1   **Recovery Plan for Scots Pine Blister Rust Caused by *Cronartium pini***

2

3   Mee-Sook Kim,[1*] Jarkko Hantula,[2] Juha Kaitera,[3] Paul J. Zambino,[4] Stephen Woodward,[5]

4   Bryce A. Richardson,[6] Jane E. Stewart,[7] Pauline Spaine,[8] David C. Shaw,[9] Yu Takeuchi,[10] Ned

5   B. Klopfenstein[6]

6

7   [1]U.S.D.A. Forest Service, Pacific Northwest Research Station, Corvallis, OR 97331, U.S.A.

8   [2]Natural Resources Institute Finland, Latokartanonkaari 9, FI-00790 Helsinki, Finland

9   [3]Natural Resources Institute Finland, Paavo Havaksen tie 3, FI-90570 Oulu, Finland

10   [4]U.S.D.A. Forest Service, Forest Health Protection, Coeur d'Alene, ID 83815, U.S.A.

11   [5]University of Aberdeen, School of Biological Sciences, Aberdeen, Scotland, UK

12   [6]U.S.D.A. Forest Service, Rocky Mountain Research Station, Moscow, ID 83843, U.S.A.

13   [7]Colorado State University, Department of Agricultural Biology, Ft. Collins, CO 80525,

14   U.S.A.

15   [8]U.S.D.A. APHIS, PPQ-PHP-IRM, Plants for Planting Policy, Riverdale, MD 20737, U.S.A.

16   [9]Oregon State University, Department of Forest Engineering, Resources & Management,

17   Corvallis, OR 97331, U.S.A.

18   [10]North Carolina State University, Center for Integrated Pest Management, Raleigh, NC

19   27606, U.S.A.

20   *Corresponding author: M.-S. Kim; E-mail: meesook.kim@usda.gov

21

22   Keywords: invasive forest pathogen, National Plant Disease Recovery System, pine stem rust,

23   resin-top disease

Mee-Sook Kim
Plant Health Progress

24 **Table of Contents**

38

39   This recovery plan is one of several plant disease-specific documents produced as part of the

40 National Plant Disease Recovery System (NPDRS) requested by the Homeland Security

41 Presidential Directive Number 9 (HSPD-9). The purpose of the NPDRS is to ensure that the tools,

42 infrastructure, communication networks, and capacity required for mitigating impacts of high-

43 consequence, plant-disease outbreaks are implemented so that a reasonable level of crop production

44 is maintained.

45   Each plant disease-specific plan is intended to provide a brief summary of the disease,

46 assess the status of critical recovery components, and identify disease management research,

47 extension, and education needs. These documents are not intended to serve as stand-alone

48   documents that address all of the many and varied aspects of plant disease outbreaks, all of the

49   critical decisions that must be determined, or all of the actions needed to achieve effective response

50   and recovery. These plans are, however, documents that will help the USDA to guide further efforts

51   directed toward plant disease recovery.

52

53   **Executive Summary**

54   Scots pine blister rust caused by *Cronartium pini*, which includes the fungal rust pathogen

55   with either a heteroecious life-cycle (previously known as *Cronartium flaccidum*) or an

56   autoecious life-cycle (formerly known as *Peridermium pini* or *Endocronartium pini*), is capable

57   of infecting many Eurasian pines including *Pinus sylvestris* (Scots pine), *P. pinaster* (maritime

58   pine), *P. pinea* (Italian stone pine), *P. halepensis* (Aleppo pine), *P. mugo* (mugo pine), *P. nigra*

59   (Austrian pine or black pine), *P. brutia* (brutia pine or Turkish pine), *P. densiflora* (Japanese red

60   pine or Korean red pine), *P. radiata* (Monterey pine or radiata pine), *P. koraiensis* (Korean pine),

61   *P. massoniana* (Masson pine), *P. tabuliformis* (Manchurian red pine), *P. taiwanensis*

62   (Taiwan red pine), *P. pumila* (Siberian dwarf pine), *P. uncinata* (Swiss mountain pine), *P.*

63   *wallichiana* (Himalayan pine or Bhutan Pine), *P. takahasii*, and *P. yunnanensis* (Yunnan pine).

64   According to population genetic studies, the two forms of *C. pini* have not been differentiated by

65   presently available DNA sequencing analyses, likely because gene flow occurs between the two

66   forms. However, the aecia of the two forms of the rust pathogen differ in the heterozygotic state,

67   which can only be observed in the heteroecious form. The heteroecious form completes its life

68   cycle alternating between pines and various species of flowering plants (Angiospermae) (see

69   Table 2 for a list of alternate host species); the related autoecious form spreads directly from pine

70   to pine. Scots pine blister rust is widely distributed across Eurasia. The impact is most severe on

71   Scots pine and several Mediterranean pines.

72   Susceptibility of native North American pine species and populations to Scots pine blister

73   rust is mostly unknown at this time, although *P. radiata* and *P. ponderosa* (ponderosa pine) are

74   reported to be susceptible. *Pinus resinosa* (red pine), which is closely related to known hosts,

75   should be considered as a potential pine host. However, if the Scots pine blister rust pathogen

76   possesses or gains the capacity to infect North American pines, the economic and ecological

77   impacts could be quite significant, and the potential influences of climate change and other

78   environmental factors remain unknown. The direct cost to control white pine blister rust (caused

79   by *C. ribicola*) since its introduction into North America during the early 1900s has been

80   estimated at over 1 billion in current US dollars, and this disease has caused much greater indirect

81   losses through reduced forest productivity and ecological impacts.

82   Scots pine is one of the most widely distributed conifers in the world. It grows naturally

83   from Scotland east to the Pacific Ocean, from the 69th latitude in Scandinavia to the

84   Mediterranean Basin. In addition, Scots pine has been widely planted in colder regions of North

85   America, and it has become naturalized in the northeastern and midwestern United States. It is

86   planted in North America for erosion control, ornamental purposes, and pulp/timber production,

87   but its primary economic value is as a Christmas tree crop. According to the 2019 Census of

88   Horticultural Specialties in the United States, nearly 2,857 operations sold 11.7 million

89   Christmas trees valued at $357.1 million in 2019, and Scots pine is one of the most commonly

90   used Christmas tree species in the United States.

91   Scots pine blister rust is also called resin-top disease and top-dieback of pine for

92   affected trees in all age and size classes. Symptoms in pine include stem swelling, branch

93   flagging, excessive pitch flow, and top-kill, and, in the alternate hosts, leaf spotting. The rust

94   pathogen is spread in nature by wind-borne spores, which require live hosts for infection.

95   However, the rust pathogen can also be transported on infected plant materials that can be non-

96   symptomatic. Early infections of host plant infections by *C. pini* are difficult to detect and

97   diagnose, but molecular techniques offer a potential approach for early detection and diagnosis.

98   Scots pine blister rust is widespread across Eurasia, and it has long been a major factor in

99   reducing forest productivity in Europe; however, this rust disease has not been found in North

100   America. The safest plant protection policy for North America would be to prohibit the importation

101   of pine and non-pine hosts of Scots pine blister rust. If host plants were imported, a thorough visual

102   inspection for signs and symptoms of Scots pine blister rust should be conducted, followed by a

103   quarantine and/or extended monitoring. Early detection of Scots pine blister rust at port facilities

104   can provide some defense against introduction. However, non-symptomatic infections in this slow-

105   developing disease could easily be overlooked by visual inspections, so out-plantings should be

106   monitored for several years. Further diagnostic techniques, such as microscopy and simple DNA-

107   based tools, can be used to confirm rust pathogen infection and identity in symptomatic plants. The

108   following strategies may help to prevent the introduction of the Scots pine blister rust pathogen:

109

110   • Ban importation of living Scots pine trees/seedlings for nursery trade (*Pinus* spp. from all

111   countries, except Canada, Japan, and South Korea, are currently prohibited from

112   importation to the United States); allow importation of known angiosperm alternate hosts

113   only as seed (or at least as dormant and leafless plants).

114   • Determine potential susceptibility of North American pines to Scots pine blister rust.

115   • Establish a monitoring system for Scots pine blister rust and other invasive rust pathogen

116   species, especially in tree nursery and Christmas tree farm settings near likely points of

117   introduction.

118   • Develop time-efficient, species-specific molecular tools to detect and identify *C. pini*.

119   • Develop models that predict potential spread of the Scots pine blister rust pathogen

Mee-Sook Kim

120   from introduction points using distribution of suitable hosts and bioclimatic models

121   that identify suitable climate niches across the geographic ranges of diverse hosts.

122   • Improve educational awareness about potentially invasive rust pathogens among plant

123   diagnosticians, extension agents, forest managers, nursery growers, Christmas tree

124   growers, horticulturalists, and the general public.

125   • Conduct genetic analyses of the Scots pine blister rust pathogen and its known and potential

126   hosts to predict potential invasive risks in North America.

127

I. Introduction

129   The causal agent of Scots pine blister rust (resin-top disease; top-dieback of pine) is

130   *Cronartium pini* (Willd.) Jørstad [(syn. *Cronartium flaccidum* (Alb. & Schwein.) G. Winter,

131   *Peridermium pini* (Pers.) Lév., *C. asclepiadeum* (Willd.) Fr., *Endocronartium pini* (Pers.) Y.

132   Hiratsuka)] (Fig. 1). The sexually reproducing heteroecious form of the Scots pine blister rust

133   pathogen, formerly known as *C. flaccidum,* completes its life cycle by alternating between pines

134   mostly in the subgenus *Pinus* (hard pines) and flowering plants of various families. Scots pine

135   blister rust is also caused by an autoecious form of the rust pathogen, formerly known as

136   *Peridermium pini* and *Endocronartium pini,* that spreads directly from pine to pine.

137   Scots pine blister rust infects many *Pinus* species in Europe and Asia. The heteroecious

138   form causes severe damage in natural forests on *P. sylvestris* L. (Scots pine) in northern Finland;

139   whereas, the heteroecious form of *C. pini* is reported on Scots pine, *P. pinaster* Ait. (maritime

140   pine), *P. pinea* L. (Italian stone pine), *P. halepensis* Mill. (Aleppo pine), *P. mugo* Turra (mugo

141   pine), and *P. nigra* Arn. (Austrian pine or black pine) in southern Europe. Other reported *Pinus*

142   host species of *C. pini* include *P. brutia* Ten. (brutia pine or Turkish pine), *P. densiflora* Siebold

143   & Zucc. (Japanese red pine or Korean red pine), *P. radiata* D.Don (Monterey pine or radiata

144   pine), *P. koraiensis* Siebold & Zucc. (Korean pine), *P. massoniana* Lamb. (Masson pine), *P.*

145   *tabuliformis* Carrière (Manchurian red pine), *P. taiwanensis* Hayata (Taiwan red pine), *P. pumila*

146   Regel (Siberian dwarf pine), *P. uncinata* Ramond ex DC. (Swiss mountain pine), *P. wallichiana*

147   A.B.Jacks. (Himalayan pine or Bhutan Pine), *P. takahasii* Nakai, and *P. yunnanensis* Franch.

148   (Yunnan pine) (CABI 2020). North American pines reported to be susceptible to *C. pini* include

149   *P. radiata* (CABI 2020), and *P. ponderosa* Douglas ex C.Lawson (ponderosa pine) (Gibbs and

150   Kaitera 2018). The autoecious form of *C. pini* causes damage on Scots pine and mugo pine

151   (Kaitera and Nuorteva 2008). Of the Eurasian pine hosts, Scots pine and Austrian/black pine are

152   commonly planted in North America. Needle symptoms have been reported after artificial or

153   natural exposure to *C. pini* inoculum on other native and exotic two-needle pines that occur in the

154   United States (Raddi and Fagnani 1978). The alternate (telial) hosts for the heteroecious form of

155   *C. pini* belong to the angiosperm families: Gentianaceae, Balsaminaceae, Loasaceae, Paeoniaceae,

156   Tropaeolaceae, Verbenaceae, Apocynaceae, Orobanchaceae, Acanthaceae, Plantaginaceae,

157   Scrophulariaceae, Solanaceae, Papaveraceae, Saxifragaceae, and Myricaceae.

158   Scots pine blister rust is widely distributed across Europe and Asia. Both the heteroecious

159   and the autoecious forms of *C. pini* cause severe damage on pines (Fig. 2), where they produce

160   branch and stem lesions. Lesions caused by the heteroecious form typically kill the tree more

161   rapidly than those caused by the autoecious form. The rust is most severe on Scots pine and

162   several of the Mediterranean pine hosts. Scots pine blister rust has been reported in widely

163   ranging Eurasian countries including Armenia, Austria, Azerbaijan, Belgium, Bosnia and

164   Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Georgia,

165   Germany, Great Britain, Greece, Hungary, Italy, Kosovo, Latvia, Lithuania, Macedonia,

166   Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russia (from Europe to far

167   eastern Russia), Serbia, Slovenia, Spain, Sweden, Switzerland, Turkey, and Ukraine (CABI 2020,

168 Özkazanç and Maden 2013). In Asia, a rust referred to as Scots pine blister rust is also found in

169 China, Japan, Kazakhstan, Korea, and Taiwan (CABI 2020).

170

GEOGRAPHIC DISTRIBUTION OF SCOTS PINE

172   Scots pine (sometimes previously referred to as 'Scotch' pine) is one of the most widely

173 distributed conifers in the world. Its native range extends from Great Britain and Spain east

174 through Siberia, south to the southern Caucasus region and north to Lapland. Scots pine has been

175 widely planted in New Zealand and the colder regions of North America, and it has become

176 naturalized in the northeastern, midwestern, and Pacific northwestern United States. Scots pine is

177 the only pine native to northern Europe and once formed much of the Caledonian Forest of the

178 Scottish Highlands. In its northern distribution, it ranges from sea level to 914 m (3000 ft) in the

179 British Isles; whereas, in its southern distribution, Scots pine grows at higher elevations, from

180 1219 to 2590 m (4000 to 8500 ft).

