Australian Government

Department of the Environment and Energy

Background document:

Threat abatement plan for disease in natural ecosystems caused by *Phytophthora cinnamomi*

2018

The Department would like to thank all who contributed to the development of this national plan.

The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

Image credits

Front cover: Wildflowers on Mondurup Peak, Stirling Range in 1993 © Rob Olver
Back cover: Mondurup Peak, Stirling Range in 2010 © Department of Biodiversity, Conservation and Attractions, Western Australia

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1. Introduction

Thousands of Australia's native plants and ecological communities are threatened by the soil-borne plant pathogen *Phytophthora cinnamomi*, with over 2000 potential host species in Western Australia alone (Shearer et al., 2004). *P. cinnamomi* is a serious risk to biodiversity in all Australian states and territories except the Northern Territory. It causes disease, known as Phytophthora dieback, in a diverse range of native, ornamental, forestry and horticultural plants. Described as a 'biological bulldozer', Phytophthora dieback is destroying bushlands, heathlands, woodlands and forests that are the habitat for rare and threatened flora and fauna species.

'Dieback caused by the root-rot fungus[1] *Phytophthora cinnamomi*' is listed as a key threatening process under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

This background document complements the statutory *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi (DoEE, 2018). The threat abatement plan outlines the actions proposed to abate the threat. This background document provides supporting information including on the biology of the pathogen, its population dynamics, spread, diagnosis, impacts on biodiversity, and management measures.

2. Background

2.1 The scope of the problem and history of the pathogen in Australia

At least 32 species of *Phytophthora* occur in various parts of Australia. Following a survey of soils along a 70 kilometre pipeline easement in Victoria, Dunstan et al. (2016) found that *Phytophthora* species were more widespread, abundant and diverse in natural ecosystems than had been estimated. While *Phytophthora cinnamomi* has caused the most significant impacts to date, other destructive species are emerging, most notably *P. arenaria*, *P. constricta*, *P. cryptogea*, *P. elongata*, *P. gregata*, *P. megasperma* and *P. multivora*. *P. multivora*, linked to declining ecosystems in Western Australia, has also been detected in the natural site of *Wollemia nobilis* (Wollemi Pine) in the Greater Blue Mountains World Heritage Area in New South Wales. Puno et al. (2015) have found this endangered species to be susceptible to *P. multivora*.

Phytophthora cinnamomi was first described on the island of Sumatra, Indonesia, in 1922, as the cause of stripe canker on cinnamon trees (Rands, 1922). The likely region of origin of the pathogen is Papua New Guinea (Hardham, 2005) and the known introduced range of *P. cinnamomi* now includes Europe, North America, South Africa and the Australasia–Pacific region.

It is likely that the introduction of *P. cinnamomi* to Australia followed European settlement. Since the mid-1960s this exotic pathogen has been recognised as a cause of serious disease in native ecosystems of Australia. In the 1960s, it became clear that *P. cinnamomi* was causing disease in *Eucalyptus marginata* (Jarrah) trees in Western Australia, in native forests in East Gippsland, and in woodlands in the Brisbane Ranges in Victoria and in the Mount Lofty Ranges of South Australia.

Although many root pathogens cause disease in Australian flora species, *P. cinnamomi* has had the greatest effect and poses the greatest threat. Its patterns of disease and continuing invasion in much of southern Australia are characteristic of a pathogen newly introduced to an environment with susceptible flora. The major evidence for the pathogen being non-endemic to Australia is:

1. the predominance of the A2 strain of *P. cinnamomi* in the Australian environment. If Australia was the centre of origin, a greater balance between the A1 and A2 strains would be expected
2. the high level of susceptibility of many Australian native plant species, which suggests that the plants did not evolve with the pathogen.

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1. It is now understood that *P. cinnamomi* is not a fungus. This was the name of the key threatening process when it was registered under the EPBC Act.

Other evidence for *P. cinnamomi* being non-endemic is that most occurrences follow human occupation, land use and activities.

P. cinnamomi can affect a wide range of life stages across several Australian plant families. It reacts with its hosts in a number of distinct ways, ranging from symptomless infection restricted to root tissue (for example, in some grasses) to complete invasion of root and stem tissue.

The consequences of infection of a susceptible plant community will usually be the following:

- inability of infected plants to develop new shoots, flowers, fruit and seed
- extinction of populations of some flora species
- a dramatic modification of the native plant community's structure and composition
- a significant reduction in primary productivity and functionality
- habitat loss and degradation for dependent flora and fauna; to date these have been irreversible
- local extirpation and a significant loss of genetic diversity
- major declines in some animal species due to the loss of shelter and nesting sites or food sources.

After the pathogen's effects on a plant community have taken their course, with time the smaller number of resistant species that remain recolonise areas affected by the pathogen. These areas are generally less productive, have more open overstorey (altering hydrological and physicochemical aspects of the soil) and provide a modified habitat for dependent fauna and flora.

Threat of an epidemic exists where dominant species of particular plant communities are inherently susceptible to Phytophthora dieback and those communities are in areas where environmental conditions favour the pathogen. Warm, wet soils, especially those with impeded drainage, favour sporulation and movement of *P. cinnamomi*, as well as its growth within plant tissue.

Serious epidemics do not necessarily always follow the arrival of *P. cinnamomi* into uninfected plant communities, and the pathogen can occur in environments where the effects are not immediately apparent. In some cases visible symptoms may take years to manifest after the initial infection.

2.2 The pathogen

P. cinnamomi is a microscopic soil-borne organism that attacks the roots and collar of susceptible plants. Depending upon environmental conditions and plant susceptibility, it can destroy plant communities and put several species at risk of extinction (see appendices A, B and C in the *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi (DoEE, 2018)). In plant communities where most dominant species are resistant to *P. cinnamomi*, its effects are characterised by the attrition of minor structural components, making disease detection difficult.

2.2.1 Taxonomy and life cycle

P. cinnamomi is often referred to as a fungus because of its filamentous growth and ability to cause plant disease. However, in taxonomic terms it is more closely related to algae than to fungi. It is commonly referred to as a water mould. It is classified as kingdom Chromista, phylum Oomycota, order Peronosporales, family Peronosporaceae, genus *Phytophthora*, species *cinnamomi*.

In the vegetative state, *P. cinnamomi* occurs as mycelia, which consist of branched filaments termed hyphae. The mycelium produces two types of spores asexually: zoospores (produced within sporangia) and chlamydospores. A third type of spore, oospores, can result from sexual recombination of A1 and A2 mating strains of the pathogen or they can form from a single mating strain.

When mature, sporangia range in size from 50 to 70 microns (or 0.05 to 0.07 millimetres) in length. Under favourable conditions (free water and mild temperatures) *P. cinnamomi* readily produces sporangia.

Each sporangium can produce up to 30 zoospores, each less than 10 microns in diameter. Zoospores are short-lived (two to three days) and have two flagella which enable them to swim for short distances through water (25 to 30 millimetres, with soil porosity a factor in how far they will travel). At the end of the motile phase the flagella are lost and the zoospore encysts. While all spores have the capacity to directly infect plants, zoospores are thought to be the major infection propagule.

Chlamydospores are round, average 41 microns in diameter and are commonly thin-walled, although thick-walled chlamydospores have been observed.

The sexually produced oospores are round and thick-walled, with a diameter in the range 19 to 54 microns, and are considered highly resistant to degradation. Oospores are hard-coated and can withstand dry conditions in soil and in dead plant tissue for many years. Figure 1 depicts the generalised life cycle of *P. cinnamomi*.

When a zoospore encounters a root, the zoospore cyst produces a germ-tube which chemically and physically breaches the protective surface of the root. Once inside the plant the germ-tube develops into a mycelium and grows between, and into, the plant cells. The pathogen may exit the infected root at some point, starting new infections. Infection leads to impairment of the plants' physiological and biochemical functions, including uptake of water. This is why symptoms of Phytophthora dieback can appear initially similar to those of water stress.

Figure 1 Generalised life cycle of *Phytophthora cinnamomi*

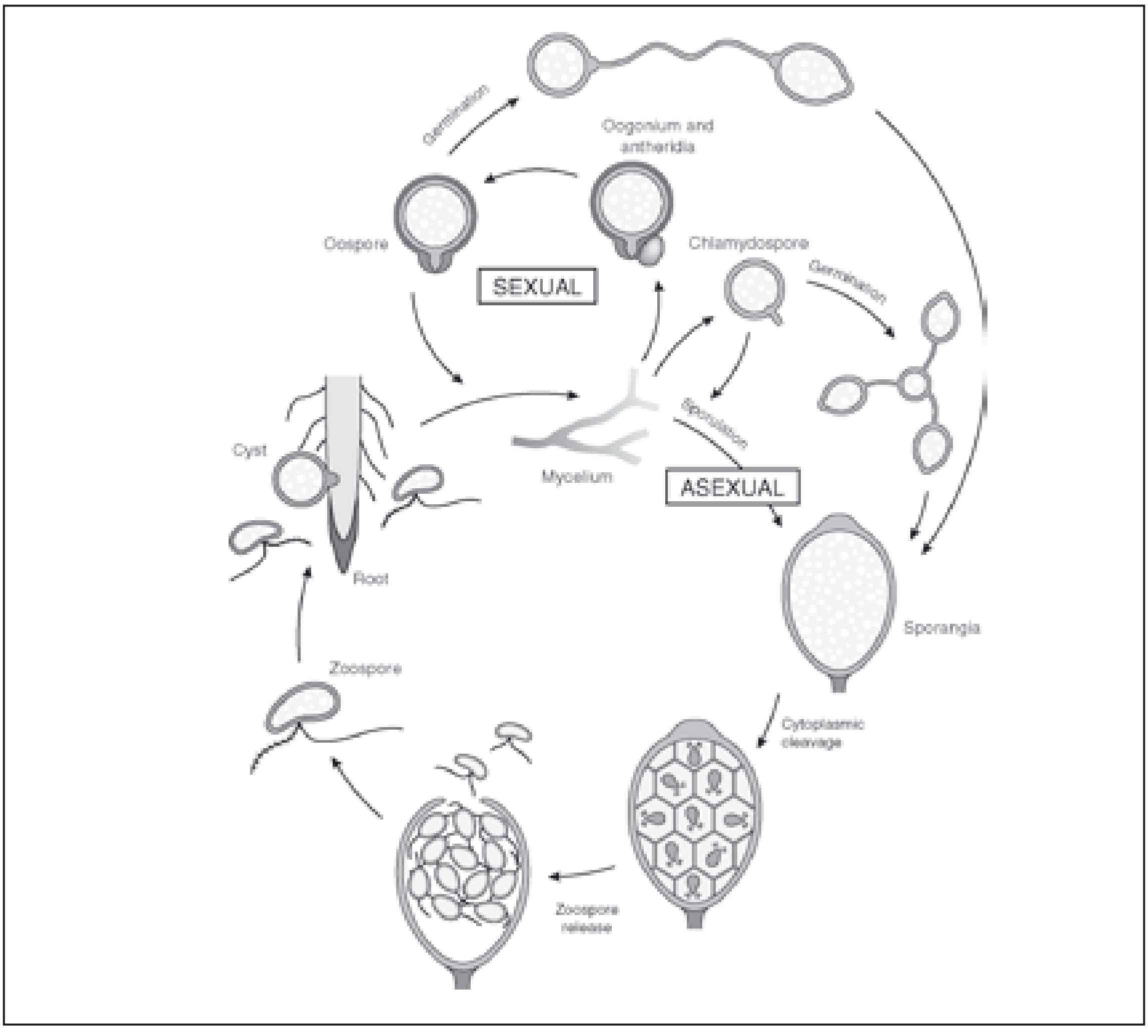


Diagram courtesy of Professor A Hardham, Australian National University, Canberra, ACT, published in Hardham (1999)

2.2.2 Pathogen survival

There are still significant gaps in our knowledge of the exact mechanisms of the pathogen's long-term survival. Of the asexual spores, chlamydospores are the more resistant to degradation and therefore enable *P. cinnamomi* to survive for long periods under unfavourable conditions. They potentially provide a source for reinfection of seedlings or long-distance spread via soil movement.

