

## *Phytophthora* Species, New Threats to the Plant Health in Korea

Ik-Hwa Hyun<sup>1</sup> and Woobong Choi<sup>2\*</sup>

<sup>1</sup>Plant Quarantine Technology Center, Animal and Plant Quarantine Agency, Suwon 443-400, Korea

<sup>2</sup>Department of Biotechnology and Bioengineering, Donggeui University, Busan 614-714, Korea

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Given the lack of a resistant genetic pool in host plants, the introduction of exotic invasive pathogens can result in epidemics that affect a specific ecosystem and economy. Plant quarantine, which is designed to protect endemic plant resources, is a highly invaluable safeguard that should keep biosecurity with increasing international trade and global transportation. A total of 34 species of plant pathogens including *Phytophthora infestans* were documented as introduced from other countries into Korea from 1900 to 2010. The genus *Phytophthora*, classified in oomycetes, includes more than 120 species that are mostly recognized worldwide as highly invasive plant pathogens. After 2000, over 50 new species of *Phytophthora* were identified internationally as plant pathogens occurring in crops and forest trees. In Korea, *Phytophthora* is also one of the most serious plant pathogens. To date, 22 species (about one-fifth of known species) of the genus have been identified and reported as plant pathogens in the country. The likelihood of new exotic *Phytophthora* species being introduced into Korea continues to increase, thus necessitating intensive plant quarantine inspections. As new potential threats to plant health in Korea, six *Phytophthora* species, namely, *P. alni*, *P. inundata*, *P. kernoviae*, *P. pinifolia*, *P. quercina*, and *P. ramorum*, are discussed in this review with focus on history, disease, biology, management, and plant quarantine issues.

**Keywords :** eradication, exclusion, exotic plant pathogens, plant quarantine, *Phytophthora* species, *P. alni*, *P. inundata*, *P. kernoviae*, *P. pinifolia*, *P. quercina*, *P. ramorum*

### Invasive exotic plant pathogens and *Phytophthora* spp.

An ecosystem is characterized by diverse but balanced biological factors that stem from long-term co-evolution, during which hosts and pathogens interact with each other under various environmental conditions. Plant pathogens infect host plants, which accordingly develop protective mechanisms. Native plant pathogens may not cause dramatic yield loss unless plants are subjected to extreme environmental changes that are conducive to disease development. The introduction of exotic plant pathogens, however, can result in new disease epidemics that can be ecologically and economically difficult to manage. In human history, a number of exotic invasive plant pathogens have considerably influenced the lives of plants and human beings (Agrios, 2011). *Phytophthora infestans*, which causes late blight in potato, is considered as one of the most destructive exotic plant pathogens; for instance, it was responsible for the Irish potato famine that resulted in the death of more than a million people (Schumann, 1991). *P. cinnamomi*, the causal agent of root rot in a wide range of hosts worldwide, has spread more than 100 years from its presumed center of origin within southeast Asia (Hardham, 2005). The introduction of *Cryphonectria parasitica*, which causes chestnut blight, resulted in the virtual destruction of American chestnut forests through most of their natural ranges in the US. The damage was inflicted over the course of 30 years. Subsequently, the pathogen was introduced to Europe and affected native chestnut trees in the region (Anagnostakis, 1987).

As indicated by documents, the exotic plant pathogens in Korea have a history of more than 100 years. A total of 34 species were introduced from other countries from 1900 to 2010 (NPQS, 2010). A rapid increase in the identification of newly arriving species occurred after 1970, a year accompanied by the growth of global-scale trade that took place in conjunction with the industrial development of Korea. The risk of invasion by exotic plant pathogens has

\*Corresponding author.

Phone) +82-51-890-2279, FAX) +82-51-890-2632

E-mail) wbchoi@deu.ac.kr

recently become a more serious matter because of the increase in the number of agricultural products imported into the country. Such increase was facilitated by the expansion of the Free Trade Agreement. In addition to new species, new strains are introduced into certain regions, thereby potentially resulting in unexpected damage to plant health. New strains that differ from native or old strains have pathogenic properties or fungicide resistance and can therefore induce newly emerging epidemics. Moreover, genetic exchange between old and new strains may produce “super strains” that possess increased aggressiveness. Under this backdrop, the exclusion and eradication of exotic plant pathogens are major targets stipulated in plant health and quarantine regulations.

The genus *Phytophthora*, known as the “plant destroyer,” is an oomycete previously classified as a fungus but is now considered a fungal-like member of the Kingdom Chromista (Agrios, 2011). The genus currently comprises more than 120 known species (Kroon et al., 2012). After 2000, more than 50 new *Phytophthora* species were identified worldwide as plant pathogens in crops and forest trees. This rapid increase in the recognition of new *Phytophthora* species was facilitated by the use of efficient molecular technology and intensive surveys. Many molecular techniques, such as protein electrophoresis, determination of isozyme pattern, PCR-based DNA fingerprinting, and direct sequencing of internal transcribed spacer (ITS) and genes, have been adopted for the effective and rapid identification of the species belonging to *Phytophthora*. (Kroon et al., 2012).