181   Scots pine trees can typically attain a height of 24 m (80 ft), a diameter in excess of 0.9

182 m (3 ft), and an age of 200 years, or, exceptionally, a height of 46 m (150 ft), a diameter of 1.7

183 m (5½ ft), and an age of 700 years. Scots pine requires full sun and the absence of excessive

184 grazing to establish from seed, and it can quickly invade disturbed areas. In the United States,

185 Scots pine has been planted for erosion control, ornamental purposes, and pulp/timber

186 production; however, its primary economic value is currently as Christmas trees (Agricultural

187 Marketing Resource Center 2008), although other conifers are becoming more favored,

188 recently.

189

NOMENCLATURE/TAXONOMY OF SCOTS PINE BLISTER RUST

191   The rust fungi (Basidiomycota: Pucciniomycetes: Pucciniales) are a large, diverse group

192   of biotrophic fungi that reproduce only in living plant tissue, containing the family Cronartiaceae,

193   which comprises three genera (*Cronartium*, *Endocronartium*, and *Peridermium*). Among the

194   many important plant pathogens in this group are the pine stem rust fungi *Cronartium* and

195   *Peridermium*. The taxonomy of the Scots pine blister rust pathogen has been particularly

196   confusing, owing to a relationship between the host-alternating and pine-to-pine forms that were

197   previously known as *C. flaccidum* and *P. pini* (*E. pini*), respectively. Foresters and mycologists

198   have long recognized the similarity of the rust diseases caused by these fungi and the apparently

199   identical morphology of their spores produced on infected pine stems and branches. The chief

200   difference between the pine-borne spores of the two rust fungi is their infection of flowering

201   plants and pines vs. sole infection of pines. Hiratsuka (1968) reported developmental differences

202   in spore germination (and life cycle), which prompted him to name the pine-to-pine form

203   *Endocronartium pini*. However, molecular evidence points to a very close evolutionary

204   relationship between these rust pathogens (e.g., Vogler and Bruns 1998). Hantula et al. (2002)

205   provided morphological and molecular evidence demonstrating Scots pine blister rust pathogens

206   as a single species with alternative life cycles. Later, other population studies also confirmed

207   that Scots pine blister rust pathogens belong to a single species (Samils et al. 2011, 2021). As a

208   consequence, the two forms of *C. pini* have not been differentiated by presently available DNA

209   sequence analyses or aeciospore morphology, although an analysis of

210   homozygotic/heterozygotic loci can potentially differentiate the rust pathogen forms in the

211   aecial stage (Kasanen 1997). Although the morphology of the Scots pine blister rust pathogen

212   shares some similarities to other rust pathogens, DNA sequences (e.g., ITS) of the Scots pine

213   blister rust pathogen are distinct from other known rust pathogen species. For this reason, the

214   Scots pine blister rust pathogen could be detected by molecular means for quarantine control.

215   Recently, the Scots pine blister rust fungus has been renamed as *C. pini* (Willd.) Jørstad.

216   (Species Fungorum 2021, Wijesinghe et al. 2019). In this review, we refer to Scots pine blister

217   rust without distinguishing between its life cycle forms. However, the Scots pine blister rust

218   form is reported when specific studies pertain to a specific life-cycle form.

219

220   **II. Biology and Symptoms**

221   **LIFE CYCLE**

222   A typical *Cronartium* species that alternates between pine and angiosperm hosts has five

223   spore stages; nomenclature, morphology, and nuclear condition given here are from Cummins and

224   Hiratsuka (2003) (Fig. 3).

225

226   Stage 0 – Spermatia—borne in spermogonia.

227   Spermogonia are hermaphroditic structures containing female receptive hyphae and male

228   spermatia. Spermogonia occur in the outer pine stem cortex under the host periderm and

229   produce spermatia in a sugary fluid, which is attractive to insects.

230   Monokaryotic haploid (N) spermogonia produce haploid, uninucleate spermatia that are

231   small, thin-walled, and globose to flask-like in shape. Spermatia are transferred by insects to

232   other spermogonia, where, following union with a receptive hypha, a dikaryotic (N+N) mycelium

233   is produced that eventually produces aecia.

234

235   Stage 1 – Aeciospores—borne in aecia.

236   Aecia develop in the stem cortex of a host pine and are often associated with hypertrophy of the

237   stem tissue. The aecium is a structure that produces chains of binucleate, warty, thick- walled,

238   pigmented aeciospores that are bordered by a prominent papery peridium. The host cortex ruptures

239   as the aecia mature, the peridium ruptures, and aeciospores are released. Aeciospores are dispersed

240   aerially, and, following germination, produce a dikaryotic mycelium in angiosperm plant species

241   that serve as alternate hosts.

242

243   Stage 2 – Urediniospores—borne in uredinia.

244   Urediniospores, like aeciospores, are dikaryotic. Urediniospores and aeciospores both infect the

245   non-pine hosts through stomata and give rise to a mycelium that can form uredinia or telia.

246   However, urediniospores can cause a repeating cycle of infections on the non-pine hosts without a

247   sexual stage. The uredinium develops from subepidermal mycelium, and urediniospores erupt

248   through the epidermis. Urediniospores are spiny, borne individually, and aerially dispersed.

249

250   Stage 3 – Teliospores—borne in telia.

251   The telium arises from subepidermal, heterokaryotic hyphae that may have previously produced

252   urediniospores, and develops into an erumpent, hair-like column of dark, thick-walled

253   teliospores on the non-pine host. Teliospores are not dispersed, but are the site of karyogamy

254   and produce metabasidia (2N) that undergo meiosis, leading to formation of an elongate, septate

255   basidium and basidiospores.

256

257   Stage 4 – Basidiospores—borne on basidia.

258   Basidiospores are globose, thin-walled, haploid (N) spores that develop on projections of the

259   basidia called sterigmata, which aid forcible ejection of the basidiospores. Basidiospores are

260   discharged away from the telium and dispersed in moist air currents to a pine host needle or

261   shoot. Basidiospores germinate and infect pine needles through stomata. The haploid mycelium

262   grows down the needle and into the stem; when the mycelium reaches sufficient quantity and

263   density, spermogonia will be produced to complete the cycle.

264   Cummins and Hiratsuka (2003) describe the life cycle of *Peridermium pini* as endocyclic

265   and justify their nomenclature of *Endocronartium pini*. In this case, spores that morphologically

266   resemble aeciospores are produced on the pine host, dispersed, and directly infect other pines.

267   Spermogonia may also be produced.

268   The heteroecious form of Scots pine blister rust infects a host pine through needle

269   stomata (Ragazzi and Dellavalle Fedi 1992), but symptoms on the branch or main stem only

270   become apparent later in development. Infection of the autoecious form can also occur through

271   wounds (Kaitera and Nuorteva 2008). In pine, the Scots pine blister rust fungus produces several

272   types of reproductive structures that are observed as either tiny sacs of a sugary "nectar" with

273   spermatia (Fig. 4A) or small, white, or light orange bladders (Fig. 4B) filled with powdery,

274   orange-colored aeciospores. Both the heteroecious and autoecious forms produce spermogonia

275   and aecia. Spermogonia usually form within a swelling of the phloem, 1 (autoecious form) to 2

276   (heteroecious form) years after infection (Kaitera and Nuorteva 2008). Aecia formation follows a

277   year after the spermogonia are produced, and aecia formation can last in the same lesion for up to

278   8 years (Kaitera 2003). Diseased branches become swollen; after release of the aeciospores, the

279   bark cracks, darkens, and the end of the branch is killed if the branch becomes girdled. Infection

280   in a main stem by the Scots pine blister rust pathogen can also produce spermatia and

281   aeciospores. The disease first appears as a diamond-shaped, resinous canker, and eventually

282   girdles the stem, which kills the distal part of the branch or acropetal portion of the stem. Insects

283   carry spermatia among Scots pine blister rust cankers of diseased pines and aid in fertilization.

284   After formation of aecia, aeciospores can develop in aecia several years after fertilization.

285   Aeciospores are released in summer, and they can be wind carried for long distances to infect a

286   suitable host. The Scots pine blister rust pathogen grows downwards in a pine stem >10 cm

287   (several inches) per year. Small trees are killed within several years of infection; larger trees are

288   often infected in the middle of the crown, so if not killed by a girdling, resinous canker, an

289   infected tree may persist for decades with a dead top, hence the name "resin-top disease" (Fig. 2).

290

291   <div align="center">**III. Spread and Risk Map**</div>

292   **SPREAD OF THE SCOTS PINE BLISTER RUST PATHOGEN**

293   Although natural spread of the Scots pine blister rust pathogen is principally via aerial

294   dispersal, important differences between the two life-cycle forms of the rust pathogen determine if

295   infection occurs pine-to-pine or through an alternate host. Infection of a pine by the heteroecious

296   form eventually results in production of specialized structures (spermogonia) that mediate cross-

297   fertilization (genetic exchange) by transfer of insect-vectored spermatia to the receptive hyphae of

298   a separate infection. In late spring through summer, hyphae fertilized in the previous year form

299   blister-like aecia with yellow-pigmented, thick-walled aeciospores that aerially disseminate the

300   rust pathogen to the alternate host. Although most dispersal is likely limited to within ca. 10 km

301   (ca. 6 miles) and is mostly much closer, a very small proportion of aeciospores may be carried

302   >300 km (>200 miles) from the parental canker. The first spore stage produced on alternate hosts,

303   uredinia with urediniospores (Fig. 4), may increase infection on the same or different alternate

304   host plants, which can affect some further rust dispersal. More importantly, the uredinial stage can

305   produce a large, nonsexual amplification of inoculum under some environmental conditions, such

306   as increased temperature and/or moisture during critical periods that promote urediniospore

307   amplification. In late summer or early autumn, another spore stage, the teliospore, is produced.

308   The teliospores produce the final spore stage, the basidiospores, that are ejected into the air and

309   dispersed by the wind. Since basidiospores are delicate, they are usually dispersed <10 km (ca. 6

310   miles), but typically for much shorter distances. If a viable basidiospore lands on a pine needle,

311   germinates, grows into the needle (usually through a stomata), and avoids a resistance response

312 by the host, the pine becomes infected. Although a description of the sexual process in the pine-

313 to-pine form is subject to disagreement, the initial stages resemble those of the spermogonia and

314 aecia with the difference that aeciospores infect a pine host directly without intermediate stages

315 on alternate hosts.

316   Alternate hosts of the Scots pine blister rust pathogen reside in diverse angiosperm

317 families and genera. Based on inoculation tests in Scandinavia, the genera *Loasa, Nemesia,*

318 *Melampyrum, Tropaeolum, Vincetoxicum, Pedicularis*, and *Paeonia* are all reported as alternate

319 hosts of the Scots pine blister rust pathogen (Kaitera et al. 1999). Kaitera and Nuorteva (2003a)

320 reported that *C. pini* produces uredinia and telia on *Melampyrum nemorosum* and on Finnish

321 *Vincetoxicum hirundinaria*. Elsewhere in Europe, evidence is growing that *C. pini* commonly

322 spreads in nature on other alternate hosts in the cow-wheat family of herbaceous plants

323 (*Melampyrum* spp.) (Kaitera et al. 2005). Newly described hosts within the *Melampyrum* genus

324 are *M. pratense*, *M. nemorosum*, and *M. arvense*. Previously known alternate hosts are *V.*

325 *hirundinaria* (Swallow-wort) (Fig. 5) and *M. sylvaticum* (small cow-wheat). Other susceptible

326 species have been observed in the genera *Veronica* (Kaitera et al. 2015, 2018), *Hyoscyamus*

327 (Kaitera et al. 2015), *Nicotiana* (Kaitera et al. 2015), *Bartsia* (Kaitera and Hiltunen 2012; Kaitera

328 et al. 2012), *Rhinanthus* (Kaitera et al. 2015, 2018), *Euphrasia* (Kaitera et al. 2012, 2018),

329 *Castilleja* (Kaitera et al. 2015), *Odontites* (Kaitera et al. 2018), *Saxifraga* (Kaitera et al. 2015,

330 2018), *Myrica* (Kaitera et al. 2012, 2015), *Caiophora* (Kaitera et al. 2012), *Asclepias* (Kaitera and

331 Hiltunen 2012), *Apocynum* (Kaitera et al. 2015), *Swertia* (Kaitera et al. 2015, 2018), *Impatiens*

332 (Kaitera et al. 2012, 2015), and *Papaver* (Kaitera et al. 2018) (Fig. 5).

