specialized structure (spermogonia) which mediates cross-fertilization (genetic exchange) by transfer of insect-vectored spermatia to the receptive hyphae of a different rust infection. Fertilized hyphae during the late spring through summer form a blister-like aecia with yellow-pigmented, thick-walled aeciospores that aerially disseminate the rust to the alternate host. Although most dispersal is likely limited within several miles

and mostly closer, a small proportion of spores may be carried hundreds of miles from the parental canker. The spore stage produced on the alternate host, uredinia with urediniospores (Figure 2), increases infection on both the same and different alternate host plants so there is some further rust dispersal but more importantly a large, nonsexual amplification of inoculum. At summer's end, another spore stage is produced (see appendix for detail on life cycle). In the following spring, the final spore stage is a basidiospore that is ejected into the air and dispersed by the wind. Since this spore is delicate, it is usually dispersed less than several miles (usually much less). If a viable spore impacts a pine needle, germinates, grows into the needle (usually through a stomata), and avoids a resistance response by the host, the pine is infected. Although a description of the sexual process in the pine-to-pine form (*P. pini*) is subject to disagreement, the initial stages resemble that of the spermogonia and aecia with the difference that the aeciospores infect a pine host without the intermediate stages on alternate hosts.

Alternate hosts of Scots pine blister rust are in diverse angiosperm families and genera. In Scandinavia, the genera *Loasa, Nemesia, Melampyrum, Tropaeolum, Vincetoxicum, Pedicularis* and *Paeonia* (Kaitera et al. 1999) are all reported as alternate hosts. Kaitera and Nuorteva (2003) reported that *C. flaccidum* produces uredinia and telia on *Melampyrum nemorosum* and on Finnish *Vincetoxicum hirundinaria*. In Europe, evidence is growing that *C. flaccidum* commonly spreads on other alternate hosts in the cow-wheat family of herbaceous plants (*Melampyrum* spp.) (Kaitera et al. 2005). Newly described hosts within the *Melampyrum* genus are *M. pretense*, *M. nemorosum*, and *M. arvense*. Alternate hosts already known are Swallow-wort (*V. hirundinaria*) (Figure 2) and small cow-wheat (*M. sylvaticum*).

Figure 2. Urediniospores of *Cronartium flaccidum* on Swallow-wort (*Vincetoxicum hirundinaria*) (Photo by Glasdia von C.v.Tubeuf).

IV. Monitoring and Detection

Although widespread in Eurasia, Scots pine blister rust has not been found in North America. Thus, exclusion of these pathogens is the first line of defense.

This will require effective monitoring and detection procedures. Based on past introductions of plant pathogens, importation of infected primary or alternate host material represents the most likely pathway of introduction. Host material, such as whole plants or leaf and stem tissue from the host plants listed above, represents the highest risk for harboring the pathogen. Japanese black pine (*P. thunbergii*), mugo pine (*P. mugo*) or other 2 or 3 needled pines, commonly used for bonsai, pose a significant risk if imported as whole plants.

Scots pines in each region of the U.S. should be routinely monitored in order to detect Scots pine blister rust outbreaks. State departments of Agriculture should be requested to include Scots pine blister rust in their pests of special interest during their inspections of nurseries and Christmas trees. State, federal, and private organizations should be requested to inspect for Scots pine blister rust in Scots pine forest product and resource conservation plantings. These requests should be accompanied by descriptions of the disease (symptoms, signs, biology), a sampling protocol, and a list of laboratories equipped to provide proper identification of the pathogens. The USDA APHIS - Cooperative Agricultural Pest Survey Program (http://www.aphis.usda.gov/plant_health/plant_pest_info/pest_detection/pestlist.shtml) and Forest Service - Forest Health Monitoring Program (http://fhm.fs.fed.us/) should collaborate with state departments of Agriculture for monitoring and detecting Scots pine blister rust.

Early detection of Scots pine blister rust at port facilities represents the first and best defense against introduction. The safest policy would be to prohibit the importation of primary and alternate host plants and plant parts into North America; however, the importation of host plant seed would represent virtually no risk for this pathogen.