In Korea, 22 *Phytophthora* species, including *P. cactorum*, *P. capsici*, *P. cinnamomi*, *P. infestans*, *P. nicotianae*, *P. palmivora*, *P. parasitica*, *P. sojae*, and *P. syringae*, have been identified and reported to cause diseases mainly in crop plants (KSPP, 2009). Amid growing concerns over plant health in the country, crop plants have been highlighted as priority types of vegetation for management. A deterrent to this goal is the fact that about 70% of Korean territory is covered by mountainous areas. The decades-long and extensive tree planting campaigns spearheaded by the Korean government have resulted in huge biomass- and biodiversity-related changes in the forest ecosystem. Such changes, in turn, have enabled natural resource abundance in forests. Given the increasingly important roles of forest ecosystems in industries and citizen service, more intensive care should be directed toward appropriately maintaining ecosystem health. The case of pine wood nematode is a well-known example of an exotic pest that exerted serious effects on a forest system. This pest particularly affected pine trees and the pine wood industry. After introduction

from Japan via contaminated logs, pine wood nematode spread to the southern region of the peninsula and has recently proliferated over the northern part given the climatic change that affects the activity of vector insect, Japanese pine sawyer. The introduction of new *Phytophthora* species into Korea would threaten plant health both in agricultural and natural forest ecosystems.

This review focuses primarily on *Phytophthora* species that threaten the health of forest trees. Six *Phytophthora* species, namely, *P. alni*, *P. inundata*, *P. kernoviae*, *P. pinifolia*, *P. quercina*, and *P. ramorum*, were chosen because of their potential effects. The discussion of these species revolves around history, disease, pathogenic biology, management, and plant quarantine issues.

### ***Phytophthora* species that exert potential threats on plant health in Korea**

#### ***P. alni* as causal agent of alder root rot**

**History.** An unusual *Phytophthora* species was isolated from dying alder, *Alnus glutinosus*, in southern Britain in 1993 and 1994 (Gibbs, 2003). It killed approximately 10% of the alders in the region within a few years of its early discovery (Brasier et al., 1995). The pathogen was initially identified as *P. cambivora*, a well-known pathogenic fungus that attacks broadleaved trees but previously unreported for its occurrence in alder. The pathogen was later identified as a new species and formally named *Phytophthora alni* by Brasier et al. (2004).

**Disease.** Alder root rot widely grows in Europe, specifically in 18 countries, namely, Austria, Belgium, Czech Republic, England, Estonia, France, Germany, Hungary, Ireland, Italy, Lithuania, The Netherlands, Poland, Scotland, Slovakia, Slovenia, Spain, and Sweden ([www.forestry.gov.uk/palni](http://www.forestry.gov.uk/palni)). *P. alni* has recently been found in North America (Adams et al., 2008). In 2007, Oregon listed *P. alni* as one of its “100 most dangerous invasive species.” It causes lower stem bark lesions, root and collar necrosis, and crown dieback that are typical of other *Phytophthora* diseases. Diseased trees do not show crown symptoms until most of the bark at the base of a tree has been killed (Brasier et al., 1995). Typical symptoms in affected trees are abnormally small, yellow, and sparse leaves and the presence of tarry or rusty exudations on stem lesions. *P. alni* attacks a relatively narrow host range, which includes *Alnus cordata*, *A. glutinosa*, *A. incana*, and *A. viridis* (Brasier et al., 1995). In greenhouse inoculation trials, *Castanea sativa* (chestnut), *Juglans regia* (walnut), and *Prunus avium* (sweet cherry) were determined as experimental hosts (Santini et al.,

2006). Heavy loss of alders due to *Phytophthora* infection can cause significant ecological effects, such as changes in forest composition, soil composition, and wildlife food and habitat, as well as increased soil erosion (<http://spfnic.fs.fed.us/exfor/data/pestreports.cfm?pestidval=28&langdisplay=english>). Local spread from points of *P. alni* introduction is unlikely related to the movement of oospores because these structures have poor survival ability in soil (Delcan and Brasier, 2001). More likely, zoospores and plant debris that contain mycelium contribute to pathogen movement at this scale. Alders are key trees in wetlands and riparian environments, where they stabilize river and stream banks. In these habitats, the presence of saturated or flooded soils and the occurrence of water movement enhance the spread of zoospores and debris. This scenario is supported by observations of higher disease incidence among alders that grow near rivers than among those growing some distance away (Gibbs et al., 1999).