333

334 **RISK MAPPING OF SCOTS PINE BLISTER RUST**

335 A risk map for Scots pine blister rust pathogen was created based on the temperatures required for

336   germination of *C. pini* aeciospores. The temperature range of *C. pini* aeciospore germination was

337   previously determined as 5 - 30°C, and telia formation was enhanced by precipitation (Ragazzi

338   1983; Ragazzi et al 1986). The areas with suitable weather conditions were characterized using

339   tools within the Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS)

340   and PRISM climatic data from 2000 to 2019 (PRISM Climate Group 2021; SAFARIS 2021). In

341   addition, the distribution of *Pinus* species was incorporated in the climate suitability map. The

342   risk map represents a combination of pine distribution (including all *Pinus* species and assuming

343   equal susceptibility for all *Pinus* species) and incidence of perceived weather that is considered

344   favorable for infection (Fig. 6). However, caution is warranted in interpreting this model because

345   it does not account for differences in different pine species' susceptibility to and host suitability

346   for Scots pine blister rust. Furthermore, this model does not incorporate information associated

347   with potential alternate hosts of *C. pini*. An improved prediction model based on more accurate

348   host and climate data would more precisely predict geographic areas at risk from *C. pini*

349   infection.

350

351   **VI. Monitoring, Detection, and Identification**

352   Although widespread in Eurasia, Scots pine blister rust has not been found in North

353   America. Thus, exclusion of *C. pini* is the first line of defense to protect North America from Scots

354   pine blister rust. Preventing the introduction of *C. pini* will require effective monitoring and

355   detection procedures. Based on past introductions of plant pathogens, importation of infected

356   primary or alternate host material represents the most likely pathway of introduction. Host

357   materials, such as whole plants or leaf and stem tissue from the host plants listed above, represents

358   the highest risk for harboring the pathogen. *Pinus thunbergii* Parl. (Japanese black pine), mugo pine

359   or other two- or three-needled pines, commonly used for bonsai, pose a significant risk if imported

Mee-Sook Kim
Plant Health Progress

360   as whole plants.

361   Scots pines in each region of the United States should be routinely monitored to detect

362   any outbreaks of Scots pine blister rust. The United States Departments of Agriculture (USDA),

363   Animal and Plant Health Inspection Service (APHIS) should be requested to include Scots pine

364   blister rust in their diseases of special interest for inspections of nurseries and Christmas trees.

365   State, federal, and private organizations should be requested to inspect for Scots pine blister rust

366   in Scots pine forest and resource conservation plantings. These requests should be accompanied

367   by descriptions of the disease (symptoms, signs, biology), a sampling protocol, and a list of

368   laboratories equipped to provide proper identification of the pathogens. The USDA APHIS -

369   Cooperative Agricultural Pest Survey Program

370   (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/pest-detection) and Forest Service -

371   Forest Health Monitoring Program (https://www.fs.fed.us/foresthealth/protecting-forest/forest-

372   health-monitoring/) should collaborate with state Departments of Agriculture for monitoring and

373   detecting Scots pine blister rust. USDA Extension programs (https://nifa.usda.gov/extension) at

374   Land Grant Universities should also be employed to educate growers and landowners.

375   Early detection of Scots pine blister rust at port facilities represents the first and best defense

376   against introduction. The safest policy would be to prohibit the importation of primary and alternate

377   host plants and plant parts into North America; however, the importation of host plant seed would

378   represent only minimal risk for carrying *C. pini*. *Pinus* spp. seed is allowed to be imported into the

379   United States from all countries.

380   Perennial host plants that are regulated as prohibited or as Not Authorized Pending Pest

381   Risk Analysis (NAPPRA) are imported under a USDA APHIS Controlled Import Permit

382   (PPQ588: https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-

383   information/permits/plants-and-plant-products-permits/prohibited/cip). Scots pine plants imported

384   under this permit are required to follow quarantine procedures outlined in the permit. Quarantine

385   procedures allow time for symptoms and signs of *C. pini* infection to develop, which may not

386   have been expressed at the time of importation; quarantined plants that manifest signs or

387   symptoms of *C. pini* infection must be destroyed according to USDA-APHIS-PPQ regulations. A

388   thorough visual inspection of signs and symptoms of Scots pine blister rust should be conducted

389   under a controlled environment (i.e., a biological containment greenhouse or a type II biological

390   safety hood). Pine host symptoms include fusiform-shaped swelling (Figs. 4 and 7), resinosis of

391   stem or branches (Fig. 7A), and/or yellow flecking of needles. Primary host signs include sticky,

392   yellow, malodorous spore nectar and/or yellow-orange pustules on the stem or branches, and/or

393   powdery yellow-orange spores (Fig. 4). Symptoms on angiosperm hosts include small spots (1–4

394   mm across) of yellow or lighter green than surrounding tissues on the underside of leaves.

395   Angiosperm host signs include orange pustules (uredinia) or hair-like fungal structures (telia)

396   protruding from the underside of leaves (Fig. 5). Visual diagnoses can be made with a hand lens

397   or dissecting microscope; however, signs and symptoms may be latent for 3 to 4 years in infected

398   pine host material, and up to a month in leafy alternate hosts. Non-symptomatic infections could

399   be easily overlooked by visual inspections, especially upon arrival of recently infected materials.

400

401   **DIAGNOSIS OF THE PATHOGEN**

402   Morphological features of aeciospores and/or urediniospores of *C. pini* are not specific

403   enough to allow rapid identification of this rust pathogen species, but identification can be

404   accomplished with DNA sequence-based tools (Hantula et al. 2002). Rust spores, whether

405   collected from leaves, cankers, aecia, or uredinia (from the host/alternate host), spore traps, or

406   washes from plants, would first be subjected to DNA extraction prior to subsequent analyses.

407   Aeciospores have a thick outer wall, and DNA extractions can be conducted using a CTAB

408   method (Samils et al. 2021; Chen et al. 1993). Several approaches have been used and/or

409   developed to distinguish *C. pini* from other *Cronartium*/*Peridermium* species, yet, species-

410   specific identification tools have not yet been developed for *C. pini*. A common method for *C.*

411   *pini* identification is based on Sanger sequencing of ribosomal DNA regions, including the ITS2

412   and IGS-1. The ITS2 and IGS-1 regions can be amplified using polymerase chain region (PCR)

413   with primers Rust3 and ITS4 (Moricca and Ragazzi 1998; White et al. 1990) for the ITS2 region

414   and H and 5B (Moricca and Ragazzi 1998; Buchko and Klassen 1990) for the IGS-1 region.

415   Generated sequences are then compared to sequences within databases, such as the National

416   Center of Biotechnology Information (NCBI) database (https://blast.ncbi.nlm.nih.gov/Blast.cgi),

417   using BLAST algorithms to determine similarity of sequences to reference sequences of known

418   and verified rust species. Using currently available tools and techniques, detection of *C. pini*

419   could require a few days or even weeks. Development of species-specific molecular tools,

420   including quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP) detection,

421   or antibody-based assays would help to identify *C. pini* more rapidly in newly invaded geographic

422   regions. Microsatellite markers, Pp1 and Pp2, could be used for identification and gaining a better

423   understanding of genetic diversity of *C. pini* across geographic regions. These microsatellite

424   markers were first developed by Kasanen et al. (2000), and these markers were subsequently

425   adapted by Samils et al. (2011) to allow amplification of the shorter simple sequence repeat

426   amplicons. Using these markers and Amplified Fragment Length polymorphism (AFLP), Samils

427   et al. (2021) identified six genetically distinct Bayesian clusters across 14 sampled locations in

428   Finland and Sweden.

429

430   **V. Response**

431   The response to all plant health emergencies in the United States is under the authority of

432   USDA-APHIS-Plant Protection and Quarantine (PPQ) delegated by the Secretary of Agriculture

433   under the Plant Protection Act of 2000.

434   If a detection of *C. pini* were confirmed by a USDA-APHIS-PPQ recognized authority,

435   APHIS would be in charge of the state(s) where detection has occurred. For typical first detections

436   of an exotic pathogen, response would begin with an initial assessment. For a nursery site, a Rapid

437   Assessment Team (RAT) consisting of state and federal experts on *Cronartium* and associated

438   regulatory personnel may be deployed on-site to collect additional plant, soil, and water samples to

439   conduct epidemiological investigations and initiate environmental delimiting surveys outside the

440   nursery grounds. Possible actions include quarantines of infested or potentially infested production

441   areas, prohibiting movement of infected or potentially infected materials in commerce, host removal

442   and destruction, requiring adherence to sanitary practices, and application of registered fungicides

443   and disinfectants. Trace-forward and trace-back surveys would be required for locations that have

444   sent or received potentially infected nursery stock to/from the nursery with a confirmed pathogen

445   detection. APHIS could impose quarantines and regulatory requirements to control and prevent the

446   interstate movement of quarantine-significant pathogens or regulated articles (high risk host

447   material), and APHIS works in conjunction with states that impose actions parallel to APHIS

448   regulatory actions to restrict intrastate movement. The RAT would also attempt to ascertain if the

449   introduction was intentional or accidental. If the organism in question is a select agent covered

450   under the Agricultural Bioterrorism Act of 2002, federal and local law enforcement may be

451   involved in the initial assessment to determine if a bioterrorism event or biocrime event has

452   occurred.

453   The USDA-APHIS-PPQ response also depends on where *C. pini* is found (e.g., forest,

454   plantation, or nursery) and how widespread it is based on the initial RAT assessment and

455   associated delimitation surveys. For example, if *C. pini* were found in a pine plantation, attempts

456   would be made to eradicate the pathogen through several measures including plant

457   destruction/eradication, soil/surface dis-infestation, trace-forwards, and trace-backs similar to

458   management of *Phytophthora ramorum* in the United States (Rizzo et al., 2005). Likewise, the

459   practicality of eradication in a forest setting would be assessed by the RAT and a technical

460   working group of *Cronartium* experts and a recommendation will be made as to the potential for

461   eradication of the infestation on a case-by-case basis.

462

463   **VI. USDA Pathogens Permits and Regulatory Issues**

464   USDA-APHIS-PPQ permits for plant pests and biological control organisms, fall under

465   the authority of the Plant Protection Act, codified under 7 CFR 330. A PPQ 526 Permit is required

466   for importation and interstate movement of all plant pests and infected plant materials, including

467   diagnostic samples, regardless of their quarantine status. The receiving person must have been

468   granted an authorized permit. Information on PPQ 526 Permits can be found at:

469   https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/regulated-

470   organism-and-soil-permits. Applicants may also call PPQ Permit Services at Telephone (301)

471   734-0841, Toll Free (866) 524-5421 or e-mail Pest.Permits@usda.gov.

472   USDA-APHIS regulates the importation of *Pinus* species. *Pinus* spp. are Not Authorized

473   Pending a Pest Risk Analysis (NAPPRA):

474   https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/plants-and-

475   plant-products-permits/plants-for-planting/ct_nappra), and are prohibited from importation into the

476   United States from all countries except Canada, Japan, and South Korea (effective on May 20,

477   2013). Importation of two- and three-needled pines are prohibited from Japan and Korea with *C.*

478   *pini* (listed as *C. flaccidum*) listed as one of the USDA pests of concern

479   (https://www.aphis.usda.gov/aphis/resources/farmbill/fb-pests/farmbill-pest-list).

480 **VII. Economic Impact and Compensation**

481   Economic impacts are difficult to estimate and are dependent on the nature of the

482 introduction and introduction pathways and the pathogenicity/virulence of the introduced *C. pini*

483 on native and exotic plant species. If Eurasian pine species remain the only hosts of Scots pine

484 blister rust in North America, the greatest economic impacts will be largely limited to nurseries

485 and Christmas tree plantations that grow Scots pine and to cities and homeowners that will bear

486 the cost of removal of dead or hazardous landscape and urban trees.