In Western Australia, *P. cinnamomi* has been shown to survive asymptomatically in a range of native annual and herbaceous perennial species (Crone et al., 2012; Crone et al., 2013a), and in some species to survive as a biotroph. In some hosts it can produce numerous selfed oospores which would allow it to survive adverse conditions when necessary (Crone et al., 2013b). These research findings have important implications for the future management of Phytophthora dieback.

2.2.3 Geographic and climatic occurrence

The impact of Phytophthora dieback in a native plant community can vary depending on a combination of factors, including temperature, rainfall and soil type. The area of native vegetation affected by Phytophthora dieback exceeds a million hectares in Western Australia, many hundreds of thousands of hectares in Victoria and Tasmania, and tens of thousands of hectares in South Australia.

In Australia, *P. cinnamomi* does not usually cause severe impacts in undisturbed vegetation at sites that receive a mean annual rainfall of less than 400–600 millimetres and are north of latitude 30° (O'Gara et al., 2005b). While rainfall is a key factor influencing the distribution of Phytophthora dieback, there are many other factors that influence disease expression (that is, conducive temperature, geology and soil conditions co-occurring with susceptible plant hosts, including pH, fertility, moisture and texture).

There are five broad climatic zones vulnerable to Phytophthora dieback:

- north Queensland in elevations above 750 metres with notophyll-dominant vegetation and acid-igneous geology
- the northern New South Wales / southern Queensland border region
- areas of Mediterranean climate (warm to hot, dry summers and mild to cool, wet winters) where annual rainfall exceeds 400 millimetres, in southern Western Australia and South Australia and southern Victoria as far east as Wilsons Promontory
- areas with moderate temperature variation but erratic rainfall regimes—at low elevations of the coastal plain and foothills between Wilsons Promontory and south of the border between Victoria and New South Wales
- winter-dominant rainfall areas in maritime climates of coastal and submontane Tasmania.

Work by Newby (2014) on vulnerable areas in the Greater Blue Mountains World Heritage Area considered the climate and landscape suitability for *P. cinnamomi* via species distribution models. Results indicated that *P. cinnamomi* was most likely to occur where rainfall was 1300 millimetres per annum, minimum temperatures were between 11.5°C and 13.5°C, and topsoil was approximately six to eight per cent clay. The study predicted it would not occur where rainfall was below 550 millimetres per annum, the minimum temperature remained above 18°C and the topsoil clay content exceeded 37 per cent. The modelling helped to identify parts of the landscape most likely to contain the pathogen for sampling.

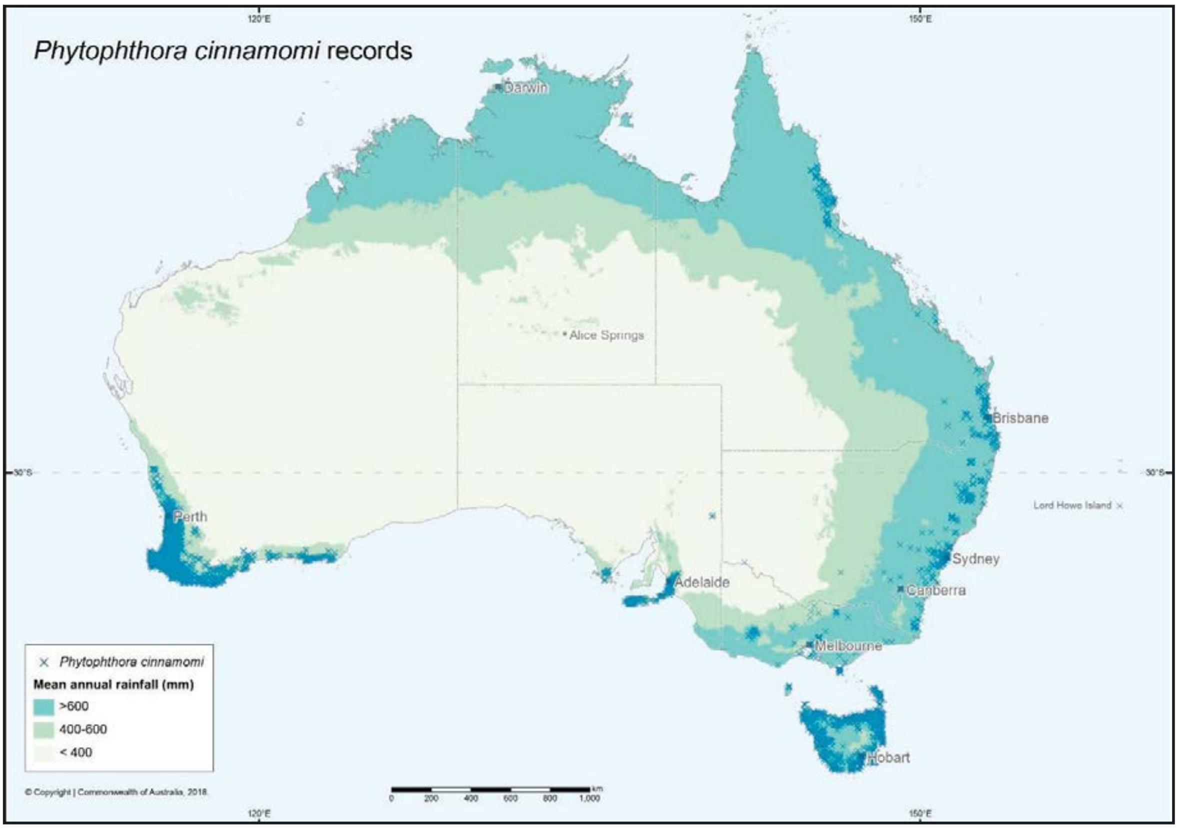
Although rainfall is clearly sufficient for the establishment of *P. cinnamomi* in the wet–dry, tropical and subtropical north of Australia, there are scant data to indicate that *P. cinnamomi* is a problem in undisturbed native ecosystems of northern Western Australia or the Northern Territory.

P. cinnamomi occurs in coastal Queensland. Although it is considered to be restricted to the wet coastal forests, many of these areas are designated as conservation reserves or state forests and are managed for recreation and conservation purposes. Visitor access, and therefore the risk of spread of *P. cinnamomi*, will need to be addressed. Additionally,
P. cinnamomi is a serious concern in the Wet Tropics of Queensland World Heritage Area of northern Queensland, where the disease is complex, differs considerably from that in the temperate south of the continent and appears to be related to prior significant disturbance of sites (Gadek & Worboys, 2003, cited in O'Gara et al., 2005a).

P. cinnamomi has a high impact at 800–1000 metres in Western Australia's Eastern Stirling Range Montane Heath and Thicket threatened ecological community. There is still speculation about the role of the pathogen in damage to undisturbed montane regions above 800 metres, such as those found in the southern Great Dividing Range, the Central Highlands of Tasmania, and the upland and highland rainforests of central and far north Queensland.

Burgess et al. (2017) have produced a distribution map (current and projected) for *P. cinnamomi*. The greatest disease impact is apparent in areas combining conducive soils, susceptible hosts and ideal climate for disease expression (warm and wet winter/spring, followed by dry summer). These are the climatic conditions of the south-west of Western Australia, where the greatest impacts are observed in heathlands on nutritionally poor soils dominated by Proteaceae.

Figure 2 *Phytophthora cinnamomi* records



This figure does not represent the precise distribution of the pathogen in Australia and is for general information, not management purposes. A list of data contributors is at Appendix C.

2.2.4 Areas of susceptibility and distribution

The vulnerable zone is the geographic region in which conditions enable dieback to occur and persist. Some states in Australia have identified broad zones where biodiversity assets are susceptible to the threat of *P. cinnamomi*. The environmental criteria used to identify these zones vary from state to state and are summarised below. The biomes that appear to be least threatened are the wet–dry tropics and the arid and semi-arid regions of the continent (Environment Australia, 2001). Cahill et al. (2008) provides a comprehensive review of the regional impact of *P. cinnamomi*.

Western Australia

The Western Australian Department of Biodiversity, Conservation and Attractions (2017) defines the vulnerable zone of Western Australia as all areas of the south-west land division west and south of the 400 millimetre rainfall isohyet.

Tasmania

The vulnerable zones of Tasmania include areas where there is a coincidence of:

- susceptible native vegetation in open communities
- non-calcareous moist soils
- elevation below 700 metres
- average annual rainfall greater than 600 millimetres.

Victoria

Where susceptible native species or plant communities occur, the areas in Victoria that are considered vulnerable to the threat of *P. cinnamomi* are:

- all elevations in sites of Mediterranean climate from the west of the state across to Wilsons Promontory where average annual rainfall exceeds 600 millimetres
- the temperate rainfall regimes at low elevations of the coastal plain and foothills between Wilsons Promontory and the area south of the Victoria and New South Wales border.

South Australia

In South Australia, any site with susceptible vegetation growing on neutral to acid soils where the average annual rainfall is greater than 400 millimetres is considered vulnerable to the threat of *P. cinnamomi* (Phytophthora Technical Group, 2006).

The present known distribution in South Australia includes numerous conservation areas and national parks, forest reserves and many roadside reserves in the Mount Lofty Ranges, on Fleurieu Peninsula and on Kangaroo Island.
P. cinnamomi is also suspected to be present on Lower Eyre Peninsula.