**Biology.** The optimum temperature of *P. alni* in culture is 22.5–25.0°C, with an upper temperature limit at about 30°C (Brasier et al., 2004). The pathogen is homothallic and produces oospores in culture, but viability is very low and no germination occurs (Brasier et al., 2004). The pathogen has several unusual properties and has been suggested as a new species hybrid, which probably emerged relatively recently (Brasier et al., 1995). Because this new *Phytophthora* hybrid does not consist of a single entity but comprises a range of phenotypically diverse allopolyploid genotypes, *P. alni* was classified into three subspecies: *P. alni* subsp. *alni* (*Paa*), *P. alni* subsp. *multiformis* (*Pam*), and *P. alni* subsp. *uniformis* (*Pau*) (Brasier et al., 2004). Ioos et al. (2006) demonstrated that *Paa* may have been generated on several occasions by hybridization between *Pam* and *Pau* or between their respective ancestors. *Pau* may have *P. cambivora* as a species ancestor, whereas *Pam* appears to have grown by itself either via ancient reticulation or via autopolyploidization (Ioos et al., 2006). The variants differ in terms of virulence and pathogenicity toward European alders, but *Paa* appears to be the most aggressive and pathogenic to such tree species (Brasier and Kirk, 2001). The two other variants, *Pam* and *Pau*, appear to be significantly less aggressive than *Paa* but are still considered pathogenic. The *Paa* variant is regarded as the primary agent that kills alders in Europe and is the most frequently occurring subspecies in the region.

**Plant quarantine issues.** Alder trees, including *A. sibirica*, *A. firma*, and *A. japonica*, are important species in Korean forest ecosystems. When *P. alni* is introduced from for-

eign countries, the aforementioned alder species may be severely damaged. This pathogen has been regulated as a quarantine pathogen since 2006. Careful inspection should be conducted during quarantine procedures, especially on nursery plants that harbor the pathogen.

#### ***P. inundata* as causal agent of root and collar rot**

**History.** A new *Phytophthora* species occurring in horse chestnut was reported in the UK in early 1970, and this *Phytophthora* was informally designated as belonging to the O-group (Brasier et al., 1993). Brasier et al. (2003) formally identified this pathogen as a new species and named it *P. inundata*, which has also been isolated from a variety of riparian habitats in Europe (Brasier et al., 2003). They occurred in susceptible hosts, such as the ornamental *Aesculus* and *Salix* spp., and from commercially cultivated *Olea* and *Prunus* spp. after soil flooding or water logging (Brasier et al., 2003). *P. inundata* was isolated from parsley crops and soil around carrot in Australia (Cunnington et al., 2006), diseased alfalfa roots in the US (Ho et al., 2006), foot and root rot of citrus trees in Chile (Vial et al., 2006), and more recently, from native vegetation in Australia (Stukely et al., 2007). Furthermore, the pathogen was isolated from pistachio trees and infected sugar beet and *Solanum dulcamara* roots in Iran (Mostowfizadeh-Ghalamfarsa et al., 2006). These results indicate that the worldwide distribution of *P. inundata* is not restricted to trees.

**Disease.** *P. inundata* causes root and collar rot in ornamental and horticultural shrubs and trees, including *Aesculus*, *Olea*, *Salix*, tobacco, *Prunus*, and *Viburnum*. It was also found in alfalfa roots (Parkunan, 2010). Despite these valuable findings, little is known about the disease dispersal and disease cycle of *P. inundata*.

**Biology.** *P. inundata* is grouped within major ITS clade 6 (Cooke et al., 2000), and its closest relative in the clade is the homothallic *P. Humicola*, as confirmed in a recent study on *Phytophthora* species from ITS clade 6 subclade I (Jung et al., 2011). It has nonpapillae sporangia, fairly large oogonia with thick-walled oospores, amphigynous antheridia, and a distinctive colony type. No chlamydospore was observed in many trials (Brasier et al., 2003; Safaiefarahani et al., 2013). *P. inundata* shows optimal growth at 30°C and a high upper temperature limit for growth of 35–37°C (Brasier et al., 2003). The pathogen is classically heterothallic, with A1 and A2 compatibility types (Brasier et al., 2003), but it shows many cases of unsuccessful mating, indicating a partial breakdown of the sexual mechanism in the species. Safaiefarahani et al. (2013) reported limited

variance among isolates from different plants in terms of pathogenicity, molecular attributes, and morphological traits. The authors suggested the possibility of recent derivation of *P. inundata* from other *Phytophthora* species.

**Management.** Nested-PCR has been employed as a diagnostic tool for identifying *P. inundata*; this method is also a reliable and effective way of detecting infection in host plant parts and infested soil (Safaiefarahani et al., 2013). Appropriate water management is highly recommended in the cultivation of known hosts with *P. inundata* infection. The practical application of fungicide treatment methods, such as the use of phosphonates, requires further investigation.

**Plant quarantine issues.** *P. inundata* has not been listed as a quarantine pathogen in Korea. A pest risk assessment is required for *P. inundata* to be included in the list and for the species to be further examined.