487   Restrictions on moving potentially infected hosts and eradication of infected materials in

488 nurseries and Christmas tree farms could cause enormous economic losses amounting to millions

489 of dollars (U.S.). According to the National Christmas Tree Association, Scots pine is one of the

490 most planted commercial Christmas trees in North America. Currently, Oregon, North Carolina,

491 Michigan, Pennsylvania, Wisconsin, Washington, New York, and Virginia are the top Christmas

492 tree-producing states in the United States. Most Scots pine is grown primarily in the Lake States,

493 with Michigan and Wisconsin as the top producers of Christmas trees. Scots pine is one of the

494 top five species of Christmas trees sold in the United States though it is difficult to obtain an

495 exact value for the Scots pine market. According to the Census of Horticultural Specialties in the

496 United States, nearly 2,857 operations sold 11.7 million Christmas trees valued at $357.1 million

497 in 2019.

498   Impacts will depend on how widespread the introduction is, how fast spread might occur

499 among areas where Scots pine has been planted, and whether or not measures to control spread

500 are implemented. Because Christmas trees have a much shorter production cycle (compared with

501 the life cycle of pine trees in forests), some areas that are slow to be affected by the introduced

502 rust pathogen could transition to other, more resistant or immune conifer species or genotypes

503 before losses from Scots pine blister rust or restrictions in tree movement impact the local

504   Christmas tree production operations.

505   A worse-case scenario would be if *C. pini* already possesses or gains the capacity to infect

506   native North American pines, which is not completely unexpected, given the large known host

507   range of the pathogen on pine and non-pine hosts. *Cronartium pini* is known to infect several

508   aecial hosts. Based on previous inoculation tests, aecial hosts appear to be primarily restricted to

509   select Eurasian two-needled pine species in the section *Pinus* (Mittempergher and Raddi 1977;

510   Raddi and Fagnani 1978; Kaitera and Nuorteva 2008). Largely unsuccessful inoculations of North

511   American pine species, section *Trifoliae* (ponderosa pine and *P. contorta* Douglas ex Loudon

512   (lodgepole pine)) and section *Pinus* (red pine) have been reported (Raddi and Fagnani 1978;

513   Kaitera and Nuorteva 2008); however, *C. pini* was able to cause needle spotting on some North

514   American species. Needle spotting was found on lodgepole pine, *P. echinata* Mill. (shortleaf

515   pine), *P. elliottii* Engelm. (slash pine), and red pine. In addition, mycelium was detected in needle

516   tissue of ponderosa pine, but none of these North American pines supported the generation of

517   pycnia (spermogonia) or aecia under the test conditions (Raddi and Fagnani 1978). Among native

518   North American section *Pinus* species, resistance to Scots pine blister rust is apparently relatively

519   high. Subsequent inoculation tests by Kaitera and Neorteva (2008) also showed no symptoms on

520   seedlings of Scot pine blister rust on lodgepole pine and red pine.

521   A likely route of potential *C. pini* invasion in North America could come from the

522   widespread use of Scots pine, mugo pine, and Austrian/black pine in urban landscapes and

523   Christmas tree plantations. These species are also naturalized in northern regions of the United

524   States increasing the risk that an introduction could spread beyond urban landscapes, and providing

525   the Scots pine blister rust pathogen with more opportunities to find novel alternate hosts or to cycle

526   directly back to *Pinus* (autoecious lifecycle). The presence of *C. pini* in North America could also

527   conceivably provide more opportunities for this rust to jump to *Pinus* species in the section

528   Trifoliae. Although previous inoculation tests show that native North American pine species appear

529   to be at low risk for infection from *C. pini*, such inoculation tests cannot be conducted in the

530   environment of North America, and environment will likely influence the pathogenicity of *C. pini*.

531   Another substantial threat is that *C. pini* could potentially hybridize with native pine rust

532   pathogens that also have broad and overlapping alternate host range [similar to the detected rust

533   hybrid in North America between introduced *C. ribicola* J.C. Fisch., agent of white pine blister rust,

534   and native *C. comandrae* Peck, a blister rust of lodgepole pine (Joly et al., 2006)], a scenario of *C.*

535   *pini* or hybrids acquiring pine hosts that are currently resistant may also be possible. If such a

536   scenario occurred, the economic and ecological impacts would be unpredictable, but potentially far

537   greater than that posed by non-adapted or non-hybridized *C. pini*.

538

539   **VIII. Mitigation and Disease Management**

540   If Scots pine blister rust becomes sufficiently established and eradication is precluded,

541   infested and threatened sites can be managed to mitigate impacts. Consistent restriction of *C. pini*

542   dispersal and colonization would reduce further losses and restrict the ability of *C. pini* to adapt to

543   its new environment and potentially new hosts. An understanding of Scots pine blister rust

544   impacts on trees, populations, communities, and ecosystems is also useful for rehabilitation. The

545   immediate objective of mitigation and management is efficient and effective minimization of

546   damage to natural systems and loss of resource value. Activities range from disease control

547   tactics, such as pruning, thinning, and removal of infected seed trees (trees grown for seed

548   production), to program strategies, such as adaptive environmental assessment and management.

549   Successful mitigation and management must confront with five principal issues: 1) long-distance,

550   aerial dispersal of the Scots pine blister rust pathogen, 2) multiple hosts of which many are

551   (probably) unknown, 3) differing objectives of various managers, 4) a Scots pine blister rust

552   pathogen that capable of both sexual and clonal reproduction, and 5) a rapidly changing

553   environment due to climatic, ecological, and socioeconomic factors.

554

555   **DISEASE CONTROL**

556   The life cycle of the Scots pine blister rust pathogen, *C. pini*, has vulnerabilities that can

557   be exploited to prevent infection (by enhancing host escape) or minimize disease damage

558   (influencing pathogen–host compatibility). General methods to control pine stem rusts include the

559   use of chemicals to prevent infection, eradication or separation of alternate hosts from pine hosts,

560   natural biological agents that reduce reproduction of the rust pathogen, and cultural management

561   of host populations (silviculture) or individuals (arboriculture). Genetic manipulation can focus

562   on selection, breeding, and deployment of hosts with greater resistance or tolerance to Scots pine

563   blister rust disease.

564   Chemical controls might prevent host infection by the Scots pine blister rust pathogen

565   and reduce pathogen vigor, viability, and inoculum production; however, few specific studies

566   are reported for Scots pine blister rust. Control trials have included prophylactic chemicals to

567   protect pines, salts and herbicides to kill alternate hosts, antibiotics to clear infections, and

568   insecticides to control insect vectors. Triadimefon has been demonstrated to be a useful

569   prophylactic for white pine blister rust (Pitt et al. 2006). Yao and Peixin (1991) report that

570   application of Topsin® and triadimefon to a canker surface was effective in eliminating aecial

571   sporulation of Scots pine blister rust pathogen in China. Salt spray can kill alternate hosts, but

572   eradication was only practical in proximity to a pine plantation and likely would require

573   intensive applications. Maloy (1997) reviewed the history of control of *C. ribicola* in the United

574   States, including abandoned efforts with antibiotics and herbicides. Pappinen and von

575   Weissenburg (1996) describe how pine-top weevil wounding pine twigs increased Scots pine

576   blister rust infection, which suggests that this disease could perhaps be managed in part by

577   reducing pine-feeding insects. Studies on the effective use of insecticides to reduce insect

578   vectors (that carry either spermatia or aeciospores) are apparently unavailable.

579   Control of pine stem rusts with biological agents has focused on rust canker-associated

580   fungi that interfere with rust sporulation. Early work investigated *Tuberculina maxima*, which is

581   a secondary fungus on cankers of many pine stem rusts caused by different pathogens, including

582   Scots pine blister rust, but it has not been shown to be effective. Previous attention also focused

583   on *Cladosporium tenuissimum*, which acts as an antagonistic hyperparasite. When suspensions of

584   the mycoparasite *Trichoderma atroviride* were applied to *C. ribicola* aecia on *P. armandii*

585   Franch. (Chinese white pine) in China, aeciospores were destroyed (Li et al. 2013).

586   Cultural activities provide numerous opportunities to mitigate damage by Scots pine

587   blister rust. Although management for stem rusts must consider details of each specific

588   pathosystem, general approaches developed for other *Cronartium* rusts and invasive tree

589   pathogens have potential relevance (for general review see Waring and O'Hara 2005). Potential

590   disease problems can often be avoided with careful matching of site and tree selection.

591   Because some microclimates are more favorable for development of Scots pine blister rust and

592   some sites have close proximity between uninfected trees and inoculum, hazard at some sites

593   may be sufficiently high that alternative management, such as the use of non-host species, or

594   host pines with adaptive traits (i.e., greater resistance should be considered; Pei and Brodie

595   1995). In Finland, Kaitera and Nuorteva (2008) observed that susceptibility to *C. pini* infection

596   varied among host provenances, with interactions with rust source and weather. In their study,

597   lodgepole pine (native to North America) was not infected. Raddi and Fagnani (1978) also

598   noted differences in susceptibility of Italian pines and some resistance in ponderosa pine

599   (native to North America). The potential existence of different *C. pini* races with varying

600 virulence among hosts must also be considered, although this feature has not yet been

601 established.

602   Whether thinning to improve stand growth or removing diseased trees (sanitation or

603 salvage), management practices can mitigate disease loss, depending on numerous interacting

604 factors. Kaitera (2002) observed that thinning Scots pine did reduce *C. pini* infection compared

605 to unthinned plots, but year-to-year variation was high in both thinned and unthinned treatments.

606 Such results are not unexpected because thinning affects microclimate to increase foliage drying,

607 which would likely decrease *C. pini* spore germination. Thinning can also increase dispersal of

608 *C. pini* spores within a stand, enhance alternate host persistence, and result in wounding (a

609 potential infection pathway). Generally, thinning, fertilization, and augmentation with

610 mycorrhiza are considered beneficial to stand growth; however, these activities could also

611 potentially increase Scots pine blister rust by increasing susceptible tissue. As with species

612 preference, thinning effects on Scots pine blister rust are not simple to predict.

613   Pruning can remove infected branches before the rust pathogen enters the trunk,

614 eliminate branches that may become infected later and lead to lethal trunk cankers, and improve

615 wood quality as knot-free timber. In some situations, trunk cankers can be excised, rendered

616 inactive by chemical or biological agents, and/or contained over time through host resistance

617 reactions. Because pruning and individual canker treatments are labor-intensive and time-

618 sensitive activities, the economics of treatment are important in determining whether this type

619 of control is practical for saving individual trees, especially since significant reduction in

620 inoculum should not be expected.

621   Although eradication of the alternate host has been effective for mitigating impacts of

622 other rust diseases in certain regions, host eradication is generally not practical for Scots pine

623 blister rust. The range of hosts that contribute to pine infection is large, diverse, and includes the

624   pine itself in northern regions where the autoecious form prevails. Nonetheless, reducing the

625   proximity of pine to alternate hosts can reduce but not eliminate *C. pini* infections especially in

626   sites where only heteroecious rust occurs. Genetic control tactics can be effective for future

627   generations and can be implemented by favoring natural reproduction from less-diseased trees or

628   outplanting seedlings from resistant parents. Variation in blister rust incidence among Scots pine

629   provenances has been reported by Kaitera (2003) and some cultivars of some alternate host

630   species are immune. Selection in natural stands or breeding programs can increase the frequency

631   of resistance in the host, but the potential for *C. pini* evolution must also be considered.

632   Designing and monitoring a genetic control tactic should therefore consider the several host–

633   pathogen interactions of resistance, virulence, tolerance, and aggressiveness. Hybridization or

634   genetic exchange among different rust pathogens or hosts could also affect the ability to

635   reproduce or sustain disease (Brasier 2001). Although resistance-breeding programs (e.g., Murray

636   1964) are expensive due to management and associated research costs, they can provide not only

637   improved seed but also valuable genetic information (Kinloch 1972). Federal cooperative genetic

638   tree-improvement programs at several locations are currently addressing several pine stem rusts

639   other than Scots pine blister rust.

640   Disease control tactics should be employed in a strategic context. Given the complexity

641   and uncertainty of mitigating Scots pine blister rust and managing infested ecosystems for a

642   novel disturbance, adaptive management is especially appropriate (Williams et al. 2009).

643   Decisions over control (and monitoring) of pine stem rusts are frequently made with use of rust

644   hazard models that typically provide landscape or stand projections of infection likelihood,

645   incidence, or damage severity (e.g., Van Arsdel et al. 1961).

646

647

648 **RISK MANAGEMENT**

649   Even during the phase of mitigation and management, it is important to identify risk

650 factors and consider alternative outcomes of treatment. The epidemiology and damage from

651 Scots pine blister rust varies in space and time due to differences in climate, soil type, stand age,

652 host species, growth, genetics, and other unknown factors (Murray et al. 1969; Greig 1987;

653 Kaitera et al. 1994).

654   Risk management techniques (see U.S. EPA 2003; Lovett et al. 2006) provide procedures

655 to incorporate complexity and uncertainty into hazard maps and simulation models. For example,

656 a regional map of predicted severity of white pine blister rust based on synoptic climate, a lake

657 effect, and alternate host distribution was developed by Van Arsdel et al. (1961). McDonald et al.