If host plants were imported, they should be subject to quarantine procedures for 4 or 5 years because symptoms and signs may not be expressed before that time. A thorough visual inspection of signs and symptoms of Scots pine blister rust should be conducted under a controlled environment (i.e., a biological containment greenhouse or a type II biological safety hood). Primary host symptoms on pine include fusiform-shaped swelling and/or resinosis of stem or branches and yellow flecking of needles. Primary host signs include sticky yellow spore nectar or yellow-orange pustules on the stem or branches and powdery yellow-orange spores. Symptoms on alternate, angiosperm hosts include small spots (1–4 mm across) of yellow or lighter green than surrounding tissues on the underside of leaves. Alternate host signs include orange pustules (uredinia) or hair-like fungal structures (telia) protruding from the underside of leaves. Visual diagnoses can be made with a hand lens or dissecting microscope; however, signs and symptoms may be latent for 3 to 4 years in infected pine host material, and up to a month in leafy hosts. Non-symptomatic infections could be overlooked by visual inspections, especially upon arrival of recently infected materials.

Further diagnostic techniques, such as microscopy and DNA sequencing can be used to ensure rust species identification. Morphological characters can be used to determine genus and PCR (polymerase chain reaction) followed by DNA sequencing can determine species. DNA extracted from spore or leaf material or, in some cases, infected leaf material can be used for PCR analysis. Perhaps other diagnostic methods will be derived from rapidly developing, high-throughput DNA sequencing technologies.

V. Response

The response to all plant health emergencies in the United States is under USDA-APHIS-Plant Protection and Quarantine's authority delegated by the Secretary of Agriculture under the Plant Protection Act of 2000.

After a detection of *C. flaccidum* has been confirmed by a USDA-APHIS-PPQ recognized authority, APHIS, in cooperation with the appropriate state department(s) of agriculture, is in charge of the response. The response will begin with an initial assessment. For a nursery site, the Rapid Assessment Team (RAT) consisting of state and federal *Cronartium* experts and regulatory personnel may be deployed on-site to take additional plant, soil, and water samples in order to conduct epidemiological investigations and to initiate environmental delimiting surveys outside the nursery grounds. Possible actions include quarantines of infested or potentially infested production areas, prohibiting movement of infected or potentially infected articles in commerce, host removal and destruction, requiring adherence to sanitary practices and the application of registered fungicides and disinfectants. Trace forward and trace back surveys would be needed at locations sending or receiving potentially infected nursery stock to/from the confirmed nursery. APHIS imposes quarantines and regulatory requirements to control and prevent the interstate movement of quarantine-significant pathogens or regulated articles (high risk host material), and works in conjunction with states which impose actions parallel to APHIS regulatory actions to restrict intrastate movement. The Rapid Assessment Team will also attempt to ascertain if the introduction was intentional or accidental. If the organism in question is a select agent covered under the Agricultural Bioterrorism Act of 2002, federal and local law enforcement may be involved in the initial assessment to determine if a bioterrorism event or biocrime event has occurred.

The USDA-APHIS-PPQ response will also depend on where *C. flaccidum* is found (forest, plantation or nursery) and how widespread it is based on the initial assessment by the Rapid Assessment Team and associated delimitation surveys. If *C. flaccidum* is found in a pine plantation, attempts will be made to eradicate the pathogen through several measures including plant destruction/eradication, soil/surface dis-infestation, trace-forwards, and trace-backs similar to management of *P. ramorum* in the United States. The practicality of eradication in

a forest setting will be assessed by the Rapid Assessment Team and a technical working group of *Cronartium* experts and a recommendation will be made as to the potential for eradication of the infestation on a case by case basis.

VI. USDA Pathogens Permits

USDA, APHIS, PPQ permits for plant pests and biological control organisms, falls under the authority of the Plant Protection Act, codified under 7 CFR 330. A PPQ 526 Permit is required for importation and interstate movement of all plant pests and infected plant materials, including diagnostic samples, regardless of their quarantine status. The receiving person must have the permit. No separate permit is required for host material if the host material is not intended for propagation. A PPQ 526 Permit is also required for importation and interstate movement of soil for the purpose of isolating or culturing microorganisms from the soil.