#### ***P. kernoviae* as causal agent of trunk canker, leaf blight, and stem dieback**

**History.** An unknown *Phytophthora* species was discovered from a bleeding lesion on a mature European beech, *Fagus sylvatica*, and concurrently from *Rhododendron* in 2003 in the southwest of England during surveys on *P. ramorum*. The new *Phytophthora* was informally designated *Phytophthora* taxon C and later named *P. kernoviae* by Brasier et al. (2005). Since then, *P. kernoviae* has also been found in Scotland, Ireland, and New Zealand (EPPO, 2013).

**Disease.** Two different symptoms are observed: bleeding cankers and leaf lesions (Brasier et al., 2005). Identifying the symptoms caused by *P. kernoviae* can be a confusing task because such symptoms are similar to those caused by *P. ramorum*. *P. kernoviae* sporulates on foliage hosts and is dispersed by rain to bole hosts where cankers develop. The pathogen attacks *Aesculus hippocastanum*, *Annona cherimola*, *Castanea sativa*, *Drimys winteri*, *Fagus sylvatica* (European beech), *Gevuina avellana* (Chilean hazelnut), *Hedera helix*, *Ilex aquifolium*, *Liriodendron tulipifera* (tulip tree), *Lomatia myricoides*, *Magnolia* sp., *Michelia doltsopa*, *Pieris* spp., *Podocarpus salignus*, *Prunus laurocerasus*, *Quercus ilex* (holm oak), *Q. robur* (English oak), *Rhododendron ponticum*, *Sequoiadendron giganteum*, and *Vaccinium myrtillus* (EPPO, 2013). On the basis of experience with *P. ramorum*, the host range of *P. kernoviae* is expected to expand with time and more surveys. A regularly updated host list can be found on the Defra website ([http://](http://www.gov.uk/defra)

[www.gov.uk/defra](http://www.gov.uk/defra)). Caduceus sporangia with zoospores most probably spread locally by water splash or through airborne mist droplets. Under suitable conditions, asexual reproduction takes place and new sporangia are produced. Oospores have been produced by *P. kernoviae* under laboratory conditions but have not been observed in naturally infected plants. Chlamydospores have never been observed in the laboratory or in the field (EPPO, 2013). Further studies on the disease cycle of *P. kernoviae* are needed. Long-distance spreading can be facilitated by the movement of infected rhododendron, beech, and other hosts. *P. kernoviae* is apparently not a root pathogen, but it can be isolated from soil. Soil movement may also spread the disease. *P. kernoviae* appears to be more virulent than *P. ramorum* on some hosts. The potential risk of lateral transfer of genes from other *Phytophthora* should be examined further. Similar to *P. ramorum*, *P. kernoviae* presents a risk to both forestry and nursery industries (EPPO, 2013).

**Biology.** The optimal temperature for *P. kernoviae* growth on carrot agar is approximately 18°C, with the upper growth temperature limit at around 26°C (Brasier et al., 2005). This temperature maximum is slightly higher than those of *P. hibernalis*, *P. illicis*, and *P. nemorosa* but significantly lower than those of *P. botryosa*, *P. heveae*, *P. katsurae*, *P. meadii*, and *P. megakarya* (Gallegly and Hong, 2008). These temperature differences can be used as an additional characteristic that distinguishes *P. kernoviae* from other species with a similar morphology. The growth characteristics on agar and morphological features of *P. kernoviae* are described in Brasier et al. (2005). The pathogen is homothallic and produces amphigynous antheridia and caducous and conspicuously papillate sporangia (Brasier et al., 2005). Although oospore production is abundant in culture, the pathogen's ability to produce oospores in naturally infected plant tissues remains unknown (Brasier et al., 2005). Because chlamydospores have not been reported for this species, oospore production and subsequent survival can serve as critical epidemiological factors. The origin of *P. kernoviae* is currently unknown.

**Management.** *P. kernoviae* can be detected in host tissue by direct isolation, ELISA, and real-time TaqMan PCR (EPPO, 2013). However, because *P. kernoviae* has also been associated with asymptomatic tissues, monitoring poses special challenges for inspectors and regulators. Such challenges are attributed to the possibility that roots and asymptomatic tissues may be hidden pathways of movement. Two real-time TaqMan diagnostic procedures for the detection of *P. kernoviae* have been reported in the literature:

one relies on the ITS region in detection and the other uses the spacer region in the ras-related protein *Ypt1* (Schena et al., 2006). Thus far, control measures are essentially based on the destruction of infected plants, particularly rhododendrons in infected woodlands. More studies on possible practical control measures are required.

**Plant quarantine issues.** The introduction of *P. kernoviae* to Korea can threaten both forest and nursery systems. A necessary task is to create a *P. kernoviae* risk map that considers climate, host density, sporulation potential, and introduction pathways. A monitoring program is also required to determine whether *P. kernoviae* has occurred or has been introduced to Korea.

#### ***P. pinifolia* as causal agent of pine needle blight**

**History.** Since 2004, a new disease that affects *Pinus radiata* has occurred in the Arauco province of Chile and subsequently spread to other areas. Referred to as “Daño Foliar del Pino” (DFP), the disease was officially named the pathogen *P. pinifolia* by Duran et al. (2008).