658 (1981) developed an epidemiological simulation model for white pine blister rust that projects

659 growth and mortality of *P. monticola* Douglas ex D.Don (western white pine) within infested

660 stands that considered the abundance of hosts, climate, and site productivity. The potential

661 influence of climate change on white pine blister rust has also been examined (Dudney et al.

662 2021). Such approaches, maps, and models can be useful where many complex factors must be

663 considered in selecting a disease management regime.

664   Typically, rust-hazard assessments have been based on environmental and demographic

665 processes without regard for evolutionary (e.g., genetic and environmental) interactions. The

666 outcome of these interactions, however, can have profound effects on the naturalization of an

667 introduced pathogen and the resulting condition of the affected ecosystem (see Parker and Gilbert

668 2004). An uncertain risk that increases the difficulty in planning mitigation is the potential for a

669 pathogen to shift to a new host. *Pedicularis* and *Castilleja* are among several genera of flowering

670 plants that are included as potential alternate host species of Scots pine blister rust. Although the

671 susceptibility to Scots pine blister rust has not been determined for many species of *Pedicularis*

672   and *Castilleja* endemic to North America, they are known hosts of other pine stem rusts and

673   should be considered as potential hosts of Scots pine blister rust as well. The risk is not that North

674   American populations of *Pedicularis* and *Castilleja* (or other alternate hosts such as *Euphrasia*

675   and *Rhinanthus*) would be jeopardized, but that these alternate hosts could act as a *C. pini*

676   inoculum source to infect pines or even serve as an alternate host for a hybrid rust pathogen. The

677   North American pines, which are potential hosts of Scots pine blister rust, are also hosts of other,

678   native pine stem rusts.

679   As mentioned, hybrids between a different Eurasian pine stem rust (*C. ribicola*) and a

680   North American stem rust (*C. comandrae*) has been observed as sporulating aecia on pine at a

681   few locations (Joly et al. 2006), but no alternate host has been reported for this rust hybrid. If

682   Scots pine blister rust were established in North America, opportunities could occur that could

683   facilitate hybridization of rust pathogens. Because of the pine and angiosperm host ranges and

684   the conditions favoring *C. pini* infection, the likelihood and consequences of *C. pini* hybrid

685   pathogens arising is difficult to predict (see Brasier 2001 for hybrids in non-rust pathogens).

686

687   **XI. Research, Extension, and Education Priorities**

688   **RESEARCH PRIORITIES**

689   Many questions remain about the ecological behavior of the heteroecious and autoecious

690   forms of *C. pini* even within its native range. Predicting actual impacts of Scots pine blister rust

691   on potential hosts is a formidable task because of potential influences of host/pathogen genetic

692   structure and the interaction of environment on virulence/resistance reactions. Although the

693   Scots pine blister rust pathogen has been reported in eastern Asia, much less is known about the

694   pathogen in eastern Asia than in Europe. Because great genetic variation could occur across the

695   native ranges of *C. pini* and its hosts, research is needed to develop effective diagnostic

696   techniques to characterize *C. pini* at the species, subspecies, and population levels, while also

697   furthering our understanding the geographic distribution of the heteroecious and autoecious

698   forms. Pathogen characterization is the initial step needed to assess variation in life cycle, host

699   ranges, variation in virulence, and environmental optima for infection. Information gathered

700   from such studies will allow improved predictions of geographic areas and host species at risk

701   from *C. pini*.

702   Management of rust diseases often relies on resistance breeding programs, and this

703   approach offers promise for Scots pine blister rust. Biological control also offers promise

704   toward managing different forms of *C. pini*; therefore, continued research efforts are needed to

705   identify biological control agents and associated techniques for enhancing biological control of

706   Scots pine blister rust.

707

708   **Most Important**

709   • Determine if historical reports or herbarium records exist of rust disease on North

710   American pines in historical European arboreta and other plantings, where Scots pine

711   blister rust occurs. A search for these records/reports can initially focus on rust diseases

712   on pine clades with a close phylogenetic relationship with Scots pine.

713   • Use inoculation tests in infested countries to determine potential aecial and telial hosts

714   of Scots pine blister rust in plants that occur naturally or are planted in North America.

715   • Conduct phylogenetic analyses of known and potential non-pine hosts of Scots pine

716   blister rust.

717   • Develop prediction models of potential spread of Scots pine blister rust based on

718   distribution of aecial and telial hosts combined with present and future climate models.

719   • Conduct phylogenetic analysis of the Scots pine blister rust pathogen (*C. pini*) and other

720   pine stem rust pathogens present in North America (e.g., *C. arizonicum* Cummins, *C.*

721   *coleosporioides* f. album Ziller, *C. comandrae*, *C. ribicola*, and *P. harknessii*

722   J.P.Moore).

723 • Conduct population genetic analysis to determine the genetic diversity of *C. pini* across

724   its native range.

725 • Determine the range of pine hosts and non-pine, alternate hosts, and environmental

726   requirements for each genetic group of *C. pini.*

727

728 **Highly Important**

729 • Assess potential sources of Scots pine blister rust resistance in aecial host (pine) populations

730 of North America.

731 • Begin assessments of potential biological control agents for Scots pine blister rust.

732

733 **Needs Evaluation**

734 • Evaluate potential genetic information and assess status of germplasm collections for diverse

735 geographic sources of potential pine hosts of Scots pine bister rust in North America.

736 • Establish sentinel tree and alternate host plantings, preferably using known susceptible

737 seed sources, in areas with Scots pine blister rust to help in early detection and establish a

738 baseline of susceptibility against which the results from genetic screening can be compared.

739

740 **EXTENSION PRIORITIES**

741 Rust pathogens are difficult to identify reliably based solely on morphology and symptoms.

742 Periodic surveys of rust on aecial and telial hosts should include sensitive (e.g., DNA-based)

743 diagnostic protocols to identify rust pathogens, their hosts, and distribution.

744   The following action items must be developed:

745   • Cooperate with National Plant Diagnostic Network (NPDN) to develop tree-rust diagnostic

746   tools that accurately identify tree-rust pathogens.

747   • Conduct surveys of potential aecial and telial hosts using DNA-based diagnostic tests to

748   identify rust pathogens.

749   • Develop means to prevent the introduction/spread of *C. pini* via movement of aecial

750   and telial hosts.

751   • Develop and circulate educational materials describing Scots pine blister rust

752   (symptoms, signs, biology) and comparing with rust diseases currently present, and

753   describing the threats associated with introduction of the Scots pine blister rust

754   pathogen.

755

756   **EDUCATION PRIORITIES**

757   • Educate plant pathologists, plant health professionals, extension agents, forest managers,

758   nursery growers, Christmas tree growers, horticulturalists, general public, etc. about potentially

759   invasive rust pathogens, including *C. pini*.

760   • Develop targeted education programs directed toward areas that may be at high risk for Scots

761   pine blister rust, such as Christmas tree growers or horticultural nurseries.

762   • Engage Master Gardener and Master Naturalist programs and other relevant existing outreach

763   programs to educate stakeholders about Scots pine blister rust and other potentially invasive tree

764   rust pathogens.

765   • Integrate Scots pine blister rust into state and regional "pest detector" educational programs

766   that focus on non-native invasive pests.

767

768 **ACKNOWLEDGEMENTS**

776

777   **X. References**

778   Agricultural Marketing Resource Center. 2008. Christmas trees. Ag Marketing Resource

779   Center, Ames, IA. Retrieved 21 May 2021 from https://www.agmrc.org/commodities-

780   products/forestry/christmas-trees

781

782   Brasier, C. M. 2001. Rapid evolution of introduced plant pathogens via

783   interspecific hybridization. BioScience 51:123-133.

784

785   Buchko, B., and Klassen, G. R. 1990. Detection of length heterogeneity in the ribosomal DNA

786   of *Pythium ultimum* by PCR amplification of the intergenic region. Current Genetics 18:203-

787   205.

788

789   CABI. 2020. *Cronartium flaccidum* (Scots pine blister rust) in: Invasive Species Compendium.

790   Wallingford, UK: CAB International. Retrieved 21 May 2021 from

791   https://www.cabi.org/isc/datasheet/16148

Mee-Sook Kim
Plant Health Progress

792   Chen, X. M., Line, R. F., and Leung, H. 1993. Relationship between virulence variation and

793   DNA polymorphism in *Puccinia striiformis*. Phytopathology 83:1489-1497.

794

795   Cummins, G. B., and Hiratsuka, Y. 2003. Illustrated genera of rust fungi. American

796   Phytopathological Society Press. St. Paul, MN.

797

798   Dudney, J., Willing, C. E., Das, A. J., Latimer, A. M., Nesmith, J. c. B., and Battles, J. J. 2021.

799   Nonlinear shifts in infectious rust disease due to climate change. Nature Communications 12:5102.

800

801   Gibbs, J., and Kaitera, J. 2018. Resin Top Disease. In; Hansen, E.M., K.J. Lewis, and G.A.

802   Chastagner (Editors). Compendium of Conifer Diseases. APS Press, St. Paul, Minnesota,

803   USA.

804

805   Greig, B. J. W. 1987. History of *Peridermium* stem rust of Scots pine (*Pinus sylvestris* L.) in

806   Thetford Forest, East Anglia. Forestry 60:193-202.

807

808   Hantula, J., Kasanen, R., Kaitera, J., and Moricca, S. 2002. Analyses of genetic variation suggest

809   that pine stem rust *Cronartium flaccidum* and *Peridermium pini*belong to the same species.

810   Mycological Research 106:203-209.

811

812   Hiratsuka, Y. 1968. Morphology and cytology of aeciospores and aeciospore germtubes of host-

813   alternating and pine-to-pine races of *Cronartium flaccidum* in northern Europe. Canadian Journal

814   of Botany 46:1119-1122.

815

816   Joly, D. L., Langor, D. W., and Hamelin, R. C. 2006. Molecular and morphological evidence for

817   interspecific hybridization between *Cronartium ribicola* and *C. comandrae* on *Pinus flexilis* in

818   Southwestern Alberta. Plant Disease 90:1552.

819

820   Kaitera, J. 1999. *Cronartium flaccidum* fruitbody production on *Melampyrum* spp.

821   and some important alternate hosts to pine. European Journal of Forest Pathology 29:391-398.

822

823   Kaitera, J. 2002. Short-term effect of thinning on *Pinus sylvestris* damage and sporulation

824   caused by *Cronartium flaccidum*. Scandinavian Journal of Forest Research 17:158-165.

825

826   Kaitera, J. 2003. Susceptibility and lesion development in Scots pine saplings infected with

827   *Peridermium pini* in northern Finland. Forest Pathology 33:353-362.

828

829   Kaitera, J., Aalto, T., and Jalkanen, R. 1994. Effect of resin-top disease caused by *Peridermium pini*

830   on the volume and value of *Pinus sylvestris* saw timber and pulp wood. Scandinavian Journal of

831   Forest Research 9:376-381.

832

833   Kaitera, J., and Hantula, J. 1998. *Melampyrum sylvaticum*, a new alternate host for pine stem rust

834   *Cronartium flaccidum*. Mycologia 90:1028-1030.

835

836   Kaitera, J., and Hiltunen, R. 2011. Susceptibility of *Pedicularis* spp. to *Cronartium ribicola* and *C.*

837   *flaccidum* in Finland. Forest Pathology 41:237-242.

838

839   Kaitera, J., and Hiltunen, R. 2012. New alternate hosts for the rusts *Cronartium ribicola* and

840   *Cronartium flaccidum* in Finland. Canadian Journal of Forest Research 42:1661-1668.

841

842   Kaitera, J., Hiltunen, R., and Samils, B. 2012. Alternate host ranges of *Cronartium flaccidum* and

843   *Cronartium ribicola* in northern Europe. Botany 90: 694-703.

844

845   Kaitera, J., Hiltunen, R., and Hantula, J. 2015. *Cronartium* rust sporulation on hemiparasitic plants.

846   Plant Pathology 64:738-747.

847

848   Kaitera, J., Hiltunen, R., Kauppila, T., and Hantula, J. 2017a. Five plant families support natural

849   sporulation of *Cronartium ribicola* and *C. flaccidum* in Finland. European Journal of Plant

850   Pathology 149:367-383.

851

852   Kaitera, J., Hiltunen, R., and Hantula, J. 2017b. *Nasa, Nemesia* and *Euphrasia*:

853   New alternate hosts of *Cronartium* spp. Forest Pathology 47:6

854

855   Kaitera, J., Kauppila, T., and Hantula, J. 2018. New alternate hosts for *Cronartium* spp.: *Odontites*,

856   *Euphrasia*, *Rhinanthus* and *Papaver*. Forest Pathology 48:1-8.

857

858   Kaitera, J., Kalleinen, L., Mikkilä, J., and Hantula, J. 2017c. *Cronartium flaccidum* sporulates on

859   new *Euphrasia* species in natural habitats in Finland. Forest Pathology 47:6.