New South Wales and the Australian Capital Territory

Clear criteria for what constitutes an area's vulnerability to the threat of *P. cinnamomi* in New South Wales and the Australian Capital Territory are not available for two major reasons:

- There is insufficient knowledge of the susceptible species in New South Wales and the Australian Capital Territory.
- There is variable susceptibility of plant species depending on climatic conditions—some species only appear susceptible during sustained periods of unusually high rainfall.

In New South Wales, *P. cinnamomi* causes large-scale disruption of native ecosystems and occurs in a number of national parks and nature reserves. The full extent of distribution of *P. cinnamomi* throughout New South Wales is largely unknown due to survey limitations. However, recent surveys indicate that the pathogen is more widespread than previously thought.

Queensland

The average annual rainfall in the wet tropics of far north Queensland rarely limits the establishment of *P. cinnamomi*. As in New South Wales and the Australian Capital Territory, the pathogen tends to have a cryptic nature and is frequently isolated from soils beneath symptom-free vegetation. However, plant disease attributed to *P. cinnamomi* in natural tropical ecosystems of far north Queensland is commonly associated with some prior disturbance (particularly roads) on sites that have the following characteristics:

- elevation above 750 metres
- notophyll-dominant vegetation
- acid-igneous geology (Worboys & Gadek, 2004, cited in O'Gara et al., 2005a).

Although Phytophthora dieback is reported in upland subtropical rainforests of the Eungella Plateau, west of Mackay, and from the wallum heathlands in the south-east of the state, there has been no assessment of what criteria may be useful in categorising vulnerable vegetation.

Northern Territory

To date there is no confirmed record of Phytophthora dieback in undisturbed native vegetation in the Northern Territory. The environmental conditions are not conducive to the establishment and persistence of the pathogen in susceptible native plant communities.

2.2.5 Potential impacts of climate change

Climate change induced fluctuations in average rainfall may change the distribution of Phytophthora. For example, by 2030 the southern tablelands region of Australia is predicted to exhibit differences in average rainfall of between
-10 per cent and +15 per cent of current annual precipitation, with rainfall decreases in winter and spring (Grose et al., 2015). A major reduction in rainfall could reduce the impact of the pathogen in some areas. In contrast, increased evaporation rates resulting from higher temperatures and more frequent extreme rainfall events could lead to greater run-off and pathogen dispersal (Cahill et al., 2008). Furthermore, stress in native plant communities resulting from altered climatic conditions could interact with Phytophthora dieback.

Scott et al. (2013) used existing datasets on *P. cinnamomi* distribution together with strategic soil surveys from regions outside the pathogen's known distribution range. The study used CLIMEX modelling to determine its likely distribution in 2070 based on the CSIRO-Mk3.0 global climate model. The modelling demonstrates that areas with previously unfavourable conditions, particularly at altitudes above 700 metres, may experience an increase in disease incidence as these regions become warmer over time. In addition, in areas where rainfall is predicted to decrease, disease incidence is likely to decline.

Modelling developed by Burgess et al. (2017) predicts that the pathogen's potential range is wider than previously believed. Soil samples from subalpine regions in eastern Australia and central Tasmania indicate that *P. cinnamomi* has established in isolated locations at these higher elevations. Under predicted climate change these areas will become more suitable for the pathogen and may result in more widespread distribution. This work will be useful to managers and policymakers involved in ensuring the future containment of Phytophthora.

Seasonal changes can influence the impact and spread of the pathogen. For example, wetter summers could be favourable to spread and increase the impact of *P. cinnamomi*, and drier winters less so. Any possible reduction in pathogen activity due to lower winter rainfall could be offset by soil temperatures increasing to a level that is more conducive to pathogen activity. Lucas (2003) found in glasshouse experiments that simulating a drought over summer increases the resistance of Jarrah to *P. cinnamomi*.

Physiological changes in host plants and in the pathogen could also be factors in the impact of climate change. *P. cinnamomi* is fully capable of adapting to new environmental conditions and of developing virulence on new hosts during asexual growth (Hardham, 2005).

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Meteorology (2015) predict Australian annual average temperature will increase by 0.6 to 1.3°C above the climate of 1986–2005 by 2030 under an intermediate emission scenario (RCP4.5). Under predicted climate scenarios, both drought and fire are likely to become more frequent, adding to pressures on listed species (Cochrane et al., 2011).

Monitoring the health of high-priority susceptible species and communities over time (for example, *Banksia* or grasstree woodland) will provide an indication of the impact of the pathogen on priority native species and communities in a changing climate.

The effect of vegetation change on soil temperatures is harder to predict than air temperature changes. This may be a major determinant of the changed distribution of Phytophthora in some situations.

With a rise in extreme weather events, parts of south-west Western Australia are experiencing an increase in episodic high summer rainfall, broadening the climatic and temporal range of areas vulnerable to Phytophthora dieback (Massenbauer, pers comm, 2017). Although mean annual winter and spring rainfall in this area is decreasing (Hope et al., 2015), temperatures are becoming warmer during these periods, creating conditions conducive to disease expression down to at least the 400 millimetre annual mean isohyet. The pathogen can remain dormant for long periods until increased moisture and higher air and soil temperatures provide ideal conditions for sporulation. These conditions can occur during any time of the year in south-west Western Australia (Massenbauer, pers comm, 2017).

2.2.6 Interaction of Phytophthora with other threats

Multiple processes may interact with Phytophthora to increase extinction risk. An extinction risk tool used by Barrett et al. (2008) identified five taxa from the Stirling Range National Park in Western Australia as being at high risk of extinction. The combination of the pathogen with other threatening processes such as fire, herbivory (Rathbone & Barrett, 2017), aerial canker disease and climate change pushes these taxa further towards extinction.

Phytophthora activity might be greater in some circumstances following a fire because there are fewer plants to use the available water and sites are more prone to elevated soil moisture (Cahill et al., 2008). Growing understanding of the interactions between Phytophthora and other threats to biodiversity will increasingly inform management decisions—for example, when evaluating the costs and benefits of minimising fire frequency.

From measurements of the percentage of dead or dying species in heathlands in south-western Australia, Moore et al. (2014) hypothesise that the likely increase of open sites and wetter conditions immediately after a fire would create ideal conditions for the spread of Phytophthora to surviving species. This interaction has important implications for the future of plant communities threatened by infestation from the pathogen.

In urgent fire management situations there may be a breakdown of hygiene protocols. If contaminated water, vehicles and equipment are used during fire suppression or prescribed burns, Phytophthora can spread into clean areas.

An effect of burning is to increase the levels of nutrients in soils, which could increase sporulation rates (Moore, 2005; Dixon, pers comm, March 2017, from information provided by Professor GA Zentmyer). This can create management challenges for reducing the spread of Phytophthora to new areas.

Forestry operations have the potential to spread the pathogen via machinery, vehicles and equipment. In addition, thinning of the forest can result in elevated water levels and temperatures ideal for the rapid growth of Phytophthora (Bunny et al., 1995). Other high-disturbance activities with a risk of spreading the pathogen include mining, road construction or maintenance, and installation and maintenance of infrastructure for utilities such as water and gas pipes, power lines and telecommunications. Stringent hygiene protocols during these operations can lower the risk of spread.

Feral animals are another potential vector for Phytophthora. Studies by Kliejunas and Ko (1976), Krull et al. (2013) and Li et al. (2014) indicate that feral pigs (*Sus scrofa*) can spread the pathogen through soil movement on their feet, snouts and fur and by passing viable spores in their faeces.

Browsing by native herbivores may also influence disease expression (Rathbone & Barrett, 2017). Slower recovery after fire and a reduction in vegetation cover is anticipated to create or prolong environmental conditions that are more conducive to disease.

Section 2.2.5 above discusses the potential effects of climate change in relation to Phytophthora.

2.2.7 Transmission and spread

Moist or wet conditions are ideal for the spread of Phytophthora dieback. Active (or autonomous) spread of Phytophthora involves the pathogen moving itself—predominantly by zoospores and mycelial growth. Coarse-textured soils with large pores and water-filled root channels allow zoospores to swim up to 30 millimetres. Mycelia can grow through roots and spread to adjacent healthy plants where root-to-root contact occurs, enabling the pathogen to spread up and across slopes from a disease centre.

Passive spread depends upon an independent party or object carrying the pathogen. Movement of any water, soil or plant material infested with Phytophthora can spread dieback. Phytophthora can spread passively in overland and subsurface water flow. Animals may also act as vectors of infested soil, particularly where there is digging or soil disturbance behaviours. This movement is greater on sticky clay soils and wet peats than on drier, well-drained soils of low organic content.

Humans can spread Phytophthora dieback faster and further than any other vector. This occurs as a result of road building and maintenance, emergency and land management activities, commercial activities (such as timber harvesting, mineral exploration and the nursery trade) and human recreational activities (such as bushwalking and off-road vehicle activities). In southern Australia, this is especially the case when these activities are undertaken during the spring or periods of high summer rainfall, when conditions are most conducive to pathogen reproduction and plant infection.

Survival, establishment and further spread are dependent on conditions at the point of delivery—in particular, sufficient moisture for the pathogen and the presence of living host tissue. The success of establishment for new centres of infection is also dependent on population levels in the soil at the point of pick-up and the quantity transferred. Most of the large centres of infection that exist today in southern temperate Australia occurred as a result of human activity, often as a direct result of introducing infected soil or road-building materials to vulnerable uninfected areas.

2.2.8 Rates of spread

The timescale for natural spread depends upon the topography, vegetation and climate. Annual rates of spread at the boundaries of existing infection are highly variable, ranging from a few to hundreds of metres downslope in incised watercourses or gullies. Surveys in Western Australia have shown that the *P. cinnamomi* upslope disease extension on the Darling Plateau (East) was 0.37 metres per year compared with 2.15 metres per year for the Blackwood Sedimentary Plateau, where a perched water table provides long periods of favourable conditions conducive to proliferation of the pathogen (Strelein et al., 2006). In the Jarrah forest of Western Australia, upslope and across-slope spread seldom exceeds an average of one metre a year (Podger et al., 1996, cited in O'Gara et al., 2005a). Grant and Barrett (2003) found that the pathogen's rate of spread in south coast Banksia shrublands in deep sands ranged from 0.7 to 2.3 metres annually.

2.3 The disease

2.3.1 Impacts on native plants

Cahill et al. (2008) note the considerable variation in Phytophthora susceptibility within families, genera and species. The families Proteaceae, Ericaceae, Fabaceae, Xanthorrhoeacae and Dilleniaceae contain a large proportion of highly susceptible genera and species, whereas the families Asteraceae and Poaceae contain a disproportionately low number of susceptible species. Due to this complex variation, occurrence within a plant family or genus is a poor predictor of species susceptibility (Shearer, 2004). In addition, susceptibility of a species may not be consistent across its geographical range.