**Disease.** *P. pinifolia* is presently known to occur only in Chile, and the pathogen causes serious needle blight. Symptoms begin with a reddening of the past year’s needles in early winter. The first needles to display symptoms are those on the lower sides of branches. Needles die and assume a distinctly gray color and begin to fall. Initially, dead and dying needles are retained on branches, thereby giving trees the appearance of having been severely scorched. The needles then fall from the trees, which can be almost completely defoliated. New needle growth is unaffected and trees appear to recover until infection re-occurs in the following season. After two or three years of defoliation, trees occasionally die; death may be hastened by infection from *Diplodia pinea* (Diplodia blight of pine), which is a well-known opportunistic pathogen (Duran et al., 2008). *Pinus radiata* (Monterey pine) is the only known natural host for *P. pinifolia*, but Ahumada et al. (2013) found that *P. pinifolia* is not specific to *P. radiata* and infects many other tested *Pinus* species. In Korea, *P. densiflora*, *P. koraiensis*, and *P. thunbergii* are the major species in pine tree forests. These Korean pine tree species were not included in the pathogenicity test conducted by Ahumada et al. (2013). DFP is generally recognized in Chile as the most serious problem to have affected pine forestry in the country (Duran et al., 2008). The discovery of an aerial *Phytophthora* spp., which causes serious disease in Chilean *P. radiata*, adds to the new and serious tree-infecting aerial *Phytophthora* spp. that have recently been discovered. Newly planted seed-

lings and naturally regenerated plants die when infected in the first year of growth. Such death rate makes *P. pinifolia* a serious threat to reforestation.

**Biology.** Although the symptoms of DFP in Chile are consistent with the biology of an aerial *P. pinifolia*, many as-yet unanswered questions surround the biology of the pathogen. Sporangia are assumed to be the infective propagules, but such proposition requires experimental support. Sporangia proliferate to a limited extent in culture; thus, natural conditions in which to produce them should be developed. Infection studies that use zoospores are needed, and the infection biology and lifecycle of the pathogen remain unelucidated (Duran et al., 2008). Ahumada et al. (2013) reported that sporangia commonly remain on needles for extended periods under rainy conditions.

**Plant quarantine issues.** The National Plant Quarantine Service has prohibited the import of *P. radiata* seeds, seedlings, hard wood, and lumber from Chile since 2008.

#### ***P. quercina* as causal agent of oak decline**

**History.** *P. quercina* causes oak decline and root rot in oak. *P. quercina* was initially observed in central and southern Europe in early 1990 and formally named by Jung et al. (1999). The species name “quercina” was taken from the Latin word for oak, *quercus*.

**Disease.** Oak decline by *P. quercina* was later identified in European countries, including Austria, Belgium, France, Germany, Hungary, Italy, Luxemburg, Serbia and Montenegro, Sweden, Turkey, and the UK (Balci and Halmschlager, 2002, 2003; Cooke et al., 2005; Jönsson et al., 2003,). Above-ground symptoms include dieback in branches and parts of the crown, formation of epicormic shoots, high transparency of the crown, yellowing and wilting of leaves, and tarry exudates from the bark (Siwecki and Liese, 1991). Host plants are oak species, such as *Quercus cerris*, *Q. frainetto*, *Q. hartwissiana*, *Q. ilex*, *Q. petraea*, *Q. pubescens*, *Q. robur*, and *Q. vulcanica*. Little is known about disease development.

**Biology.** In culture, *P. quercina* shows a uniform, dome-shaped, and cottonwool-like pattern of colony growth. The optimum growth temperature is close to 25°C and no growth occurs at 30°C. *P. quercina* frequently presents sympodially branched primary hyphae. Sporangia considerably vary in size and shape, and spherical chlamydo-spores are occasionally produced. *P. quercina* is homothallic and shows a high proportion of elongated, ellipsoid, or

ovoid oogonia and the absence of amphigynous antheridia. Oospores are spherical to ovoid, and older oospore walls often turn golden-yellow (Cooke et al., 2005; Jung et al., 1999).

**Management.** The identification of isolates is based on cultural and morphological features and on comparisons with authentic cultures. The sequences (two isolates) and restriction digest patterns (nine isolates) of the internal transcribed spacer (ITS) regions of rDNA from Austrian *P. quercina* are identical. The digest patterns match those of Italian, Hungarian, and German strains (Cooke et al., 1999), including the aggressive strains used by Jung et al. (1999) for inoculation tests, although pathogenicity tests were not carried out on Austrian isolates.

**Plant quarantine issues.** Oak trees are important amenity and forest components in Korea, and *P. quercina* has been included since 2004 in the quarantine pathogen list for the inspection of imported plant material.