Information on PPQ 526 Permits can be found at: www.aphis.usda.gov/plant_health/permits/organism/index.shtml. Applicants may also call PPQ Permit Services at (301) 734-0841, Toll Free (866)524-5421 or e-mail Pest.Permits@aphis.usda.gov.

USDA, APHIS, PPQ permits, notifications and registrations for plant-specific select agents or toxins falls under the authority of the Plant Protection Act and the Agricultural Bioterrorism Protection Act, codified under 7 CFR 330 and 7 CFR 331. Entities that possess, use or transfer select agents or toxins deemed a severe threat to plant health or products must notify and register with USDA, APHIS.

Information on registrations can be found at: http://www.aphis.usda.gov/programs/ag_selectagent/. Forms can be found at the National Select Agent Registry at: www.selectagents.gov. The list of select agents and toxins deemed a severe threat to plant health is published under 7 CFR 331, and is included in the list of select agents at www.selectagents.gov/agentToxinList.htm. Applicants may also call APHIS at (301) 734-5960 or e-mail agricultural.select.agent.program@aphis.usda.gov.

VII. Economic Impact and Compensation

Economic impacts are difficult to estimate and depend on the pathway of introduction and capacity of the introduced pathogen to infect native plant species. If the only hosts of Scots pine blister rust in North America are Eurasian pine species, then the greatest economic impacts will be to nurseries and Christmas tree plantations that grow Scots pine. Restrictions to moving potentially infected hosts and eradication of infected material in nurseries and Christmas tree farms could cause enormous economic losses amounting to millions of dollars. According to the National Christmas Tree Association Scots pine is the most planted commercial Christmas tree in North America. In 2002,

Oregon, North Carolina, Michigan, Pennsylvania, Wisconsin, Washington, New York and Virginia were the top Christmas tree producing states. Most Scots pine is grown primarily in the Lake States, with Michigan as the top producer of Christmas trees in 1998. Scots pine is one of the top five species of Christmas trees sold in the United States though it is difficult to obtain an exact value for the Scots pine market. According to the United States House of Representatives (2007), the total value of the United States Christmas tree industry in 2005 was $1.4 billion, of which Scots pine was estimated to be between 20–30 % of the Christmas tree market.

A worse-case scenario would be if this rust has or gains the capacity to infect North American pines. There is some indication that *P. resinosa* (red pine) can act as a host (Raddi and Fagnani 1978). In addition, phylogenetic analysis showed that red pine is genetically close to several pines that are susceptible to *C. flaccidum* (Gernandt et al. 2005). If potential hybridization with native rusts that also have broad and overlapping alternate host range is considered, a scenario of the rust acquiring pine hosts that are currently resistant may also be possible. If such a scenario occurred, the economic and ecological impact would be far greater.

VIII. Mitigation and Disease Management

After Scots pine blister rust is sufficiently established that eradication can not be accomplished, infested and threatened sites can be managed to mitigate impacts. Continued restriction of rust dispersal and colonization reduces further losses and the ability of the rust to adapt to its new environment. An understanding of rust impacts on trees, populations, communities, and ecosystems is also useful for rehabilitation. The immediate objective of mitigation and management is efficient and effective minimization of damage to natural systems and loss of resource value. Activities range from disease control tactics, such as pruning, to program strategies, such as adaptive environmental assessment and management. Successful mitigation and management are confronted with five principal issues: 1) long-distance, aerial dispersal of the rust, 2) multiple hosts of which many are unknown, 3) differing objectives of various managers, 4) a rust capable of both sexual and clonal reproduction, and 5) a rapidly changing environment due to climatic, ecological, and socioeconomic factors.