Disease symptoms too may vary between plant species. In the early stages of disease, symptoms generally consist of retarded growth and slight drooping of the foliage. Infected broadleaf species wilt during the heat of the day and may recover at night. Roots become discoloured and die. Dark or reddish brown discolouration may extend up into the wood of the lower stem. Severely affected plants may wilt permanently and their leaves may turn brown.

Epidemic disease and the major disruption that occurs to the functioning of plant communities is not the only circumstance that could threaten the extinction of populations of susceptible plant species. Plant species that exist only as small, localised populations may be threatened with extinction due to disease occurring under less favourable conditions and causing a slow attrition of individuals in those populations.

Shrubs generally turn yellow, with dieback occurring in warm, moist periods during spring and autumn. Infected trees can produce epicormic growth but may eventually die. Infected plants may appear to recover when environmental conditions do not favour the pathogen, but dieback often occurs again when the plant is under environmental stress and the pathogen is active.

The symptoms of disease in *Xanthorrhoea* (grasstree) species are caused by a combination of damage to tissues of the roots and stem that may lead to a reduction in water and nutrient transport throughout the plant (Aberton et al., 2001). Susceptible grasstree species such as *X. australis*, *X. quadrangulata* and *X. semiplana* often decline rapidly and the plant may collapse (R Velzeboer, pers comm, 2012).

In Western Australia, it has been estimated that as many as 2000 plant species of the south-west are susceptible (Wills, 1993). Shearer et al. (2004) have estimated means of 40 per cent susceptible and 14 per cent highly susceptible (2284 species and 800 species respectively) for the 5710 described plant species in Western Australia's South-West Botanical Province.

The national best practice guidelines (O'Gara et al., 2005b) lists over 1000 native plant species known to be susceptible to disease from *P. cinnamomi* in Australia. The list has been compiled from published material, unpublished records and observations of individual researchers. Hardham (2005) suggests that *P. cinnamomi* is likely to infect over 2500 Australian native species.

Several problems arise when trying to define the susceptibility of flora species. A highly susceptible species is one that has high mortality in the field, but this may be influenced by a number of variables at the site and other environmental conditions that affect a plant's reaction to infection. The response of a species in the wild may depend on static site conditions (for example, substrate and pH) and temporal conditions (for example, rainfall and disturbances such as fire). Species may not be hosts of *P. cinnamomi* at all but may be affected by changes in vegetative structure caused by the death of surrounding plants, or there may be a spatial variation in the response of a host. For example, *Hibbertia hypericoides* (Yellow Buttercup) is highly susceptible to infection on the Swan Coastal Plain of Western Australia but rarely affected in the adjoining Jarrah forest. There can also be variability in susceptibility within a species, resulting in the same species being ascribed different levels of susceptibility in different areas (Barrett & Rathbone, 2018).

The predicted loss of genetic diversity within a species following the local extinction of populations due to *P. cinnamomi* has been investigated in the highly susceptible *Banksia brownii*. This species shows a pattern of disease-driven population extinction typical of significant numbers of threatened plant species within south-western Australia (Barrett et al., 2008). Based on microsatellite genotyping of material from extinct (ex situ seed collections) and remaining extant populations, it was estimated that some 38 per cent of genetic diversity has been lost from *B. brownii* across its range due to *P. cinnamomi* (Coates et al., 2015).

As well as killing or otherwise affecting individual plants in an area, Phytophthora will infect new plants as they grow from in situ seed banks. Over the longer term, this will exhaust the seed bank, as many ecosystems affected by Phytophthora dieback have limited seed dispersal capacity. In these situations, a localised extinction of the plant species will occur. Barrett et al. (2008) and Barrett and Yates (2015) have documented instances of local extinction.

Appendix A of the *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi (DoEE, 2018) includes susceptible threatened flora species listed under the EPBC Act at the time of publication. Some of these species may be threatened with extinction.

2.3.2 Impacts on native plant communities

Infection by Phytophthora dieback in susceptible plant communities will often result in major disruption and decline of the structure and composition of those communities. Further, the vegetation assemblages of resistant species that, with time, recolonise areas are less species rich, have more open overstorey and provide a modified habitat for dependent organisms.

In many high-rainfall areas the biomass of communities can be dramatically impacted. For example, in woodlands dominated by species of *Banksia* and *Eucalyptus* on highly susceptible sites, basal area (an index of accumulated biomass) has reduced to a fraction of its pre-infection status.

In Victoria, long-term studies have been undertaken in the Brisbane Ranges, Wilsons Promontory National Park, Grampians National Park (Weste et al., 2002) and Anglesea (Wilson et al., 1997). Species present in post-diseased areas are likely to be either resistant to *P. cinnamomi*, exhibiting few or no disease symptoms, or tolerant/fluctuating species that exhibit some disease symptoms as well as showing regrowth and recovery at times. Longer term studies in the Brisbane Ranges and the Grampians have shown changes over time in the floristic composition (Weste & Ashton, 1994; Weste et al., 2002).

A detailed examination of the floristic and structural changes in heathland communities was undertaken at two sites within the eastern Otways from 1988 to 1995 (Laidlaw & Wilson, 2003). The pathogen significantly affected not only the floristic diversity but also vegetation structure in the area. Compared to non-diseased areas, diseased vegetation had less cover of *Xanthorrhoea australis* (Grass Tree) and shrub species, and greater cover of sedges, grasses and open ground. Structural differences observed included a decline in cover, between 0 and 0.6 metres height, in diseased vegetation. Assessments of long-term changes (1989–2015) found disease progression resulting in a significant increase in post-disease vegetation and major alterations to floristic composition vegetation structure (Wilson et al., 2018 in prep; Zhuang-Griffin, 2015).

Phytophthora dieback directly threatens a range of individual plant species; it also threatens ecological communities and landscapes. In a study of Banksia woodland and *Eucalyptus marginata* forest in south-western Australia, Shearer et al. (2009) found that *P. cinnamomi* can cause changes within susceptible plant communities that affect ecosystem processes. Significant changes in plant community composition and structure have been documented in southern Western Australian shrublands following infestation (Bishop et al., 2010; Barrett & Rathbone, 2018). Phytophthora dieback can lead to reduced canopy closure, basal area, percentage ground cover and total plant species cover as well as percentage organic carbon, extractable phosphorus and extractable and total potassium. In the South-west Botanical Province, the use of hemispherical digital photographs was found to be an efficient method of quantifying the impact of Phytophthora dieback (Crane & Shearer, 2007). Shearer et al. (2012) suggested that re-establishment of vegetation cover to infested areas using resistant selections of local dominant plant species may substantially return the functionality seen in healthy areas.

In addition to direct impacts, the pathogen can also have indirect impacts on flora. For example, in South Australia, EPBC Act listed orchid species *Caladenia argocalla* (White-beauty Spider-orchid), *C. behrii*, (Pink-lipped Spider-orchid) and *C. rigida* (Stiff White Spider-orchid) receive some protection from herbivores where they grow close to the fronds of *Xanthorrhoea semiplana* (Tufted Grasstree). When grasstrees become infected with *P. cinnamomi* and die, the orchids become exposed and are vulnerable to herbivory (Petit & Dickson, 2005).

Appendix C of the *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi (DoEE, 2018) includes threatened ecological communities listed under the EPBC Act at the time of publication that may be impacted by *P. cinnamomi*.

2.3.3 Impacts on animals

Phytophthora dieback could lead to permanent losses for fauna dependent on susceptible systems for food and habitat. Wilson et al. (1994) found that Phytophthora dieback has the potential to influence the abundance and composition of many faunal communities. These effects are largely indirect, resulting from changes in plant species richness and composition and from alterations to the structural compositions of habitat. Garkaklis et al. (2004) reviewed the literature on the responses of forest animal communities to the presence of *P. cinnamomi*. This review indicated that serious impacts either were occurring or were plausible but not yet demonstrated. The greatest impact is likely to be on species requiring relatively dense, species-rich shrublands or those with restricted diets.

The presence of *P. cinnamomi* not only results in the loss of floristic diversity and compromises year-round food availability but also leads to a decline in suitable refuge for fauna (Dundas et al., 2016). A study at Cape Riche, Western Australia, by Dundas et al. (2013) found that Phytophthora dieback is likely to have a detrimental impact on *Tarsipes rostratus* (Honey Possum), identifying at least five of nine plant species visited by the species as susceptible to the pathogen. The study concluded that the pathogen's potential to cause physical and composition changes to the vegetation could contribute to reduced population density or even localised extinctions of Honey Possums. While nectarivorous species in susceptible areas are clearly at risk, the impacts of Phytophthora dieback on vegetation can also have flow-on effects on invertebrate communities and taxa. Declines or changes in invertebrates could in turn affect insectivorous fauna (Cahill et al., 2008).

Habitat of the EPBC Act listed *Parantechinus apicalis* (Dibbler) on the south coast of Western Australia is highly vulnerable to the pathogen as many key species are susceptible. The effect of disease-induced changes to the habitats of Dibblers is unknown, but Phytophthora dieback is a significant threat (Friend, 2004).

An analysis of mammals in Victoria found that, for 22 species, more than 20 per cent of their range occurs in *P. cinnamomi* affected areas (Wilson & Laidlaw, 2001). Five rare or threatened species have greater than 20 per cent of their distribution in areas susceptible to Phytophthora dieback: *Pseudomys fumeus* (Smoky Mouse), *Pseudomys shortridgei* (Heath Mouse), *Pseudomys novaehollandiae* (New Holland Mouse), *Potorous longipes* (Long-footed Potoroo) and *Petrogale penicillata* (Brush-tailed Rock-wallaby) (Cahill et al., 2008).

P. cinnamomi infestation is a threat to mammal communities in Victoria's eastern Otways (Anglesea Heath, Great Otway National Park) due to changes in habitat structure and floristics (Wilson et al., 1994, 2000; Annett, 2008; Laidlaw & Wilson, 2006). The abundance of *Antechinus stuartii* (Brown Antechinus) was significantly lower at sites infected with *P. cinnamomi*, and a significant relationship was found between the capture rate of this species and the volume of vegetation present up to 40 centimetres above ground level (Newell & Wilson, 1993). *A. agilis* (Agile Antechinus), *Rattus fuscipes* (Bush Rat), *R. lutreolus* (Swamp Rat) and *Sminthopsis leucopus* (White-footed Dunnart) were captured more frequently in non-diseased areas as compared with diseased areas. This shows that the pathogen may affect the community structure of small mammals, causing a decline in species richness as a consequence of the disease proceeding through the habitat (Laidlaw & Wilson, 2006).

Menkhorst and Broome (2006) found that Phytophthora dieback has the potential to have a very large impact on populations of the EPBC Act listed endangered Smoky Mouse. Many of the plant families and genera characteristic of Smoky Mouse habitat are particularly susceptible to the pathogen. In New South Wales, *P. cinnamomi* invasion is considered to be a process threatening the conservation of endemic populations of Smoky Mouse and *Isoodon obesulus* (Southern Brown Bandicoot). The Long-footed Potoroo is also at risk from Phytophthora dieback due to the proximity of infections to suitable habitat for this marsupial.