860

861   Kaitera, J., and Nuorteva, H. 2003a. *Cronartium flaccidum* produces uredinia and teliaon

862   *Melampyrum nemorosum* and on Finnish *Vincetoxicum hirundinaria*. Forest Pathology 33:205-

863   213.

864

865   Kaitera, J., and Nuorteva, H. 2003b. Relative susceptibility of four *Melampyrum* species

866   to *Cronartium flaccidum.* Scandinavian Journal of Forest Research 18:499-504.

867

868   Kaitera, J., and Nuorteva, H. 2008. Inoculations of eight *Pinus* species with *Cronartium* and

869   *Peridermium* stem rusts. Forest Ecology and Management 255:973-981.

870

871   Kaitera, J., Nuorteva, H., and Hantula, J. 2005. Distribution and frequency of *Cronartium*

872   *flaccidum* on *Melampyrum* spp. in Finland. Canadian Journal of Forest Research 35:229-

873   234.

874

875   Kaitera, J., Seitamäki, L., Hantula, J., Jalkanen, R., and Kurkela, T. 1999. Inoculation ofknown

876   and potential alternate hosts with *Peridermium pini* and *Cronartium flaccidum* aeciospores.

877   Mycological Research 103:235-241.

878

879   Kasanen, R. 1997. Aeciospores of *Cronartium flaccidum*, *C. ribicola* and *Endocronartium*

880   *pini* show no differences in morphology. European Journal of Forest Pathology 27:251-260.

881

882   Kasanen, R., Kaitera, J., and Hantula, J. 2000. The genetic composition of *Peridermium pini*

883   and *Cronartium flaccidum* cankers on Scots pine as revealed by two multi-allelic loci. Forest

884   Pathology 30:221-230.

885

886   Kinloch, B. B., Jr. 1972. Genetic variation in resistance to *Cronartium* and *Peridermium* rusts

887   in hard pines. Pages 445-463 in: Biology of rust resistance in forest trees: Proceedings NATO-

888   IUFRO Advanced Study Institute August 17–24 1969. Bingham, R. T., Hoff, R. J., and

889   McDonald, G. I. U.S. Department of Agriculture, Forest Service, Washington, DC.

890

891   Li, J., Yang, Y. H., Zhou, L., and Cheng, L. J. 2013. Destructive effects of a mycoparasite

892   *Trichoderma atroviride* SS003 on aeciospores of *Cronartium ribicola*. Journal of

893   Phytopathology 162:396-401.

894

895   Lovett, G. M., Canham, C. D., Arthur, M. A., Weathers, K. C., and Fitzhugh, R. D. 2006.

896   Forest ecosystem responses to exotic pests and pathogens in eastern North America.

897   BioScience 56:395-403.

898

899   Maloy, O. C. 1997. White pine blister rust control in North America: a case history.Annual

900   Review of Phytopathology 35: 87-109.

901

902   McDonald, G. I., Hoff, R. J., and Wykoff, W. R. 1981. Computer simulation of white pine

903   blister rust epidemics. I. Model formulation. Research Paper INT-258. U.S. Department of

904   Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

905

906   Mittempergher L., and Raddi P. 1977. Variation of diverse sources of *Cronartium flaccidum*. Eur J

907   Forest Pathology 7:93-98.

908

909   Moricca, S., and Ragazzi A. 1996. Culture characteristics and variation of *Cronartium*

910   *flaccidum* isolates. Canadian Journal of Botany 74:924-933.

911   Moricca, S., and Ragazzi A. 1998. Use of RFLP and SSCP analysis to differentiate the

912   pine rust *Cronartium flaccidum* and *Peridermium pini*. Mycological Research 102:666-

913   670.

914

915   Murray, J. S. 1964. Establishment of disease susceptibility plantations. Page 4 in:

916   FAO/IUFRO Symposium on Internationally Dangerous Forest Diseases and Insects. 1964

917   July 20–30. Oxford, UK.

918

919   Murray, J. S., Millar, C. S., and van der Kamp, B. J. 1969. Incidence and importance of

920   *Peridermium pini* (Pers.) Lev. in north-east Scotland. Forestry 42:164-184.

921

922   Özkazanç, N. and Maden, S. 2013. Some important shoot and stem fungi in pine (Pinus spp.)

923   and firs (Abies sp.) in western blacksea region, Turkey. Bartın Orman Fakültesi Dergisi 15:32-

924   38. https://dergipark.org.tr/en/download/article-file/39940

925

926   Pappinen, A., and von Weissenburg, K. 1996. Weevil feeding on Scots pine affects

927   germination of *Endocronartium pini*. European Journal of Forest Pathology 26:225-234.

928

929   Parker, I. M., and Gilbert, G. S. 2004. The evolutionary ecology of novel plant–pathogen

930   interactions. Annual Review of Ecology, Evolution and Systematics 35:675-700.

931

932   Pei, M. H., and Brodie, J. 1995. Inoculation of young pine seedlings with *Peridermium pini* from

933   north-east Scotland. European Journal of Forest Pathology 25:24-30.

934

935 Pitt, D. G., Meyer, T., Park, M., MacDonald, L., Buscarini, T., and Thompson, D. G. 2006.

936 Application of slow-release tablets to enhance white pine regeneration: Growth response and

937 efficacy against white pine blister rust. Canadian Journal of Forest Research 36:684-698.

938

939 Price, R. A., Liston, A., and Strauss, H. 1998. Phylogeny and Systematics of *Pinus*. Pages 49-

940 63 in: Ecology and Biogeography of *Pinus*. Richardson, D. M. ed. Cambridge University Press,

941 Cambridge, UK.

942

943 PRISM. 2021. PRISM Gridded Climate Data. Oregon State University, PRISM Climate Group,

944 Corvallis, OR. http://prism.oregonstate.edu

945

946 Raddi, P., and Fagnani, A. 1978. Relative susceptibility to blister rust caused by

947 *Cronartium flaccidum* of several species of pine. European Journal of Forest Pathology

948 8:58-61.

949

950 Ragazzi, A. 1983. Development of *Cronartium flaccidum* (Alb. et Schw.) Wint. on *Vincetoxicum*

951 *officinale* Moench in connection with some environmental factors. Phytopathologische Zeitschrift

952 108:160-171.

953

954 Ragazzi, A., and Dellavalle Fedi, I. 1992. Penetration of *Cronartium flaccidum* into pine needles.

955 European Journal of Forest Pathology 22:78-283.

956

957 Ragazzi, A., Fedi, I. D., and Mesturino, L. 1986. *Cronartium flaccidum* on *Pinus* spp.: relation of

958 inoculum concentration to symptom development. European Journal of Forest Pathology 16:16-21.

959   Rizzo, D. M., Garbelotto, M., and Hansen, E. M. 2005. *Phytophthora ramorum*: Integrative

960   research and management of an emerging pathogen in California and Oregon forests. Annual

961   Review of Phytopathology 43: 309-335.

962

963   Ruefenacht, B., Finco, M. V., Nelson, M. D., Czaplewski, R., Helmer, E. H., Blackard, J. A.,

964   Holden, G. R., Lister, A. J., Salajanu, D., Weyermann, D., and Winterberger, K. 2008.

965   Conterminous U.S. and Alaska forest type mapping using forest inventory and analysis data. USDA

966   Forest Service - Forest Inventory and Analysis (FIA) Program & Geospatial Technology and

967   Applications Center (GTAC), Salt Lake City, UT.

968

969   SAFARIS. 2021. Spatial Analytic Framework for Advanced Risk Information Systems (SAFARIS).

970   United States Department of Agriculture and North Carolina State University, Raleigh, NC.

971

972   Samils, B., Ihrmark, K., Kaitera, J., Stenlid, J., and Barklund, P. 2011. New genetic markers for

973   identifying *Cronartium flaccidum* and *Peridermium pini* and examining genetic variation within

974   and between lesions of Scots pine blister rust in Sweden. Fungal Biology 115:1303-1311.

975

976   Samils, B., Kaitera, J., Persson, T., Stenlid, J., and Barklund, P. 2021. Relationship and genetic

977   structure among autoecious and heteroecious populations of *Cronartium pini* in northern

978   Fennoscandia. Fungal Ecology 50:101032

979

980   Species Fungorum. 2021. http://www.speciesfungorum.org/names/Names.asp

981   (Accessed: June 2020).

982

983   U.S. EPA. 2003. Generic ecological assessment endpoints (GEAEs) for ecological risk

984   assessment. EPA/630/P02/004F. Risk Assessment Forum. U.S. Environmental Protection

985   Agency, Washington, DC. Retrieved 21 May 2021 from

986   https://www.epa.gov/sites/production/files/2014-11/documents/generic_endpoinsts_2004.pdf

987

988   2019 Census of Horticultural Specialties. Census of Agriculture. National Agricultural

989   Statistics Service. U.S. Department of Agriculture. Retrieved 21 May 2021 from

990   https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Census_of_H

991   orticulture_Specialties/index.php

992

993   Van Arsdel, E. P., Riker, A. J., Kouba, T. F., Suomi, V. E., and Bryson, R. A. 1961. The

994   climatic distribution of blister rust on white pine in Wisconsin. Station Paper No. 87. U.S.

995   Department of Agriculture, Forest Service, Lake States Forest Experiment Station, St.Paul,

996   MN.

997

998   Vogler, D. R., and Bruns, T. D. 1998. Phylogenetic relationships among the pine stem rust fungi

999   (*Cronartium* and *Peridermium* spp.). Mycologia 90:244-257.

1000

1001   Waring, K. M., and O'Hara, K. L. 2005. Silvicultural strategies in forest ecosystem affected by

1002   introduced pests. Forest Ecology and Management 209:27–41.

1003

1004   White, T. J., Bruns, T., Lee, S., and Taylor, J. 1990. Amplification and direct sequencing of

1005   fungal ribosomal RNA genes for phylogenetics. Pages 315-322 in: PCR Protocols: A Guide to

1006   Methods and Applications. Innis, M. A., Gelfand, D. H., Sninisky J. J., and White T. J., editors.

1007   Academic Press, San Diego, CA.

1008

1009   Wijesinghe, S. N., McKenzie, E., Wanasinghe, D. N., Boonmee, S., and Jayawardena,

1010   R. S. 2019. The genus *Cronartium* revisited. Plant Pathology & Quarantine 9: 219–238.

1011

1012   Williams, B. K., Szaro, R. C., and Shapiro, C. D. 2009. Adaptive Management: The U.S.

1013   Department of the Interior Technical Guide. Adaptive Management Working Group, U.S.

1014   Department of the Interior, Washington, DC.

1015   https://www.doi.gov/sites/doi.gov/files/uploads/TechGuide-WebOptimized-2.pdf

1016
1017

1018   Yao, J., and Peixin, W. 1991. A study on the blister rust of *Pinus massoniana* of China. Pages

1019   302-312 in: 3rd IUFRO Rusts of Pine Working Party Conference 1989 September. Banff, AB.

1020   Info. Rep. NOR-X-317. Hiratsuka, Y., Samoil, J. K., Blenis, P. V., Crane, P. E., and Laishley, B.

1021   L. Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Canada.

1022

1023   **XI. Infrastructure and Experts**

1024   The following individuals have in-depth knowledge and/or experience with Scots pine blister

1025   rust:

1026

1027   **United States**

1028   **Paul Zambino**

1029   U.S.D.A. Forest Service, Forest Health Protection

1030   Coeur d'Alene, ID 83815

1031   208-765-7493, paul.zambino@usda.gov

1032   **Bryce A. Richardson**

1033   U.S.D.A. Forest Service, Rocky Mountain Research Station

1034   Moscow, ID 83843

1035   208-883-2322, bryce.richardson2@usda.gov

1036

1037   **Ned B. Klopfenstein**

1038   U.S.D.A. Forest Service, Rocky Mountain Research Station

1039   Moscow, ID 83843

1040   208-883-2310, ned.klopfenstein@usda.gov

1041

1042   **Jane E. Stewart**

1043   Colorado State University, Department of Agricultural Biology

1044   Ft. Collins, CO 80525

1045   970-491-8770

1046   Jane.Stewart@colostate.edu

1047

1048   **Mee-Sook Kim**

1049   U.S.D.A. Forest Service, Pacific Northwest Research Station

1050   Corvallis, OR 97331

1051   541-750-7150

1052   meesook.kim@usda.gov

1053

1054   **Canada**

1055   **Richard Hamelin**

1056   University of British Columbia

1057   Vancouver, BC, Canada

1058   604-827-4441, Richard.hamelin@ubc.ca

1059

1060   **Finland**

1061   **Jarkko Hantula**

1062   Natural Resources Institute Finland

1063   Helsinki, Finland

1064   358-29-532-5419, jarkko.hantula@luke.fi

1065

1066   **Juha Kaitera**

1067   Natural Resources Institute Finland

1068   Oulu, Finland

1069   358- 29-532-5553, juha.kaitera@luke.fi

1070

1071   **Heikki Nuorteva**

1072   Natural Resources Institute Finland

1073   Helsinki, Finland

1074   358-29-532-5459, heikki.nuorteva@luke.fi

1075

1076   **Sweden**

1077   **Berit Samils**

1078   Sveriges lantbruksuniversitet

1079   Uppsala, Sweden

1080   berit.samils@slu.se

1081

1082   **Austria**

1083   **Thomas Kirisits**

1084   University of Natural Resources and Applied Life Sciences, Institute of Forest

1085   Entomology, Forest Pathology and Forest Protection

1086   Vienna, Austria

1087   43-1-47654-91601, thomas.kirisits@boku.ac.at

1088

1089   **Italy**

1090   **Salvatore Moricca**

1091   Universià degli Studi di Firenze, Scienze e Tecnologie Agrarie, Alimentari,

1092   Ambientali e Forestali

1093   Firenze, Italy

1094   salvatore.moricca@unifi.it

1095

1096   **United Kingdom**

1097   **Stephen Woodward**

1098   University of Aberdeen, School of Biological Sciences

1099   Aberdeen, Scotland, UK

1100   44-1224-272669, s.woodward@abdn.ac.kr

1101

1102   **XII. Web Resources**

1103   CABI – *Cronartium flaccidum* (Scots pine blister rust)

1104   https://www.cabi.org/isc/datasheet/16148

1105

1106   Purdue University - The Center for Environmental and Regulatory Information Systems

1107   *Cronartium flaccidum* (Alb. & Schwein) Winter

1108   http://download.ceris.purdue.edu/file/3540

1109

1110   British Columbia Ministry of Forests, Forest Practices Code, Pine Stem Rust Management

1111   Guidebook

1112   https://www.for.gov.bc.ca/ftp/HFP/external/!publish/FPC%20archive/old%20web%20site%20conte

1113   nts/fpc/fpcguide/PINESTEM/pine-toc.htm

1114

1115   EPPO Global Databse - *Cronartium flaccidum*

1116   https://gd.eppo.int/taxon/CRONFL

1117

1118   Plant Parasites of Europe - *Cronartium flaccidum*(Albertini & Schweinitz) Winter, 1880

1119   https://bladmineerders.nl/parasites/fungi/basidiomycota/pucciniomycotina/pucciniales/cronartiaceae

1120   /cronartium/cronartium-flaccidum/

1121

1122   Luke - *Cronartium flaccidum, Peridermium pini*

1123   http://www.metla.fi/metinfo/metsienterveys/lajit_kansi/crflac-n.htm (Finnish)

1124

1125   USDA APHIS – Plant Import Information

1126   https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information

1127

1128   USDA NIFA - Extension

1129   https://nifa.usda.gov/extension

TABLE 1
Pine aecial hosts of *Cronartium pini.*

Host	Geographic Region	Reference
Pinus sylvestris (Scots pine)	temperate and other regions	Kaitera and Hantula 1998
P. pinea (Italian stone pine)	Mediterranean region	CABI 2020
P. mugo (Mountain pine)	Alps and to south and east	Kaitera and Nuorteva 2008
P. nigra (Austrian pine)	Mediterranean region	CABI 2020
P. nigra subsp. *laricio* (Laricio pine) (syn. *P. nigricans*; *P.austriaca*)	Mediterranean region	
P. pinaster (Maritime pine)	Mediterranean and other regions	CABI 2020
P. halepensis (Aleppo pine)	Mediterranean region	Moricca and Ragazzi 1996
P. densiflora	Japan	CABI 2020
P. brutia	Turkey	CABI 2020
P. koraiensis		CABI 2020
P. massoniana	China	Yao and Peixin 1991
P. pumila		CABI 2020
P. radiata		CABI 2020
P. ponderosa		Gibbs and Kaitera 2018
P. tabuliformis	China	Yao and Peixin 1991
P. taiwanensis		CABI 2020
P. takahasii		CABI 2020
P. uncinata		CABI 2020
P. wallichiana		CABI 2020
P. yunnanensis		CABI 2020

1130   Pine taxonomy follows Price et al. (1998)
1131

TABLE 2
Angiosperm telial (alternate) hosts of *Cronartium pini*.

Host	Reference
Melampyrum sylvaticum	Kaitera and Hantula 1998; Kaitera et al. 1999, 2012; Kaitera 1999; Kaitera and Hiltunen 2011
Melampyrum pratense	Kaitera 1999; Kaitera et al. 2012
Melampyrum nemorosum	Kaitera and Nuorteva 2003a
Melampyrum arvense	Kaitera and Nuorteva 2003b
Pedicularis palustris ssp. *palustris*	Kaitera et al. 1999, 2012; Kaitera and Hiltunen 2011
Pedicularis sceptrum-carolinum	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2015
Pedicularis dolichorrhiza	Kaitera et al. 2012
Pedicularis lapponica	Kaitera and Hiltunen 2011
Pedicularis groenlandica	Kaitera et al. 2015
Verbena x hybrida	Kaitera and Hiltunen 2012
Verbena canadensis	Kaitera et al. 2012
Verbena officinalis	Kaitera and Hiltunen 2012
Vincetoxicum hirundinaria	Kaitera et al. 1999, 2012, 2015, 2017b; Kaitera and Hiltunen 2011, 2012
Vincetoxicum mongolicum	Kaitera et al. 1999
Vincetoxicum fuscum	Kaitera et al. 1999
Vincetoxicum nigrum	Kaitera et al. 1999
Paeonia lactiflora	Kaitera et al. 2012, 2018
Paeonia anomala	Kaitera et al. 1999, 2012; Kaitera and Hiltunen 2012
Paeonia obovata	Kaitera et al. 2012
Paeonia officinalis	Kaitera et al. 1999, 2015
Paeonia tenuifolia	Kaitera et al. 2015
Paeonia mlokosewitchii	Kaitera et al. 2017a
Paeonia oreogeton	Kaitera et al. 2017a
Grammatocarpus volubilis	
Impatiens glandulifera	Kaitera and Hiltunen 2012; Kaitera et al. 2015
Impatiens balsamina	Kaitera et al. 2012, 2015
Impatiens parviflora	Kaitera et al. 2018
Loasa (Nasa) tricolor	Kaitera et al. 2012, 2015
Loasa (Nasa) triphylla	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2017b
Loasa (Nasa) urens	Kaitera et al. 2017b
Nemesia versicolor	Kaitera and Hiltunen 2012
Nemesia strumosa	Kaitera and Hiltunen 2012
Nemesia floribunda	Kaitera et al. 2017b
Tropaeolum majus	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2015, 2017b
Veronica longifolia	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2015
Veronica incana	Kaitera et al. 2015
Veronica daurica	Kaitera et al. 2012, 2015, 2017b
Veronica grandis	Kaitera et al. 2015
Veronica krylovii	Kaitera et al. 2015
Apocynum cannabinum	Kaitera et al. 2015
Asclepias incarnata	Kaitera and Hiltunen 2012
Bartsia alpina	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2017b
Caiophora lateritia	Kaitera et al. 2012

Castilleja miniata	Kaitera et al. 2015
Delphinium elatum	
Euphrasia stricta	Kaitera and Hiltunen 2012; Kaitera et al. 2012, 2015, 2017b, 2018
Euphrasia breivipila	Kaitera et al. 2015
Euphrasia officinalis	Kaitera et al. 2015
Euphrasia minima	Kaitera et al. 2015
Euphrasia nemorosa	Kaitera et al. 2017c
Euphrasia frigida	Kaitera et al. 2017c
Gentiana verna	
Hyoscyamus niger	Kaitera et al 2015
Myrica gale	Kaitera et al. 2012, 2015
Nicotiana rustica	Kaitera et al. 2015
Odontites verna	Kaitera et al. 2018
Papaver rhoeas	Kaitera et al. 2018
Rhinanthus minor	Kaitera et al. 2015
Rhinanthus aestivalis	Kaitera et al. 2015
Rhinanthus serotinus	Kaitera et al. 2018
Ruellia elegans	
Saxifraga hostii	Kaitera et al. 2012, 2015
Saxiraga cespitosa	Kaitera et al. 2012
Saxifraga exarata	Kaitera et al. 2012
Schizanthus grahamii	
Siphonostegia chinensis	Yao and Peixin 1991
Swertia fedtchenkoana	Kaitera et al. 2012, 2015

1132
1133

1134 **Figure Legends**

1135

1136 **FIGURE 1**

1137 Scots pine blister rust (resin-top disease) caused by *Cronartium pini* on Scots pine (*Pinus*

1138 *sylvestris*). Photos by Juha Kaitera.

1139 **FIGURE 2**

1140 Damage caused by *Cronartium pini* on Scots pine (*Pinus sylvestris*). (A) Branch mortality caused

1141 by the heteroecious form, where the branch tip has died distal to a branch lesion. (B) Tree mortality

1142 caused by the heteroecious form, where the tree has been killed above a stem lesion. (C) Rust

1143 damage caused by the autoecious form. In the center, the stem leader of the tree has been killed

1144 above a stem lesion, while the lower canopy is still alive. On the right, a whole tree has been killed

1145 by Scots pine blister rust. An old stem lesion where sporulation occurred, which that is blackened

1146 and resinous, is located on the lower stem. (Photos by Juha Kaitera).

1147 **FIGURE 3**

1148 Scots pine blister rust (*Cronartium pini*) disease cycle.

1149 **FIGURE 4**

1150 (A) Spermatial droplets of the heteroecious form of *Cronartium pini* on Scots pine (*Pinus*

1151 *sylvestris*). (B) Aecia of the autoecious form of *C. pini* on Scots pine. (Photos by Juha Kaitera).

1152 **FIGURE 5**

1153 Uredinia and telia of the heteroecious form of *Cronartium pini* on *Vincetoxicum hirundinaria*

1154 (Swallow-wort) (A) and *Euphrasia officinalis* (B). (Photos by Juha Kaitera).

1155 **FIGURE 6**

1156 Scots pine blister rust (*Cronartium pini*) infection risk levels in the contiguous United States.

1157 **FIGURE 7**

1158 (A) Old sporulated lesion with new aecia of the autoecious form of *Cronartium pini* on Scots pine

1159 (*Pinus sylvestris*), (B) Swelling with spermogonia of *C. pini* on Scots pine. (Photos by Juha

1160 Kaitera).

Figure 1. Scots pine blister rust (resin-top disease) caused by *Cronartium pini* on Scots pine (*Pinus sylvestris*). Photos by Juha Kaitera.
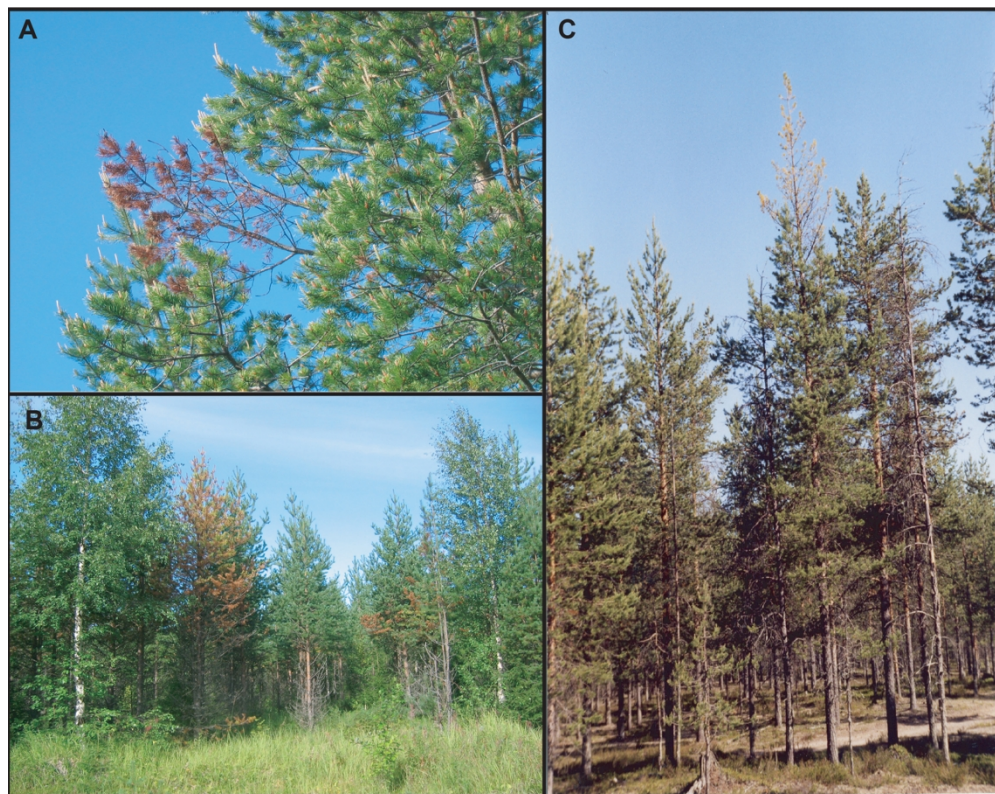
67x96mm (900 x 900 DPI)