#### ***Phytophthora ramorum*: The pathogen that causes sudden oak death**

**History.** Unknown symptoms of foliar blight and twig dieback in rhododendron plants in a nursery were first recognized in the Netherlands in 1993, then in Germany in 1995 in the same host species (Werres et al., 2001). During the same period, an unusually lethal symptom was observed in the tanoaks of forests in Mill Valley, Marin County, California (Svihra, 2001). *P. ramorum* was identified as the causal agent of this phenomenon and is currently known to cause sudden oak death (SOD) in the forests located in the Pacific side of North America and ramorum blight or dieback in woody ornamental plants in Europe (Rizzo et al., 2002; Werres et al., 2001). The pathogen has also recently been reported to cause sudden larch death in the UK (Brasier and Webber, 2010).

**Disease.** In Canada, *P. ramorum* was detected in nurseries in British Columbia from 2004 to 2007; traces of the pathogen in all locations were eradicated (Official site: Canadian Food Inspection Agency). In Europe, *P. ramorum* has been observed in more than 23 countries, including Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, the UK, Norway, Switzerland, Greece, and Croatia (Redlin et al., 2014). In California, since the first observation of pathogen occurrence in 1995, *P. ramorum* has proliferated in the forest systems of California, Oregon, and Washing-

ton along a 1,500 km stretch of forests located in the Pacific side of the region, as well as in the nursery systems of 23 states. No disease occurrence induced by *P. ramorum* has been reported for Africa, Asia, Australia, and South America. In contrast to other *Phytophthora* species, *P. ramorum*-infected plants show symptoms on the upper part of the plants and not on the root. The name “ramorum” means “branch” in Latin. Three main symptoms are observed on infected plants: leaf blight, twig blight (dieback), and stem canker. Leaf blight and twig blight are symptoms of ramorum blight disease in ornamental woody plants. Stem canker is a typical symptom of SOD, which was first referred to in the media as a phenomenon that occurs in oak forests. Ramorum leaf blight and ramorum dieback are considered acceptable academic disease names (Henricot and Prior, 2004). Nonlethal foliar infection in woody shrubs or other hosts in understories serve as a source of inoculum for trees (Davidson et al., 2005). *P. ramorum* invades susceptible trees through the bark, on which cankers with tarry or rusty exudations develop. The leaves of infected trees may later take on a brown color over a short period and the trees eventually die (Garbelotto et al., 2001). The host range of *P. ramorum* has expanded, and official websites in Canada, the EU, and the US display the updated host list. The number of host plants currently amounts to about 120–130 species.

*P. ramorum* spreads in forests through rain and wind, river and streams, and human activities (Grunwald et al., 2012). The role of a vector in *P. ramorum* disease was discussed by McPherson (McPherson et al., 2013). The effects of *P. ramorum* differ depending on ecosystem and host. In natural (forest) and semi-natural (plantation) ecosystems, extensive mortality of trees and shrubs can exert severe ecological consequences, including significant changes in the structure and composition of plant and animal communities and increased water runoff and associated soil erosion. *P. ramorum* exerts significant economic effects on forests because it reduces recreational, cultural, or commodity value and increases the costs of monitoring and eradication measures.

**Biology.** *P. ramorum* was identified by Werres et al. (2001) as a pathogen that causes leaf and twig blight in woody ornamental plants, including the rhododendron and *Viburnum* species in Europe. Rizzo et al. (2002) confirmed that *P. ramorum* is also the pathogen that causes SOD in the forests located in the Pacific region of the US. “Ramorum” refers to the disease symptoms that manifest on branches because this Latin word means “branch.” Within the genus-wide phylogeny, *P. ramorum* is classified in *Phytophthora*

Clade 8c, and its closest relatives include *P. foliorum*, *P. hibernalis*, and *P. lateralis* (Blair et al., 2008). *P. ramorum* is characterized by the production of sporangia and abundant large chlamydospores. The sporangia of *P. ramorum* are elongated, deciduous, semi-papillate, and similar to those of *P. palmivora* (Werres et al., 2001). Motile zoospores are released from sporangia; upon contact with susceptible host tissue, the zoospores encyst, germinate, and penetrate the host tissue (Davidson et al., 2005). Chlamydospores are abundantly produced within infected plant tissue and enable *P. ramorum* to survive adverse conditions in infected plant stems and leaves, plant debris on the soil surface, or soil (Tooley et al., 2008). The concept of clonal lineage has been applied in the intraspecific classification of *P. ramorum*. Originally, Ivors et al. (2006) proposed three clonal lineages, namely, EU1, NA1, and NA2, which were standardized by Grunwald et al. (2009). EU2 was later added by Poucke et al. (2012) as the fourth clonal lineage when an epidemic of sudden larch death occurred in the UK. Clonal lineages are distinguished by molecular marker systems, including AFLP, SSR genotypes, and DNA sequences. Table 1 lists the four clonal lineages and their important properties in terms of geographical distribution, habitat, growth, aggressiveness, and mating type. The geographical distribution of four known clonal lineages of *P. ramorum* is restricted to two continents, Europe and North America. EU1 presents in Europe in major clonal lineages and in the US as a minor lineage in the nurseries of Oregon and Washington. EU2 has recently been observed in the UK. NA1 is a major clonal lineage in California and NA2 occurs only in British Columbia, Canada, and Washington. Along with geographical distribution, habitat is an important factor in understanding the lifecycle of the pathogen for the purpose of managing the disease. EU1 was isolated from forests, nurseries, and gardens in Europe but only in nurseries in North America. EU2 was identified in forests and nurseries, with limited cases in the UK (Poucke et al., 2012). NA1 is a major lineage in California, Oregon, and Washington forests and is currently spreading to the east side of the US through the nursery industry. NA2 is rarely observed in California and more commonly occurring