In South Australia, Phytophthora dieback is a potential threat to the endemic and endangered *Sminthopsis aitkeni* (Kangaroo Island Dunnart) due to the loss of susceptible plants from its habitat (Gates, 2011).

Vegetation change caused by Phytophthora dieback also has the potential to threaten the persistence of *Bettongia penicillata ogilbyi* (Woylie) populations. Dense vegetation provides Woylies with shelter from predators, and changes in the structure of natural habitats can increase predation risks (Yeatman & Groom, 2012). Phytophthora infection also has a negative impact on fungal community structure and biodiversity, potentially impacting directly on the availability of food resources for the Woylie (Anderson et al., 2010, cited in Yeatman & Groom, 2012).

Invertebrate co-extinction is also likely, where narrowly host-specific insect herbivores on plants have high potential for extinction with their host, particularly as they may have a narrower geographic range than that of the plant. Local extinction has already been demonstrated in a number of cases associated with *P. cinnamomi* threatened host plants such as *Banksia brownii* and *B. montana* (Moir et al., 2011, 2012). In particular, the *B. brownii* host-specific herbivorous plant-louse *Trioza barrettae* has been listed as endangered in Western Australia given its significant decline associated with the loss of a number of *B. brownii* populations (Moir et al., 2016). Similarly, the critically endangered *Pseudococcus markharveyi* (Banksia Montana Mealybug) is dependent on *B. montana* of which there are fewer than 40 mature plants remaining.

Appendix B of the *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi (DoEE, 2018) includes threatened fauna species listed under the EPBC Act at the time of publication that may be impacted by *P. cinnamomi*.

2.3.4 Resistance to infection

There are few plants that are truly resistant to *P. cinnamomi*: the pathogen is capable of infecting the roots of all species that have been tested so far. Many species may become infected with *P. cinnamomi*, but not all species die as a result of infection. Those non-susceptible species that have been examined in detail produce a number of responses that will contain the infection to the immediate vicinity of pathogen penetration. Some plants are able to compartmentalise the pathogen once it penetrates the roots and prevent it from invading the rest of the root system and plant collar. Other plants, typically monocotyledons, are able to rapidly produce new roots to replace those infected by the pathogen and so are able to withstand infection. Field observations suggest that, in general, herbaceous perennials, annuals and geophytes are more resistant to *P. cinnamomi* than woody perennials. A study by Islam et al. (2017) indicates that *Lomandra longifolia* is highly resistant to *P. cinnamomi*. This resistance is not necessarily related to one factor; resistance at the cellular level in *L. longifolia* roots involves the coordinated response of several factors that are activated at the onset of infection.

Field observations suggest that there is also considerable variation in resistance between species within the same genus or subgenus. For example, in the genus *Eucalyptus*, most species in the subgenus *Symphomyrtus* (gums, boxes and ironbarks) are relatively resistant to infection by *P. cinnamomi*, but most species in the subgenus *Monocalyptus* (ashes, stringybarks and peppermints) are susceptible. Variation in susceptibility within the genera *Lambertia* and *Banksia* has been identified by Shearer et al. (2010, 2013).

The Centre for Phytophthora Science and Management (CPSM) at Murdoch University has compiled lists of Western Australian native plant species that are resistant to disease caused by *P. cinnamomi* (Groves et al., 2009a, 2009b). This information is available on the Dieback Working Group (DWG) website (www.dwg.org.au).

Worboys and Gadek (2004) present lists of field-resistant upland tropical rainforest species from Queensland. The lists have been compiled from field observations of resistance and the results of controlled experiments. However, the classification of a plant as resistant to *P. cinnamomi* often depends on other environmental factors (including climate) which can influence susceptibility to the pathogen. Species resistance can also vary depending on the pathogen's genotype (Howard, 2008). The susceptibility of a plant species occurs on a continuum between resistant and susceptible, with genetic components within species, between species and within genera displaying variable susceptibility. As a result, a species should be considered susceptible when greater than 50 per cent of the genetic population of the plant is killed when confronted by the pathogen.

Investigations over several years have discovered the mechanisms by which a limited number of plants are able to survive infection, including activation of defence-related genes and signalling pathways, reinforcement of cell walls, and accumulation of toxic metabolites (Professor David Cahill, pers comm, 2011). Genetically based, intra-specific variation in resistance has been demonstrated in the Western Australian native hardwood *Eucalyptus marginata* (Jarrah) (Stukely & Crane, 1994) and in the exotic plantation species *Pinus radiata* (Butcher et al., 1984).

3. Dealing with the problem

The limited management options available focus on the modification of human activities through restricting access to certain sites and deploying and enforcing hygiene procedures to minimise the spread of Phytophthora in the landscape. The two major objectives of Phytophthora dieback management are:

- to prevent the introduction or minimise the spread of Phytophthora into uninfected areas
- to reduce the impact of Phytophthora at infected sites.

To manage the problem of Phytophthora infection, a set of tools, skills and protocols has been developed based on knowledge of Phytophthora status and preferences on a geographical and species basis (section 3.1).

Active interventions that reduce transmission of Phytophthora are projects that involve quarantine or access prohibition or restriction, and/or involve a hygiene component with disinfection of machinery or inanimate objects entering an area free of the pathogen (section 3.2).

The direct application of the fungistatic agent phosphite to the host plant is expensive aerially but is a useful tool to conserve localised populations at high risk of extinction, particularly in remote areas. Studies on phytotoxicity across a range of non-target species include Barrett (2001) and Pilbeam et al. (2000). A study on long-term phosphite application detected no adverse impacts on Proteaceae (Barrett & Rathbone, 2018). However, there is much still unknown about the effects of the agent on target and non-target plant and animal species (section 3.3). Assessment of the effectiveness of management regimes requires ongoing monitoring to detect changes in disease status. The integration of these strategies and the local integration of management techniques in an adaptive management approach will maximise the success of Phytophthora dieback management (sections 3.4 and 3.5).

3.1 Identification of the disease

3.1.1 Detection

Current practice in detecting *P. cinnamomi* in the field involves the observation of visible symptoms of disease in vegetation and confirmation of its presence through sampling and laboratory analysis of soil and diseased plant tissues.

Aerial photographs (1:4500 nominal scale, but up to 1:25,000) can be used to detect the disease on a broad scale. Given sufficient disease expression, trained personnel can make decisions about the disease status of an area by stereoscopic examination of aerial photographs taken in autumn under shadowless conditions (full cloud cover). In autumn, infected plants that have died after making a final effort to respond to summer drought-breaking rains have yellow to bright orange leaves and are readily detected via aerial photographs.

Detection techniques using polymerase chain reaction (PCR) (O'Brien, 2008) enable more accurate and cost-effective detection of *P. cinnamomi* in infested soil. DNA-based detection offers improved sensitivity and higher sample throughput for the detection of *P. cinnamomi* than baiting assays (in which susceptible plant species are exposed to diluted soil samples). Williams et al. (2009), through comparative analysis using PCR-based methods in parallel with baiting assays, showed a significant increase in the detection of *P. cinnamomi* by nested PCR. As new technologies emerge, improved detection techniques may be developed and adopted. The potential application of RNA sequencing in detecting small quantities of the pathogen in large soil samples could be an integral part of the identification and certification of dieback-free materials.

3.1.2 Diagnosis

There is widespread confusion between disease caused by Phytophthora and disease and death resulting from other causes in native vegetation, largely because of the difficulty of field diagnosis. Field diagnosis of disease relies heavily on the specialist interpretation of symptoms produced by indicator species—for example, grasstrees—coupled with knowledge and information about potentially confounding environmental factors such as site and soil characteristics, fire, drought and abiotic or other biotic diseases that may mimic the symptoms of Phytophthora dieback. While it sometimes produces reliable visible symptoms in a number of hosts, in many other hosts it is not reliably detected.

The cryptic nature of the pathogen exacerbates this problem—it is visible only by microscopic examination and detectable by laboratory analysis. A positive diagnosis of *P. cinnamomi* as the causative agent of disease requires soil or tissue samples from affected plants to grow the pathogen out on agar plates. The majority of laboratories in Australia with the capacity to analyse samples for the presence of *P. cinnamomi* have used conventional identification of morphological characteristics, primarily of the characteristic hyphae and reproductive structures (Drenth & Sendall, 2001, cited in O'Gara et al., 2005a).

PCR-based methods can confirm a result from the agar plate method or facilitate the identification of further vulnerable plant species and improve the economic feasibility of sampling to detect or confirm visible evidence of infection. This should assist in the subsequent mapping of infested sites and continued monitoring of disease fronts.

3.1.3 Mapping

The current distribution of *P. cinnamomi* in Australia is not well known; however, the Western Australian Government has mapped over 700,000 hectares to date. Direct mapping, involving on-ground survey, is impractical due to high costs and the difficulties associated with sampling. Furthermore, the autonomous movement and spread of the pathogen by uncontrolled vectors means that *P. cinnamomi* distribution maps have a limited currency of one to three years.

Up-to-date maps that accurately depict the boundaries between infected and uninfected sites assist with determining both where the pathogen is and where it may spread. This informs on-ground management and assists with mitigation of the impact of disease. The costs of on-ground survey and sample analyses have made the initial mapping or updating of maps expensive and only applicable ahead of major operations requiring disease demarcation. In the future, PCR-based detection methods may reduce the costs of sample analyses. Maps of disease occurrence through interpretation of aerial photographs can be developed at a lower cost, but they do not have the same level of detail as those produced through on-ground survey. In addition, maps derived from aerial photography are generally not suitable where there is a lack of susceptible species in the dense emergent shrub or forest layer, and the scale of photography often precludes interpretation of disease symptoms under these conditions. Cahill et al. (2008) provide a comprehensive review discussing the potential for employing predictive mapping for *P. cinnamomi*.

In Western Australia, Project Dieback provides a Dieback Public Map as well as the user-registered DIDMS GRID (Dieback Information Delivery Management System Geographic Reporting Information Database)—a web-based platform for storage, viewing, basic mapping at a broad scale and sharing of spatial Phytophthora dieback information by intermediate level users. Tasmania's Natural Values Atlas offers a user-friendly web interface which provides access to authoritative and comprehensive information on Tasmania's natural values and threats to those values, including Phytophthora.

Various attempts at mapping have been made using innovative methods, such as satellite imagery; however, the success of using these methods has been constrained by the nature of the impact of *P. cinnamomi*, which is often restricted in visual impact and may be similar to symptoms from other causes of plant death, such as drought. Maps produced from the interpretation of aerial photographs do not have the same level of accuracy or detail as those produced by on-ground surveys.