Disease control

The life cycle of Scots pine blister rust has vulnerabilities that can be exploited to prevent infection (enhancing host escape) or minimize disease damage (influencing pathogen–host compatibility). Control tactics for pine stem rusts in general include the use of chemicals for host protection, eradication or separation of alternate hosts from pine hosts, natural biological agents that reduce reproduction of the rust, and cultural management of host populations (silviculture) or individuals (arboriculture). Genetic manipulation has focused on selection, breeding, and deployment of hosts with greater resistance or tolerance.

Chemical controls of the pine stem rusts might be used to prevent infection, reduce delivery of inoculum, and eliminate lesion activity; however, few specific studies are reported for Scots pine blister rust. Controls tried include prophylactics to protect pines, salts and herbicides to kill alternate hosts, antibiotics to clear infections, and insecticides to control insect vectors (see appendix for details on chemical controls).

Control of pine stem rusts with biological agents has focused on rust canker-associated fungi that interfere with rust sporulation. Early work investigated *Tuberculina maxima*, which is a secondary fungus on cankers of many species of pine stem rust, including Scots pine blister rust but it has not proven to be effective. Recent attention has turned to *Cladosporium tenuissimum*, which acts as an antagonistic hyperparasite.

Cultural activities of tending and regenerating pines provide numerous opportunities to mitigate damage by Scots pine blister rust. Although management for stem rust must consider specific details of the pathosystem, general approaches developed for other *Cronartium* rusts and invasive species have potential relevance (for general review see Waring and O'Hara 2005). Potential disease problems can often be avoided with careful matching of site and tree selection. Because of suitable microclimate for the rust and proximity of an inoculum source, some sites pose a hazard sufficiently high that considerations should be given to alternative management objectives, use of non-host species, or use of host pines with proper, adaptive traits (e.g., greater resistance). Kaitera and Nuorteva (2008) observed variation in Finland for susceptibility to infection by Scots pine blister rust by host provenances (interacting with rust source and weather). In their study, lodgepole pine (*Pinus contorta,* native to North America) was not infected. Raddi and Fagnani (1978) also noted differences in susceptibility of Italian pines and some resistance in ponderosa pine (*Pinus ponderosa,* native to North America).

Whether thinning to improve stand growth or remove diseased trees (sanitation or salvage) can mitigate disease loss depends on numerous factors. Kaitera (2002) observed that thinning Scots pine did reduce infection over that in unthinned plots, but year-to-year variation was high in both treatments. Such results should not be unexpected since thinning affects microclimate to increase foliage drying and thereby decrease spore germination. Thinning also increases spore dispersal into a stand, alternate host persistence, and wounding (an infection pathway). Generally, thinning, fertilization, and augmentation with mycorrhiza is considered beneficial to stand growth; however, these activities could potentially increase rust by increasing susceptible tissue. As with species preference, thinning effects on rust impacts cannot be simply predicted.

Pruning can remove infected branches before the rust enters the trunk, remove branches that may later become infected and lead to lethal trunk cankers, and improve wood quality as knot-free timber. In some situations, trunk cankers can

be excised, rendered inactive by chemical or biological agents, and/or contained over time through host resistance reactions. Since pruning and individual canker treatments are labor-intensive and time-sensitive activities, the economics of treatment are important in determining whether the control is practical for saving individual trees since significant reduction in inoculum should not be expected.

Although eradication of the alternate host has been effective for mitigating impacts of other rusts in certain regions, host eradication is generally not practical for Scots pine blister rust. The host range is large, diverse, and includes the pine itself in northern regions. Nonetheless, reducing the proximity of the host to alternate hosts can reduce but not eliminate infection. Genetic control tactics can be effective for future generations and be implemented as simply as favoring less-diseased trees for reproduction or as elaborately as outplanting seedlings from resistant parents. Variation by provenance in Scots pine to blister rust infection has been reported by Kaitera (2003); some cultivars of alternate host species are immune. Selection in natural stands or breeding programs can increase the frequency of resistance in the host, but the potential for rust evolution must be considered. Design and monitoring a genetic control tactic should therefore consider the several host–pathogen interactions of resistance, virulence, tolerance and aggressiveness. Hybridization or genetic exchange among different rusts or hosts can also affect the ability to reproduce or sustain disease (Brasier 2001). Although resistance-breeding programs (e.g., Murray 1964) are expensive due to management and associated research costs, they can provide not only improved seed but also valuable genetic information (Kinloch 1972). Federal cooperative genetic tree-improvement programs at several locations are currently addressing several pine stem rusts other than Scots pine blister rust.