in the nursery habitats of British Columbia, Canada, and Washington. Significant differences exist among lineages in terms of important fitness characteristics, such as growth rate and aggressiveness. EU1 and NA2 grow faster and more aggressively than does NA1 (Brasier et al., 2006; Brasier, 2003; Manter et al., 2010). However, NA1 is a major clonal lineage that causes SOD in the US. *P. ramorum* is heterothallic and exhibits different mating types for sexual reproduction. EU1 and EU2 are of mating type A1. Findings show that EU1 exhibited mating type A2 in Belgium around 2002–2003 (Werres and De Merlier, 2003). After eradication, no further occurrences of A2 mating type were observed in Europe (Vercauteren et al., 2011). NA1 and NA2 are both of mating type A2. The assessment of the risk posed by the sexual reproduction of *P. ramorum* in natural environments is complicated. The current likelihood for sexual recombination in Europe is therefore limited. By contrast, A1 (EU1) and A2 (NA1 and NA2) isolates have simultaneously occurred in the US (Grunwald et al., 2008; Hansen et al., 2003), suggesting a higher chance of sexual reproduction in the region. The main risk generated by sexual reproduction is the appearance of a “Red Queen,” a progeny with particular fitness and high aggressiveness that can circumvent plant resistance mechanisms, as was demonstrated for the US-11 lineage of *P. infestans* (Gavino et al., 2000). In the case of *P. ramorum*, the colonization of a new environment and new hosts are the main threat. The origins of the clonal lineages, except for EU1, are unknown; EU1 originated from North America, after which it dispersed from Europe to British Columbia and Washington (Grunwald et al., 2012). Then, it migrated to California and Oregon. Reasonable evidence shows that NA1 originated from nurseries in Scotts Valley, California and NA2 originated from British Columbia or Washington (Grunwald et al., 2012). The nursery industry is an important pathway for the global migration of *P. ramorum*.

**Management.** The recognition of *P. ramorum* via symptoms is difficult because the manifestations induced by *P. ramorum* are variable and often rarely distinguishable from those produced by other pathogens, including other

**Table 1.** Four clonal lineages in *P. ramorum*

Clonal lineage	Geographical distribution	Habitat	Growth/Pathogenicity	Mating type
EU1	Europe, US	nursery	faster/higher	A1
EU2	Europe	forest, nursery	–/–	A1
NA1	North America (Pacific side)	forest, nursery, garden	slower/lower	A2
NA2	North America (British Columbia, Washington)	nursery	faster/higher	A2

*Phytophthora* species. Culturing on selective media and by molecular methods have been adopted in diagnosing *P. ramorum* infection. Although culturing diagnosis is generally ineffective, this method has been used under stress environments to discriminate a certain clonal lineage from others in terms of phenotypic assessment (Franceschini et al., 2014). The method effectively differentiates EU2 from other clonal lineages with relatively simple culturing tests. Otherwise, DNA-based molecular methods, including PCR and fingerprinting, are commonly used techniques in detecting *P. ramorum* (Bilodeau et al., 2007; Tomlinson et al., 2010). Chemical treatments, such as fungicides and disinfectants, are important components of integrated pest management practices aimed at controlling and limiting the spread of *P. ramorum*. Numerous studies have examined the use of fungicides to control *P. ramorum* in ornamentals (Garbelotto et al., 2009; Perez-Sierra et al., 2011). Asymptomatic plant material is the main route of *Phytophthora* spp. introduction to nurseries. Fungicides produce asymptomatic plant material, which is the main route for the internursery spread of *P. ramorum*. Although fungicides are somewhat effective preventive treatments, repeated applications potentially lead to fungicide resistance by the pathogen, as has been observed in other *Phytophthora* spp. In addition, US and European Union regulations prohibit the application of fungicides in quarantine zones because of potential masking of the symptoms mentioned above.