Figure 2. Damage caused by *Cronartium pini* on Scots pine (*Pinus sylvestris*). (A) Branch mortality caused by the heteroecious form, where the branch tip has died distal to a branch lesion. (B) Tree mortality caused by the heteroecious form, where the tree has been killed above a stem lesion. (C) Rust damage caused by the autoecious form. In the center, the stem leader of the tree has been killed above a stem lesion, while the lower canopy is still alive. On the right, a whole tree has been killed by Scots pine blister rust. An old stem lesion where sporulation occurred, which that is blackened and resinous, is located on the lower stem. (Photos by Juha Kaitera).
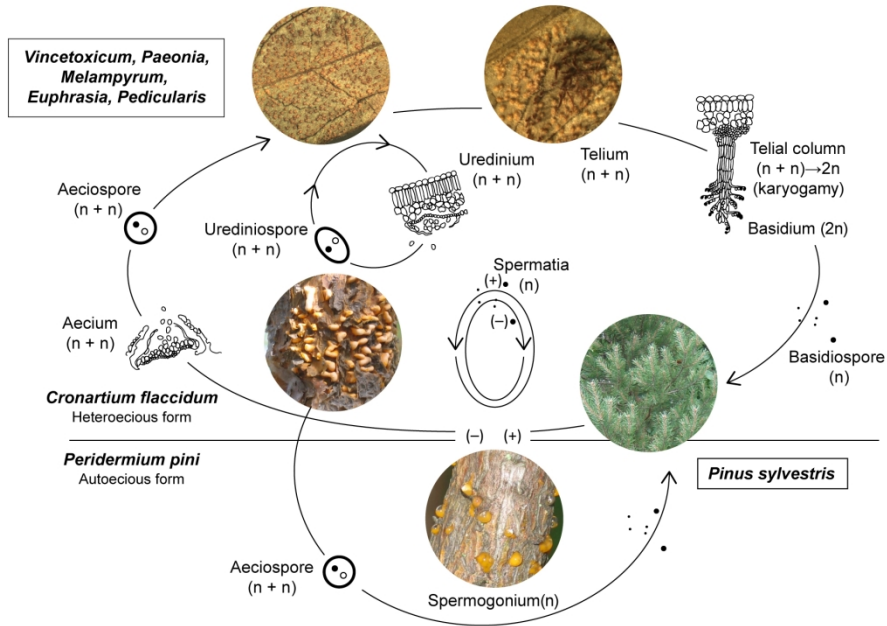
177x140mm (300 x 300 DPI)

Figure 3. Scots pine blister rust (*Cronartium pini*) disease cycle.
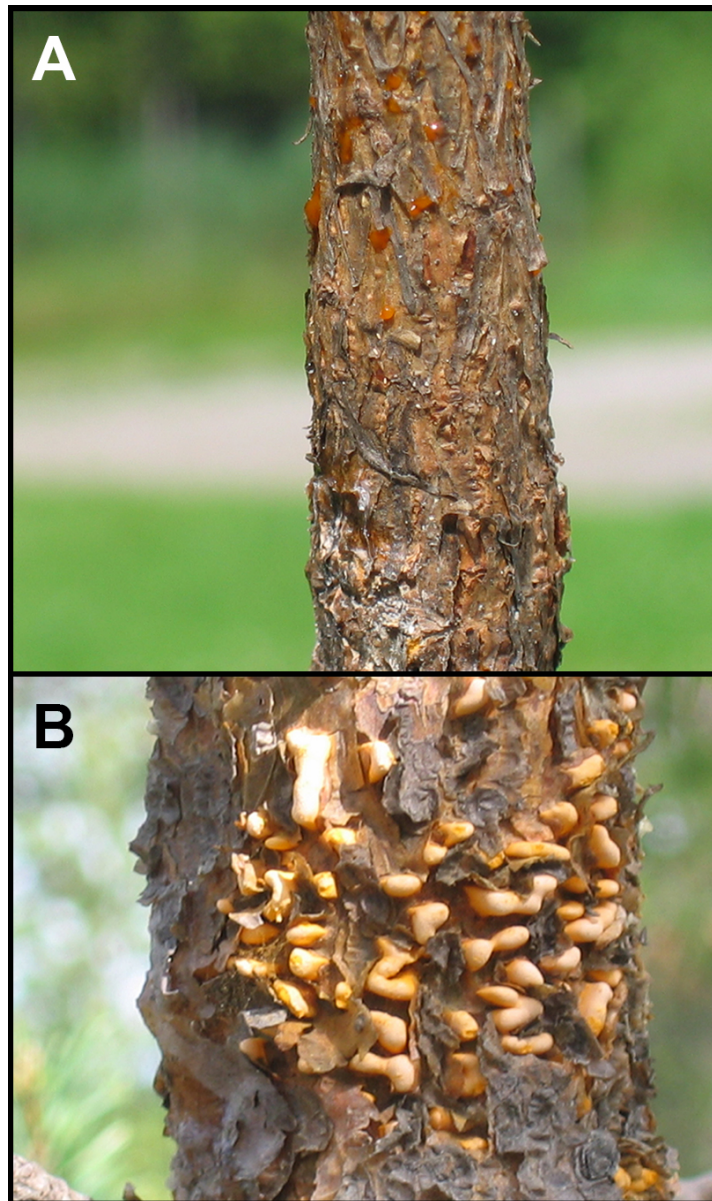
533x387mm (100 x 100 DPI)

Figure 4. (A) Spermatial droplets of the heteroecious form of *Cronartium pini* on Scots pine (Pinus sylvestris). (B) Aecia of the autoecious form of *C. pini* on Scots pine. (Photos by Juha Kaitera).
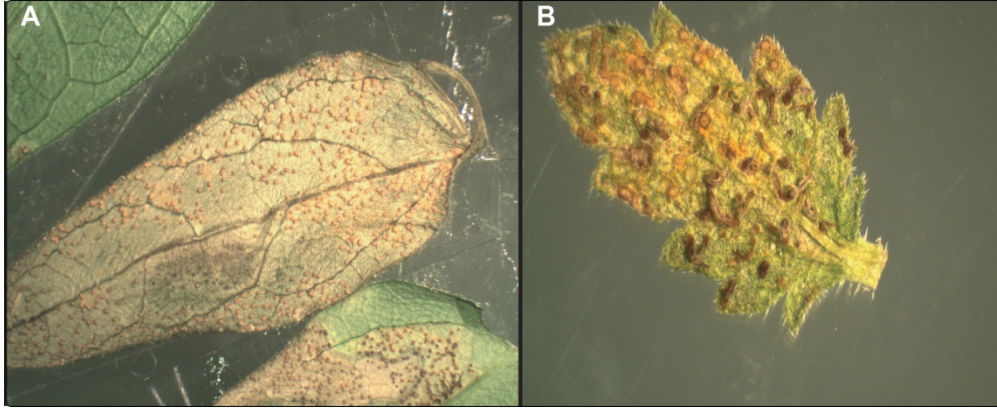
68x115mm (300 x 300 DPI)

Figure 5. Uredinia and telia of the heteroecious form of *Cronartium pini* on *Vincetoxicum hirundinaria* (Swallow-wort) (A) and *Euphrasia officinalis* (B). (Photos by Juha Kaitera).

177x72mm (300 x 300 DPI)

Scots Pine Blister Rust: *Cronartium pini* (Willd.) Jørstad

Risk Map

Risk Levels

Low

High

The risk was determined by 1) the number of days per year on average that had suiitable germination conditions using 2000 to 2019 weather data, 2) average annual precipitation from 2000 to 2019, and 3) *Pinus* spp. distribution.

0 125 250   500   750   1,000 Km

Date Created: June 10, 2021
Data Source: PRISM, 2021; SAFARIS, 2021;
  Ragazzi, 1983; Ragazzi et al, 1986;
  Ruefenacht et al, 2008
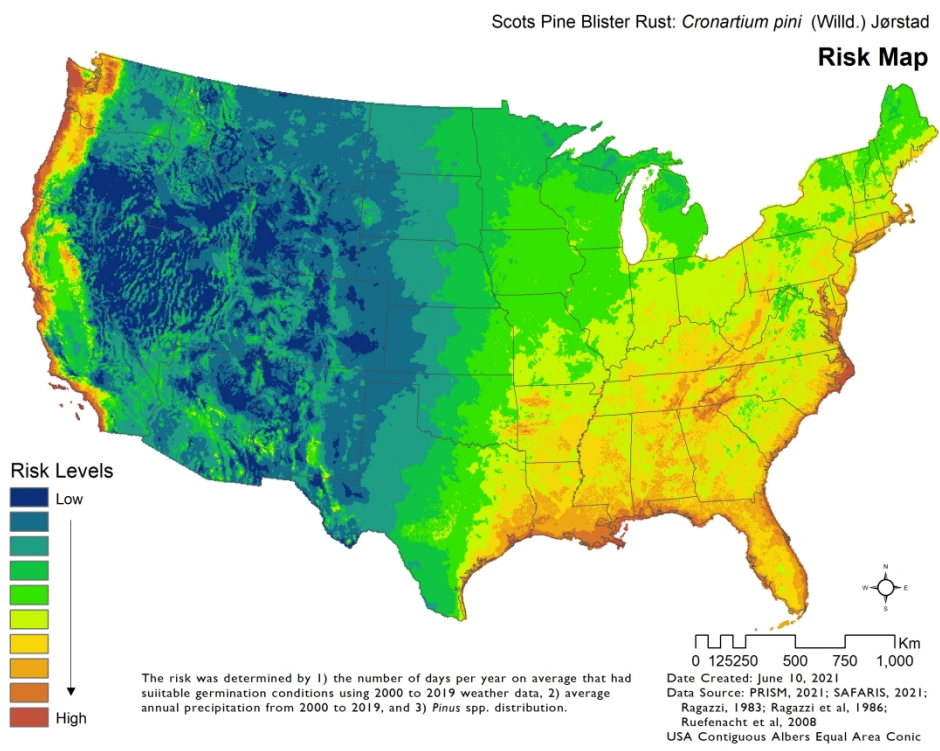USA Contiguous Albers Equal Area Conic

Figure 6. Scots pine blister rust (*Cronartium pini*) infection risk levels in the contiguous United States.
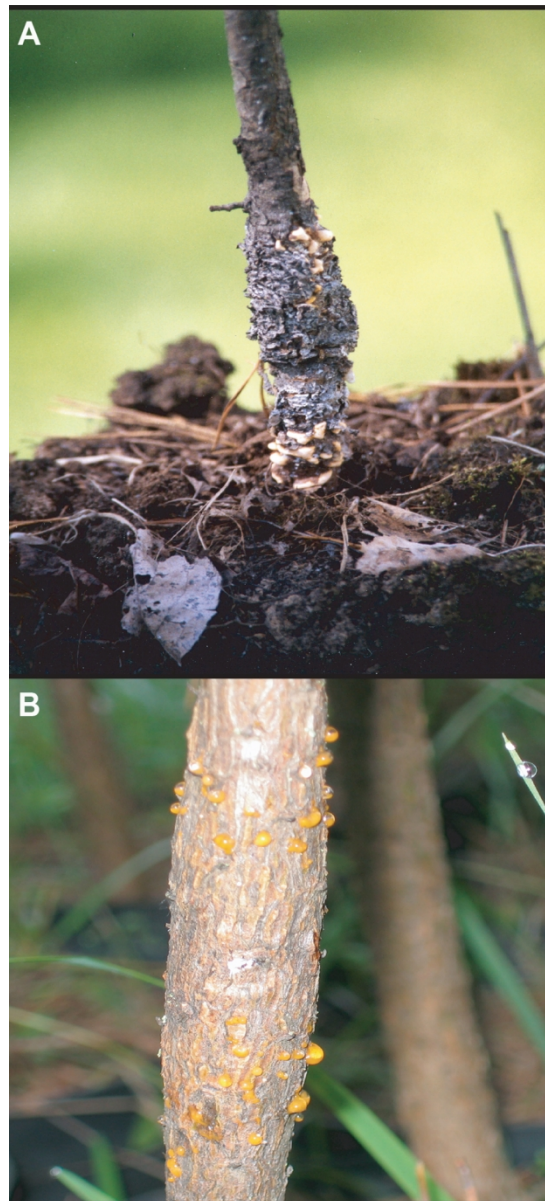
279x215mm (300 x 300 DPI)

Figure 7. (A) Old sporulated lesion with new aecia of the autoecious form of *Cronartium pini* on Scots pine (*Pinus sylvestris*), (B) Swelling with spermogonia of *C. pini* on Scots pine. (Photos by Juha Kaitera).

82x180mm (300 x 300 DPI)