Hill et al. (2009) demonstrated the ability of digital multi-spectral imaging to determine disease extent over broad areas in *P. cinnamomi*-infested heathland communities in southern Victoria. In this situation, symptoms of *P. cinnamomi* arise as a mosaic within healthy vegetation. The study found that digital multi-spectral imaging, derived from light aircraft survey, provides a non-invasive, cost-effective tool for management of Victorian heathland.

As detailed above, in the Greater Blue Mountains World Heritage Area, Newby (2014) undertook species distribution modelling using information about *P. cinnamomi* ecology. The development of new models to predict the distribution of *P. cinnamomi* with a very high level of accuracy enabled the identification of areas for sampling. This approach can reduce the area to be sampled and increase the chances of successfully finding the pathogen.

3.2 Minimising the spread of Phytophthora dieback

In the absence of any fully tested and effective mechanism to eradicate the pathogen from an area, the primary objective of disease management is to protect the biodiversity of areas at risk from Phytophthora dieback. 'Protectable areas' are defined as uninfected areas in the vulnerable zone with good prospects of remaining uninfected over the next two to three decades.

The process involves the identification of significant disease-free areas, followed by a risk analysis to determine the probability of *P. cinnamomi* introduction, the identification of potential routes of invasion and the manageability of those risks. As humans are the most significant vector of Phytophthora dieback, managing spread predominantly involves the modification of human behaviours and activities.

Land users in high-risk areas can reduce the spread of the disease by following relevant guidelines for their user group. For example, the Tasmanian Government has published a technical note on managing the risks in production forests (FPA, 2012), and the Nursery and Garden Industry Australia promotes information on the importance of hygiene in the horticultural industry (Pegg et al., 2014; Pegg & Manners, 2014). Main Roads Western Australia endeavours to manage and reduce the potential spread of the pathogen during road-building and maintenance activities. High-risk projects may require mapping of the site by a registered Phytophthora dieback interpreter, adherence to a hygiene management plan and sourcing of dieback-free basic raw materials. NRM South in Tasmania has produced a range of resources targeted at specific groups of recreational and operational land users (NRM South, 2018). The Australian Government has developed hygiene guidelines for use by funding recipients who will be working in areas of high conservation value (DoEE, 2015).

Through effective communication and training, messages such as 'Arrive clean, leave clean' and 'Check, Clean, Disinfect, Dry' can encourage behaviour change. Awareness of the threat and observance of stringent hygiene protocols is important for anyone engaging in the following high-risk activities:

a. Emergency and land management activities

- Fire management, including:
  - emergency firebreak construction
  - firefighting, if water or equipment is contaminated
  - movement of contaminated equipment into uncontaminated areas due to non-compliance with, or careless implementation of, hygiene procedures
- Flood mitigation works involving:
  - movement of contaminated gravel, sand, soil etc.
  - movement of contaminated equipment
  - Use of contaminated nursery material and soil disturbance associated with revegetation and restoration activities
  - Weed and feral animal control activities

b. Recreational activities

- Camping
- Bushwalking, geocaching, rogaining, orienteering
- Fishing and marroning/yabbying
- Mountain bike riding
- Horseriding
- Recreational vehicles (for example motor bikes, quad bikes, four-wheel drives)
- Trail biking
- Hunting

c. Commercial and other activities

- Environmental/ecological surveys or research activities (for example, flora/fauna/vegetation mapping, geological surveying)
- Tourism, particularly ecotourism
- Timber and wild flora harvesting
- Defence force training
- Mining exploration and mining
- Seed collecting
- Soil and gravel extraction
- Firewood cutting
- Apiculture (beekeeping)
- Road construction (widening, realignment, maintenance)
- Construction and maintenance of recreational tracks and walking trails
- Construction of straight-line infrastructure (for example powerlines and telecommunication structures)
- Land development
- Fencing
- Installation of drainage
- Propagation and distribution of infected plants, soil and mulch for commercial purposes (for example nursery and gardening industries)
- Cropping.

3.2.1 Access prohibition or restriction

Prohibiting access or quarantining an area can help protect biodiversity assets from Phytophthora dieback. Prohibition of access may be enforceable under legislation such as the Western Australian *Conservation and Land Management Act 1984*, the South Australian *National Parks and Wildlife Act 1972*, the Tasmanian *National Parks and Reserves Management Act 2002* and the New South Wales *National Parks and Wildlife Act 1974*.

As Phytophthora can spread easily in infected soil, plant material and water, access to specified areas may be restricted to drier periods when soils are not likely to adhere to vehicles and pedestrians. Land managers may choose to restrict all access or just vehicular traffic. Recreational activities such as bushwalking, cycling and horseriding are perceived in some areas and in some circumstances to pose a low risk and may be allowable under specific conditions. The Western Australian Department of Biodiversity, Conservation and Attractions includes hygiene assessments as part of any new trail developments, with a focus on avoiding any protectable dieback-free areas.

For sound management of access to uninfected areas, boundaries between infected and uninfected areas need to be clear. Elements that are essential to operational planning include:

- recognition of the boundaries between infected and uninfected areas
- mapping of the boundaries between the two areas as a basis for future access
- demarcation of the boundaries on the ground so that machinery operators are forewarned and avoid crossing into infected areas
- regular inspection to ensure that entry controls are being followed
- regular testing to ensure that the disease has not spread past the boundaries put in place
- assessment of the efficacy of controls.

Difficulties with these sorts of quarantine measures can arise for social and resource-related reasons, such as:

- opposition to changes in land use/access
- level of public education required
- lack of resources necessary to enforce quarantine and hygiene protocols.

3.2.2 Hygiene

Where access is permitted, hygiene refers to specific procedures designed to prevent the spread of Phytophthora by ensuring the removal of infected soil, water and plant material from machinery, vehicles, equipment and footwear before entering uninfected areas. Management options include:

- postponing activities during wet weather
- beginning activities with clean vehicles and equipment
- avoiding wet or muddy areas during activities
- leaving heavy equipment in infected areas where they are regularly used.

Permanent or semi-permanent vehicle wash-down facilities may be constructed where machinery and vehicles require routine cleaning for fixed activities. For activities without a fixed location, portable wash-down systems at the point of risk enable cleaning of machinery, vehicles and any items that come into contact with the ground.

Where high conservation values are at stake, activities such as bushwalking, horseriding and cycling may pose a risk of introduction. Signage and cleaning stations at the entrance to susceptible areas allow visitors to disinfect their footwear, tools and equipment to keep these areas disease free.

The specific difficulties associated with maintaining the integrity of the boundary between infected and uninfected areas include:

- access for suppressing wildfires and installing and maintaining firebreaks on private property boundaries
- denial of access to uninfected areas when wet soils are likely to be picked up from cryptic infections in timber-harvesting coupes and spread further within the coupes (this results in the need to stockpile timber produce during drier periods in order to limit movement of infected mud)
- mapping and demarcation in planning access for heavy equipment, to minimise the inadvertent movement of machinery from uninfected areas into infected ones, and vice versa
- access for other activities, for example bushwalking, beekeeping, drilling, wildflower collecting.

Leave No Trace Australia (www.LNT.org.au) is a national and international minimal impact education program for the recreation, tourism, outdoor education, and land and sea management sectors. It focuses on biosecurity as one of its strategic awareness outcomes, including Phytophthora dieback awareness. Working with partners at a state, national, and international level across government, non-government and industry sectors, the Leave No Trace program is delivered as a community and formal education program that seeks to raise awareness of natural and cultural heritage values and the appropriate practices to mitigate the threats to those values.

State agencies have developed nationally applicable resources detailing hygiene protocols for work and recreation in and around Phytophthora management areas. The Western Australian Dieback Working Group (DWG) has produced a number of publications with information on hygiene, including a guide to help landholders and community groups manage Phytophthora dieback in bushland (DWG, 2015). The Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) offers 'Green Card' training in awareness and management of Phytophthora dieback to staff and contractors. The DWG, in association with the DBCA, also offers Green Card training to a wide range of stakeholders, including local government, industry and community groups. This training could be redeveloped for national use to train staff and contractors working in high-priority conservation areas, including land management agency staff (refer to the case study below for further details).

Case Study

Green Card: A nationally applicable training and awareness program

The Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) has an internal 'Green Card' training and awareness program for employees and contractors who operate on its managed land. The WA Dieback Working Group (DWG) has collaborated with DBCA to further develop Green Card training so that it is suitable for all stakeholders operating on any land tenure.

The DWG maintains a list of registered trainers with significant experience in Phytophthora management. These professionals deliver the training to communities, industry and government. The DWG's project partner South Coast NRM expands this training further. The benefits of collaborating to deliver this training have been well-received by many industries, government agencies and communities in the south-west of Western Australia.

The training includes information on Australian biosecurity and uses Phytophthora as a significant and widespread example of a key threatening process to demonstrate practical biosecurity hygiene methods and strategies to a very wide audience. The training aims to increase awareness and promote positive behaviour changes. Training fees are returned directly into further stakeholder awareness-raising activities that ultimately benefit the environment and its values. Expanding this model to other relevant states and territories could significantly enhance communities' participation in mitigating biosecurity threats (including Phytophthora) in Australia. Further information is available at www.dwg.org.au/green-card.

The Tasmanian Government publication *Keeping it clean* (Allan & Gartenstein, 2010) provides thorough hygiene methodologies to minimise the risk of introduction or spread of exotic diseases into state-managed lands. This document includes disinfection and cleaning processes for many activities, including the use of vehicles and heavy machinery; firefighting; and movement of infected gravel, sand, soil or water during road construction and maintenance. To promote the implementation of such hygiene protocols, the Tasmanian Parks and Wildlife Service is providing wash-down stations and encouraging park visitors to use them in order to protect large areas of susceptible vegetation on high-profile walking tracks such as the Three Capes Track. While they are useful tools to minimise risks to priority protection areas, there are difficulties associated with implementing hygiene measures in a way that ensures optimal uptake of and compliance with these measures. The case study below discusses Tasmania's development of a memorable message to reinforce the importance of hygiene.

Case Study

Check, Clean, Disinfect, Dry: Keeping it simple to keep it clean

Tasmania's geographic isolation and strict biosecurity requirements have helped protect the island's unique environment from many introduced pests, weeds and diseases. Where these threats have established, there has been an emphasis on containing them through collaboration between government, industry and community groups across agriculture, forestry, infrastructure tourism and environmental management.

Measures to slow the spread of Phytophthora dieback in the Tasmanian environment began in the 1970s. The more recent emergence of problems like *Chytridiomycosis* (amphibian chytrid fungus disease) and potential introduction of risks such as *Didymosphenia geminata* (Didymo, a freshwater algal pest) brought the realisation that separate hygiene protocols to prevent the spread of different threats would be less effective. One simple message, applicable to a range of threats and activities, would be efficient and memorable. An easily achievable procedure would minimise confusion and encourage increased uptake.