Disease control tactics should be employed in a strategic context. Given the complexity and uncertainty of mitigating Scots pine blister rust and managing infested ecosystems for a novel disturbance, adaptive management is especially appropriate (U.S. Department of Interior 2007). Decisions over control (and monitoring) of pine stem rusts are frequently made with use of rust hazard models that typically provide landscape or stand projections of infection likelihood, incidence, or damage severity (e.g., Van Arsdel et al. 1961).

Risk management

Even during the phase of mitigation and management, it will be important to identify risk factors and consider alternative outcomes of treatment. The epidemiology and damage from Scots pine blister rust varies in space and time due to differences in climate, soil type, stand age, host species, growth, genetics, and other unknown factors (Murray et al. 1969, Greig 1987, Kaitera and Jalkanen 1995).

Risk management techniques (see U.S. EPA 2003, Lovett et al. 2006) provide procedures to incorporate complexity and uncertainty into hazard maps and simulation models. For example, a regional map of expected distribution of white

pine blister rust (*C. ribicola*) based on synoptic climate, a lake effect, and alternate host distribution was developed by Van Arsdel et al. (1961). McDonald et al. (1981) developed an epidemiological simulation model for blister rust that projects growth and mortality of white pine within infested stands and considers the abundance of hosts, climate, and site productivity. Maps and models such as these are useful where many complex factors must be considered in selecting a disease management regime.

Typically, rust-hazard assessment has been based on environmental and demographic processes without regard for evolutionary (i.e., genetic) interactions. The outcome of these interactions; however, can have profound effects on the naturalization of an introduced pathogen and the condition of the affected ecosystem (see Parker and Gilbert 2004). An uncertain risk that increases the difficulty in planning mitigation is the potential for a pathogen to shift to a new host. *Pedicularis* is one of several genera of flowering plant that include alternate host species of Scots pine blister rust. Although the susceptibility to Scots pine blister rust has not been determined for many species of *Pedicularis* endemic to North America, they are known hosts of other pine stem rusts and therefore potential hosts of Scots pine blister rust as well. The risk is not that our populations of *Pedicularis* (or other alternate hosts) would be jeopardized, but that they support an inoculum source to infect pine and serve as the alternate host for a hybrid rust. The North American pines which are potential hosts of Scots pine blister rust are also hosts of other, native pine stem rusts. Cross-fertilization of another Eurasian pine stem rust and a North American stem rust has been observed in several locations (Joly et al. 2006), but no alternate host has been reported for this rust hybrid combination. If Scots pine blister rust were established in North America, there would be ample opportunity for successful hybridization; but its consequences are not predictable (see Brasier 2001).

IX. Infrastructure and Experts

USA

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X. Research, Extension, and Education Priorities

Research Priorities

Many questions remain about the ecological behavior of *C. flaccidum* and *P. pini* within its native range. Although these pathogens have been reported in eastern Asia, comparatively little is known about these pathogens there compared to those in Europe. Because *C. flaccidum* and *P. pini* likely have great genetic variation across their native ranges, research is needed to develop effective molecular diagnostic techniques to identify these pathogens at the species, subspecies, and population level. Pathogen characterization is the initial step needed to assess variation in life cycle, host ranges, and environmental requirements so that geographic areas and host species at risk can be better predicted. Predicting actual impacts on potential hosts is a formidable task because of potential influences of host/pathogen genetic structure and the interaction of environment on virulence/resistance reactions.

Management of rust diseases often relies on resistance breeding programs. Biological control also offers promise toward managing *Cronartium flaccidum* and *Peridermium pini*; therefore, continued research efforts are need to identify biological control agents and associated techniques.