Biological control is an alternative option for managing *P. ramorum* disease. Several studies have assessed the potential of biological organisms to control *P. ramorum*. Researchers have recently identified three isolates, namely, *Penicillium daleae*, *P. herquei*, and *Metarhizium anisopliae*, which showed that fungi applied to the leaf surface can reduce the necrosis caused by *P. ramorum* (Widmer and Dodge, 2013). Whether resistance to *P. ramorum* is possible requires further examination. Nettel et al. (2011) indicated that tanoaks are susceptible to the pathogen and that no evidence of prior selection for disease resistance exists. The authors concluded that tanoak populations across the species' range are at risk.

**Plant quarantine issues.** Pathogen occurrence in Korea has not been reported, but Korean officials formulated a disease name that matches SOD because oak trees are valuable components in the forest ecosystems of Korea. In these systems, more than 10 species of oaks, including *Quercus* species, grow with complex characteristics. Oak trees are important for their roles in the ecosystem. They contribute to land greening, provide food supply for wildlife and habitats for birds and other animals, serve as material in the mushroom growing industry, and are used for recreation purposes. In Korea, oak trees have suffered from a number of diseases, including leaf spot disease, powdery mildew, stem-end branch rot, root rot, and canker

**Table 2.** Six *Phytophthora* species threatening forest tree species in Korea

Species	Disease	Year first identified	Host range	Distribution	Sexual Reproduction	Year for quarantine regulation in Korea
<i>P. alni</i>	Alder root rot	1993~1994	Alder Chestnut Walnut Cherry	Europe North America	Homothallic	2006
<i>P. inundata</i>	Root rot Collar rot	1970	Aescules Salix Chestnut	Worldwide	Heterothallic	Not listed yet
<i>P. kernoviae</i>	canker	2003	Similar to <i>P. ramorum</i> Expanding annually	England Ireland New Zealand	Homothallic	2006
<i>P. pinifolia</i>	Pine needle blight	2004	Pine	Chile	Not Examined	2008
<i>P. quercina</i>	Root rot	1993	Oaks	Europe Asia USA	Homothallic	2004
<i>P. ramorum</i>	Stem canker (SOD) Blight of leaf or twig	Early 1990'	Oak trees and woody plants	Europe, North America	Heterothallic	2004

(KSPP, 2009). Given that the host range of *P. ramorum* is extremely wide and continues to spread to expansive regions, its effects on the forest ecosystems in Korea would be critical when the pathogen is introduced into the country. The quarantine of *P. ramorum* has caused significant economic hardship to the nursery industry in Europe and North America. Internationally, regulations that prohibit the import of potentially infested material were issued by Australia, Canada, the Czech Republic, the UE, Mexico, New Zealand, South Korea, Taiwan, and the UK. In 2009, more than 68 countries, including China, either included *P. ramorum* on their lists of regulated pests or mentioned the pathogen in their legislation (Sansford et al., 2009). Evidence as to the areas where *P. ramorum* are endemic may be derived from an examination of the distribution of its closest known relatives in *Phytophthora* Clade 8c, *P. lateralis*, *P. hibernalis*, and *P. foliorum*. Following its recent discovery in Taiwan, *P. lateralis* is now considered native to Taiwan, and possibly, Japan (Brasier et al., 2010). By analogy, *P. ramorum* has therefore been suggested as originating from Taiwan and Japan and perhaps Yunnan, China. Thus far, however, surveys on *P. ramorum* in Taiwan and Yunnan have generated negative results.

## Conclusion

Table 2 shows the six *Phytophthora* species reviewed in this article. New *Phytophthora* species have been rapidly identified as plant pathogens after 1990 through large-scale surveys and more efficient detection and identification technologies. These new *Phytophthora* pathogens are geographically distributed with a widening host range and increasing effects on agriculture, environments, and related industries. In particular, the *Phytophthora* discussed in this review can cause huge losses in the Korean forest ecosystems and ornamental industry when introduced to the country. Pine (46%) and oak (18%) with associated alder trees are major components of the forest ecosystems in Korea, and *Prunus* is an important fruit tree in the country (KFPI, 2013). Managing the diseases that affect forest trees is difficult because of the lack of effective control methods and the challenges posed by treatment. The rapid increase in international transportation, tours, and global climatic change would elevate the chances that new invasive pathogens will be introduced from one region to another. The introduction of exotic plant pathogens can cause new disease epidemics that can be difficult to manage because of the lack of genetic resources for resistance. Such sources are produced by co-evolution between hosts and pathogens. Pine wilt nematode, which is not problematic in the US from where

it originated, has reached uncontrollable proportions in Japan and Korea, where nematode was newly introduced. The introduction of new plant pathogens affects not only the yield of target host plants, but also product industries and international trade. The importance of plant quarantine cannot be overemphasized because of effects of newly introduced invasive pests and pathogens. The *Phytophthora* species discussed in this review are included in the Korean Plant Pathogen Quarantine list, with the exception of *P. inundata*, which should be listed after pest risk assessment. Once listed, intensive inspection will be performed for imported plants and products. To this end, rapid and efficient detection methods should be developed and applied. Effective protocols should also be implemented in managing newly introduced pathogens.

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