Tasmania's *Keeping it clean* manual (2010) outlined the procedure required to prevent the spread of *Phytophthora cinnamomi* and three other freshwater pests and pathogens, and introduced the 'Check, Clean, Disinfect, Dry' protocol. Since then, Tasmania's Biosecurity Network has developed a range of resources to promote this message: web pages, videos and downloadable fact sheets tailored to various land and water users. Other initiatives include signage, hygiene kits, funding for wash-down stations and a strong presence at community events. An annual survey helps to refine actions by determining which user groups would benefit from support.

As Tasmania is a major tourist destination, engagement with the tourism and recreation industry is important. The Biosecurity Network works with tour companies to ensure travellers are given a simple message before they arrive in Tasmania: that routine hygiene practice can prevent the spread of serious weeds, pathogens and pests. This awareness can make all the difference.

The Biosecurity Network is working towards making 'Check, Clean, Disinfect, Dry' the universal message and practice for anyone visiting or working in Tasmania's natural and productive areas. Useful resources are available on the NRM South website at www.nrmsouth.org.au/biosecurity.

Example of a biosecurity hygiene kit

The use of a biosecurity hygiene kit to clean footwear and equipment can help minimise the spread of Phytophthora

Suggested items:

- Plastic tub with a lid (to carry items and use as a footbath)
- Spray bottle containing 70% methylated spirits and 30% water
- Stiff brushes
- Dustpan and brush
- Newspaper to cover the footwell of a vehicle
- Sealable plastic bag for sweepings and used newspaper
- Alcohol wipes or gel for hands and personal items

The Victorian Government's WeedStop Vehicle Hygiene Program covers the principles of weed spread and machinery hygiene. As these are also relevant to reducing the spread of pests and diseases, the program can be customised to deal with Phytophthora.

Regional-scale hygiene methodologies have been developed for the Wet Tropics of Queensland World Heritage Area, where dieback management procedures apply to operational works (Worboys & Gadek, 2004).

3.2.3 Potential further introductions through revegetation

In the nursery and garden industry, Phytophthora can kill potted plants and infest plant growth medium. The use of infected plant stock has the potential to spread the disease extensively in urban and rural situations and may become problematic when gardens or rehabilitation activities adjoin natural bushland. Many consumers are unaware of the threat posed by purchasing infected plants and plant medium and introducing Phytophthora into the natural environment. There is also a lack of awareness that this threat can be minimised by purchasing from certified sources.

Revegetation of much of the landscape is occurring on a broad scale across the vulnerable envelope for Phytophthora, and the threat of continued spread of the pathogen from infected stock and nurseries is potentially significant. A key objective for much of the revegetation work is to enhance or restore the landscape; however, this may be nullified if Phytophthora is introduced in the process. Managing the threat will require targeting both producers and consumers of products.

Nurseries in many states have voluntary best practice guidelines to reduce the spread of Phytophthora via infected stock. The Nursery and Garden Industry Australia (NGIA) supports the Nursery Industry Accreditation Scheme (NIASA). The NIASA is a national scheme for production nurseries, growers, growing media and potting mix businesses which operate in accordance with a set of national best practice guidelines. Further information is at the NGIA website: www.ngia.com.au.

3.2.4 Eradication

A method for eradicating very small infestations of Phytophthora has been developed and could be applied strategically in suitable areas where high-value biodiversity assets occur. The process involves a sequence of treatments: vegetation (host) destruction, fungicide and fumigant treatments, and containment barriers to protect threatened vegetation (Dunstan et al., 2010; Dunne et al., 2011).

Dunstan et al. (2010) applied these treatments at two *P. cinnamomi* infested sites with differing climate and vegetation types. *P. cinnamomi* was not recovered at three assessments of treated plots six to nine months after treatments. This method greatly increases the potential for spot-eradicating Phytophthora in patches with sandy soils dominated by root-to-root transmission. Eradication efforts in clay or rocky soils dominated by water-associated spread have proven more problematic.

A subsequent study by Crone et al. (2012) highlighted the importance of destroying all hosts, including annual and herbaceous perennial plants, with and without symptoms. These groups of plants can allow the pathogen to persist on sites after susceptible species have disappeared or have substantially reduced in numbers. This has implications for detection, diagnosis and management.

An experimental investigation of the potential efficacy of host destruction is necessary before adopting this method. It should be emphasised that clearing vegetation to remove the hosts of Phytophthora would only be suitable for very small areas. Ongoing monitoring of any eradication trial is essential and would require continuing resources.

3.2.5 Monitoring and surveillance

Effective monitoring and surveillance for the presence of Phytophthora is essential to allow timely management.

Monitoring and surveillance of plant communities provides information on disease outbreaks, as well as on distribution, prevalence and incidence of Phytophthora. It also provides information necessary for evaluating the risk the pathogen poses to biodiversity and the effectiveness and efficiency of management and risk mitigation measures.

The purpose of monitoring ranges from determining long-term patterns of pathogen spread and disease impact to determining the effectiveness of management measures and/or surveillance of pathogen movement where high conservation values are under imminent threat. Surveys can be one off, to determine whether a site is infected with the pathogen, or they can be systematic and ongoing. Systematic ongoing surveys focused on key sites provide data on the epidemiology of the disease over time. Information about pathogen occurrence, susceptible species, climate and topography can be employed to develop predictive maps for potential future occurrence and risk of introduction of the disease.

There is scant information available on the effectiveness of current management tactics, particularly hygiene measures, due to insufficient monitoring.

3.3 Treatment options to mitigate the impact of Phytophthora dieback

The autonomous spread of Phytophthora is impossible to control, and tools available to mitigate the impact of Phytophthora are limited. The strategic use of the fungistatic agent phosphite has management potential for impact reduction, containment and spot eradication. Ex situ conservation of susceptible plants is a management option for the preservation of susceptible and rare plants. The cost of these options makes only limited application practical. As a result, in situ conservation is more often the approach taken by land managers dealing with *P. cinnamomi*. The breeding of resistant plants such as Jarrah, while expensive, is another option for the rehabilitation of high-priority infected sites (see section 3.3.4).

3.3.1 Phosphite

The term 'phosphite' refers to salts of phosphonic acid (H_3PO_3). Phosphite induces a strong and rapid defence response in the treated plant, stopping pathogen spread in a large number of hosts. To be effective, phosphite needs to enter a plant's water transport system by stem injection of phosphite into trees or by spraying phosphite onto the leaves of accessible plants. Injection provides the trees with protection for at least four years (Shearer & Fairman, 2007), while spraying the leaves provides protection for one to two years (Shearer et al., 2004). Efficacy may vary between and within species being treated. Phosphite exhibits a complex mode of action, acting both directly on the pathogen and indirectly by stimulating host defence responses to inhibit pathogen growth.

At the time of publication, phosphite is the only tool available for species and communities at high risk of extinction. It is used to protect areas of high conservation value and critically endangered species from the threat of Phytophthora in Western Australia, Victoria and Tasmania. Phosphite is potentially applicable in a national context and, given limited management options, provides states and territories with an important tool. However, it should be used judiciously, with reference to available research and close monitoring of results. This will build the body of knowledge relating to the effectiveness of this form of management.

The beneficial properties of phosphite include:

- the induction of resistance to *P. cinnamomi* in otherwise susceptible plant species (Guest & Bompeix, 1990)
- its mobility in phloem and xylem (enabling application by stem injection to trees and large shrubs)
- its uptake through foliage, which enables application as a foliar spray, either manually or by broad-scale aerial application
- its quick breakdown in the soil (Guest & Grant, 1991, cited in O'Gara et al., 2005a).

Phosphite has low toxicity for many mammals, although its effects on other fauna have not yet been properly assessed. The chemical should be used as regulated and with caution in areas where threatened fauna species are known to occur.

The detrimental effects of phosphite on non-target species may include phytotoxicity, growth abnormalities and reduced reproductive capability in some species and at high application rates (Hardy et al., 2001). Lambers et al. (2013) acknowledged the importance of phosphite as a short-term solution in the absence of any alternative but cautioned that phosphorus-sensitive plants may be affected by this treatment. The study emphasised the need for further research to understand how phosphite functions and to find effective alternatives. The potential for any deleterious effects of treatment should be included in all monitoring where phosphite is being applied within native plant communities.

Barrett and Rathbone (2018) compared phosphite-treated vegetation with untreated vegetation in Kwongkan communities in the South-west Australian Floristic Region. They observed no significant adverse impacts resulting from up to 17 years of phosphite treatment and found that phosphite enhanced the survival of key susceptible species and mitigated disease-mediated changes in vegetation structure. The use of phosphite in conjunction with long-term monitoring remains an important management tool in the absence of other options.

There are also large differences in levels of control between plant species. In addition, phosphite is not an eradicant, and the pathogen remains in the soil/host plant environment even though symptoms are suppressed. The Australian Pesticides and Veterinary Medicines Authority (APVMA) administers the National Registration Scheme for Agricultural and Veterinary Chemicals in partnership with the states and territories. Phosphite is currently not registered for use in native vegetation, so an off-label permit is required from the APVMA before use. However, as legislation can vary between states/territories, it is recommended that the APVMA or the relevant state/territory APVMA coordinator be contacted for advice on permit requirements before use.

Aerial application is a rapid way to treat entire plant communities, especially where rough terrain would make ground application practically impossible or prohibitively expensive. Application on leaves (foliar) using backpack or trailer-mounted sprayers is usually restricted to small areas such as small reserves, remnant bushland and spot infections. Trunk injection of trees and large shrubs is used in strategic areas where their loss would have a high visible impact and where foliar application is impractical. Bark painting may also be effective; further development of this and other emerging techniques is necessary. Scott et al. (2015) treated infected stems of *Banksia grandis* and *Eucalyptus marginata* with liquid phosphite injections and soluble capsule implants. Results demonstrated that both methods were effective at controlling the extent of *P. cinnamomi* infection in these species.

The cost of phosphite application precludes broad-scale application to infected sites. The use of phosphite and/or ex situ conservation as a component of integrated management for a site or area requires a process of prioritisation and strategic planning. Highest priority may be given to sites assessed as ecologically or economically significant or valued by the community.

The DWG has produced instruction leaflets on spraying and stem injection of phosphite. These are available on the DWG website (www.dwg.org.au).

Case Study

Management of a biodiversity hotspot under threat

The south-west of Western Australia, from Shark Bay to the western edge of the Great Australian Bight, is an internationally recognised megadiverse hotspot. The conservation of biodiversity is a driving factor in shaping the Forest Management Plan (FMP) 2014–2023 (CCWA, 2013). Conserving biodiversity requires maintenance of a diversity of habitats and ecological processes at various spatial scales, from entire forested landscapes to specific localised habitats. It also includes sustaining populations and maintaining their genetic diversity.