Most Important

- **Conduct phylogeographic analysis of Scots pine blister rust across its native range relative to its genetic diversity.**
- **Determine the host range and environmental requirements for each genetic group of Scots pine blister rust.**
- **Conduct phylogenetic analysis of known and potential hosts of Scots pine blister rust.**
- **Develop prediction models of potential spread of Scots pine blister rust based on distribution of aecial and telial hosts combined with present and future climate models.**
- **Conduct phylogenetic analysis of Scots pine blister rust and other pine stem rusts present in North America (e.g., *C. arizonicum*, *C. coleosporioides*, *C. comandrae*, *C. ribicola*, and *P. harknessii*).**
- **Use inoculation tests in infested countries to determine potential aecial and telial hosts of Scots pine blister rust in North America.**

Highly Important

- **Assess potential sources of resistance in aecial host populations of North America.**
- **Begin assessments of potential biological control agents.**

Needs Evaluation

- **Evaluate potential genetic information and assess status of germplasm collections for diverse geographic sources of potential pine hosts in North America.**
- **Establish sentinel tree plantings in areas with Scots pine blister rust to establish a baseline for genetic screening.**

Extension Priorities

Rust pathogens are difficult to identify based on morphology and symptoms. Periodic surveys of rust on aecial and telial hosts should include sensitive (e.g., DNA-based) diagnostic tests to identify rust pathogens, their hosts, and distribution.

The following items need to be developed:

- **Cooperate with National Plant Diagnostic Network (NPDN) to develop tree rust diagnostic tools that accurately identify rust pathogens.**
- **Conduct surveys of potential aecial and telial hosts using DNA-based diagnostic tests to identify rust pathogens.**
- **Develop means to help prevent the introduction/spread of Scots pine blister rust via movement of aecial and telial hosts.**
- **Develop education materials describing the threat and the disease (symptoms, signs, biology).**

Education Priorities

- **Educate plant pathologists, plant health professionals, extension agents, forest managers, nursery growers, Christmas tree growers, horticulturalists, general public, etc. about potentially invasive rust pathogens.**
- **Develop targeted education programs directed toward areas that may be at high risk for Scots pine blister rust such as Christmas tree growers or horticultural nurseries.**
- **Master Gardener program and other relevant existing outreach programs to educate stakeholders about Scots pine blister rust and other potentially invasive rust tree pathogens.**

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Web Resources

The Peridium (http://www.rms.nau.edu/rust/)

The Whitebark Pine Ecosystem Foundation (http://www.whitebarkfound.org/book.htm)

The Minnesota Tree Improvement Cooperative projects on white pine blister rust research at http://www.cnr.umn.edu/FR/research/centcoop/mtic/wpine.html

British Columbia Ministry of Forests, Forest Practices Code, Pine Rust Management Guidebook (http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/PINESTEM/PINE-TOC.HTM).

High Elevation White Pines (http://www.fs.fed.us/rm/highelevationwhitepines/)

Appendix

I. Introduction

Pine taxonomy follows Price et al. (1998)

Pine aecial hosts of *C. flaccidum*
***Pinus sylvestris* (Scots pine) – temperate**
***P. pinea* (Italian stone pine) – Mediterranean region**
***P. mugo* (Mountain pine) – Alps and to south and east**
***P. nigra* (Austrian pine) – Mediterranean region**
***P. nigra* subsp. *laricio* (Laricio pine) – Mediterranean region (syn. *P. nigricans P. austriaca*)**
***P. pinaster* (Maritime pine) – Mediterranean region**
***P. halepensis* (Aleppo pine) – Mediterranean region**
***P. densiflora* – Japan**

Angiosperm telial (alternate) hosts of *C. flaccidum*
Melampyrum sylvaticum
Pedicularis
Vincetoxicum hirundinaria
Paeonia
Grammatocarpus
Impatiens
Loasa
Nemesia
Tropaeolum
Verbena

III. Spreads

Life cycle

Cummings and Hiratsuka (2003) describe the five spore stages of a typical *Cronartium* species that alternates between pine and angiosperm hosts.

Stage 0 – Spermogonium bearing spermatia.

> **Spermogonia are hermaphroditic structures containing female receptive hyphae and male spermatia. Spermogonia occur in the pine cortex under the host peridium and produce a sugary fluid attractive to insects. Monokaryotic haploid (N) spermogonium produce haploid, uninucleate spermatia which are small, thin-walled, and vary in shape from globose to flask-like. Spermatia are transferred by insects to another spermogonia where, following union with a receptive hypha, a dikaryotic (N+N) mycelium is produced that eventually bears aecia.**

Stage 1 – Aecium-bearing aeciospores.

Aecia develop in the cortex of a host pine and are often associated with hypertrophy of the stem. The aecium is an open cup surrounded by a prominent peridium and producing chains of binucleate, warty, thick-walled, pigmented aeciospores. When the aecium is mature the peridium ruptures and folds back to form an irregular collar around the aecium. Aeciospores are dispersed aerially and, following germination, produce a dikaryotic mycelium in angiosperm plant species that act as alternate hosts.

Stage 2 – Uredinium-bearing urediniospores

Like the aeciospores, the urediniospores are dikaryotic; however, the urediniospores are a repeating, non-sexual stage giving rise to a mycelium which may form additional uredinia or telia. The uredinium is subepidermal, dome-shaped, with a peridium, open pore, and sterile cells among the urediniospores. Urediniospores are spiny, borne individually, and aerially dispersed.

Stage 3 – Telium-bearing teliospores

The telium arises from the host epidermis and develops into an erumpent, hair-like column of dark, thick-walled teliospores embedded in a matrix. Teliospores are not dispersed but are the site of karyogamy and produce the metabasidia (2N) where meiosis occurs leading to formation of the basidiospores.

Stage 4 – Basidiospores

Basidiospores are globose, thin-walled haploid (N) spores attached to the metabasidium by a trigger-like stigma. They are discharged away from the telium and dispersed to a host needle or shoot. Basidiospores germinate to produce another generation of spermogonia.

Cummins and Hiratsuka (2003) describe the life cycle of *Peridermium pini* as endocyclic and justify their nomenclature of *Endocronartium pini*. In this case, spores which morphologically resemble aeciospores are produced on the pine host, dispersed, and directly infect other pines. Spermogonia may also be produced.

VIII. Mitigation and Disease Management

Disease control

Triadimefon has been demonstrated (Pitt et al. 2006) to be a useful prophylactic for white pine blister rust (*Cronartium ribicola*). Yao and Peixin (1991) report that application of Topsin® and triadimefon to a canker surface was effective in eliminating aecial sporulation of Scots pine blister rust in China. Salt spray can kill alternate hosts, but eradication was only practical in proximity to a pine

plantation. Maloy (1997) reviewed the history of control of *C. ribicola* in the United States, including aborted efforts with antibiotics and herbicides. Pappinen and von Weissenburg (1996) describe the role of the pine-top weevil wounding pine twigs and increasing rust infection. We are not aware of any studies on the effective use of insecticides to reduce insect vectors (carrying either spermatia or aeciospores).

Risk mapping of Scots pine blister rust

Currently, risk maps for Scots pine blister rust (*Cronartium flaccidum*) have been created by Jessica S. Engle and Roger D. Magarey (North Carolina State University, and USDA-APHIS-PPQ-CPHST-PEARL). The prediction model is based on a combination of pine density and incidence of perceived weather favorable for infection. However, caution is needed in interpreting this model because it is not based on potential pine hosts of Scots pine blister rust. Therefore, a further improved prediction model is needed to more precisely predict geographic areas at risk from *C. flaccidum* infection, which is based on more accurate hosts and climate data. The USDA Forest Service - Western Wildlands Environmental Threats Assessment Center and Forest Health Technology Enterprise Team are potential consultants for developing the risk map of Scots pine blister rust.

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