Within the FMP area, there is a network of informal reserves providing additional refuges, complemented by other measures to maintain habitat and minimise the impacts from disturbance operations in other areas. This emphasises the importance of maintaining connectivity across landscapes by minimising fragmentation and retaining (or re-establishing) ecological corridors to allow movement of species.

The FMP recognises that Phytophthora dieback continues to spread and affect the distribution and abundance of many native south-west plant species and their associated fauna. By impacting susceptible species and vegetation types, these pathogens can alter species composition and ecosystem functioning, leaving areas vulnerable to invasion by weeds. The plan prioritises minimising the risk of new invasions in areas not yet infected by *P. cinnamomi* and other related species (such as *P. multivora*).

An internally draining catchment in the Fitzgerald River National Park, within the UNESCO-listed Fitzgerald Biosphere, was the site for a successful large-scale containment project. This involved the construction of a 12-kilometre fence around the entire Bell Track infestation to prevent people and animals spreading the disease. This was followed by the installation of a plastic membrane 3 kilometres long to prevent the spread of *P. cinnamomi* through root-to-root transmission. The use of these physical barriers in conjunction with the fungicides phosphite and metham sodium has effectively contained the infestation to date, protecting the largely disease-free status of the remaining park (Dunne et al., 2011).

3.3.2 Ex situ conservation

Ex situ conservation of germplasm in seed banks is a well-established technique and possibly the last hope of conserving some susceptible species in the absence of a definitive solution to the threat of Phytophthora dieback. Compared with other types of conservation, seed banking has many benefits, including the simplicity of the technology, low cost and space requirements, the potential for long-term storage with little loss of seed viability, the applicability of the technique to a wide range of species, and greater genetic representation in seed than in vegetative material (Cochrane, 2004). Best practice guidelines and standards are available for the capture, storage and use of wild plant germplasm for long-term conservation (ANPC, 2009).

The work of the Australian Seed Bank Partnership (ASBP) is a national effort to conserve Australia's native plant diversity through collaborative and sustainable seed collecting, banking, research and knowledge sharing. Seed banking is a principal tool for the safe and efficient storage of wild plant genetic diversity and provides a resource and knowledge base to support the management and conservation of plant species and communities in Australia (ASBP website, 2017). With funding assistance from the department, the ASBP completed two projects in 2013 and 2017 to build comprehensive and genetically diverse ex situ seed collections of select threatened species at risk from *P. cinnamomi*. These collections are held in conservation seed banks across Australia for use in research, species recovery or translocation efforts.

3.3.3 Translocation

Translocation is the deliberate transfer of plants or regenerative plant material from one place to another. Purposes for translocation include (Vallee et al., 2004):

- enhancement—an attempt to increase population size or genetic diversity by adding individuals to an existing population
- reintroduction—the establishment of a population in a site where it formerly occurred
- conservation introduction—an attempt to establish a taxon at a site in which the taxon is not known to occur now or to have occurred in historical times but which is considered to provide appropriate habitat for the taxon.

Any material moved during translocation must be free of disease. Guidelines for the translocation of threatened plants in Australia (Vallee et al., 2004) take into account the benefits, risks, planning and implementation associated with the strategy. A review of these guidelines during 2017 and 2018 will result in publication of the third edition.

3.3.4 Breeding for resistance

Breeding for resistance is another potential impact mitigation method, although its application is limited without further research. There is considerable variation in resistance within a species or between species within the same genus or subgenus. Enhancing the process of natural selection for resistance may be a longer term management option for some taxa. Future research may also allow for the transfer of resistance genes into taxa that at present appear to have no resistance. However, an improved understanding of the genetic basis of resistance and the genetic diversity of *P. cinnamomi* will be essential for this work. Initially the availability of samples of *P. cinnamomi* cultures, isolated and collected from a wide range of natural ecosystems, would facilitate any research.

It has been observed that remaining and apparently healthy Jarrah trees in diseased forest are a subset of the Jarrah population that is resistant to *P. cinnamomi*. Intra-specific resistance has been demonstrated using clones of susceptible Jarrah (Stukely & Crane, 1994). There have been very real gains made in dieback-affected forests in Victoria following the use, for over 30 years, of a strategy to exploit the potential that a small percentage of individuals of otherwise susceptible species are tolerant (Marks & Smith, 1991). Sites have been successfully rehabilitated through the strategy of sowing well-prepared seedbeds with high numbers of seeds collected from trees endemic to the sites. While the resilience of the apparent resistance seen is still to be proven, the outcome to date is that the percentage that survives can provide for an adequate restocking of eucalypts on these previously dieback-affected sites. This approach also ensures that the stocking rate is high enough to potentially lower the water table and thus reduce conditions conducive to disease development.

If proven feasible, a program for breeding resistant individuals of susceptible keystone or threatened species could provide a basis for rehabilitation of sites affected by the disease, in combination with careful selection of micro-habitats that are less conducive to the pathogen.

3.3.5 Other methods of control

Soil microorganisms have been shown to be effective controls for Phytophthora in experimental conditions (El-Tarabily et al., 1996). The potential use of biocontrol agents to mitigate the spread and impact of Phytophthora could present as a more sustainable and effective approach to managing this threat in the long term. There is considerable work towards biological control agents of Phytophthora diseases in different crops, with reports of successful control using rhizobacteria, or endophytic bacteria or fungi. However, in a native ecosystem context, there are additional challenges in providing ongoing protection for a wide diversity of species compared to protecting a single agricultural species for a limited time (O’Brien & Hardy, 2014).

3.4 Wide-scale detection, diagnosis and demarcation protocols

The survey and mapping of *P. cinnamomi* distribution requires a uniform and consistent sampling standard for application across the country. While a single positive sample can confirm the presence of the pathogen at a site, it is not possible to deem a site free of the pathogen from a single or even multiple negative samples.

A systematic survey of long-infected sites in Western Australia determined that the number of samples needed to return a negative result to pronounce a site free of *P. cinnamomi* with 95 per cent confidence, is 271 (Davison & Tay, 2005). Due to the requirement for such a high number of negative samples, identifying a site as dieback free in this way would be too costly.

In the wet tropics of northern Queensland, *P. cinnamomi* was shown to be uniformly distributed in the landscape, and it was estimated that a minimum of two to four soil samples were required per 1256 square metres to predict the absence of *P. cinnamomi* with 95 per cent confidence (Pryce et al., 2001, cited in O'Gara et al., 2005a).

The European and Mediterranean Plant Protection Organisation has produced a standard for application in that region that describes diagnostic protocols for *P. cinnamomi*, including examination of symptoms, isolation, identification of the pathogen through morphological characteristics, immunological and molecular methods, and reporting (OEPP/EPPO, 2004).

3.5 Risk assessment and priority setting

One of the first steps in analysis of the risk posed by *P. cinnamomi* is the identification of areas vulnerable to disease. Most states in Australia have identified broad zones where biodiversity is vulnerable to the threat of *P. cinnamomi* due to the coincidence of susceptible vegetation and environmental conditions that are conducive to the establishment and persistence of the pathogen (see section 2.2.3). The criteria used to identify zones of vulnerability vary from state to state. In Western Australia, the State Phytophthora dieback Management and Investment Framework (Project Dieback, 2014) identifies and ranks the state's top 100 priority protection areas. Such a mechanism can help channel available resources into the most efficient and successful threat abatement options.

A risk assessment process has been developed for assessing the risk of *P. cinnamomi* to threatened species, ecological communities and areas, and ranking them as the basis for setting management priorities. This is potentially suitable for national adoption (CPSM, 2005). Models have been developed for flora, fauna habitat, vegetation communities, and areas of land. The models identify the source of risk, the likelihood of occurrence and the magnitude of the consequences. The models are semi-quantitative (that is, qualitative criteria are assigned scores), based on current scientific knowledge. However, where significant knowledge or data gaps exist, expert opinion will be required. The semi-quantitative scoring system used in developing the models enables a ranking of assets according to the risk posed by *P. cinnamomi* and the perceived ability to manage the risks. The decision flowchart contained in the model terminates with an indicative determination of disease status of the site, with three possible options: infected, uninfected, and disease status unknown.

Barrett et al. (2008) drew on this risk assessment methodology in a species risk assessment model for the rare flora of the south coast of Western Australia.

Major *P. cinnamomi* containment work undertaken at the Bell Track site in Fitzgerald National Park used a Bayesian-based risk model to assess the risks associated with the project (Dunne et al., 2011).

Within the Wet Tropics of Queensland World Heritage Area, a preliminary risk assessment methodology has been developed that guides decisions concerning implementation of hygiene measures during operational works. Studies have identified high-risk, moderate-risk and low-risk zones within the world heritage area (Worboys & Gadek, 2004). Implementation of hygiene measures is recommended for works within high and moderate risk zones in order to prevent transfer of the pathogen from infested catchments.

Tasmania has undertaken a project which established a set of priority areas for management of *P. cinnamomi* for threatened species and ecological communities that are at risk from *P. cinnamomi* (Schahinger et al., 2003). This document rated vegetation community susceptibility due to frequency of susceptible species and environmental susceptibility. The largest disease-free areas or most manageable areas (considering factors such as disease proximity, landscape features and ease of access) were selected for priority management. A regional plan for the management of *P. cinnamomi* in the Tasmanian Wilderness World Heritage Area addresses biodiversity assets at risk and identifies large disease-free areas (Schahinger et al., 2003).

In New South Wales, Keith et al. (2011) assessed the *P. cinnamomi* threat to Royal National Park through modelling the probability of infection as a function of environmental variables (soil, landscape, topographic position, aspect and slope) and mapping plant communities in which susceptible species are most abundant. These data informed maps showing the risk of plant diversity loss to *P. cinnamomi*.

In South Australia, Velzeboer et al. (2005) developed a risk assessment process based on disease status and proximity to *P. cinnamomi* infestations to prioritise threatened plant species for research and management options. As new knowledge and data become available, reviews of and improvements to the risk assessment process will be possible. Between 2007 and 2010, a study of 37 species of South Australian native plants by Kueh et al. (2012) documented various degrees of susceptibility to Phytophthora dieback.

Glossary

Biome	A large community of flora and fauna occupying a major habitat defined by their climate and dominant vegetation.
Biotroph	Plant-pathogenic fungi that establish a long-term feeding relationship with the living cells of their hosts, rather than killing the host cells as part of the infection process.
Containment	Restricting Phytophthora to a defined region.
Digital multi-spectral imaging	Multi-spectral imaging captures image data within specific wavelength ranges that are suitable for picking up dying vegetation.
Endemic	Native (flora and fauna) to a particular area.
Epicormic growth	Growth from previously dormant buds on the trunk or limb of a tree. Very common in Eucalyptus species.
Floristics	The study of the distribution, numbers, types and relationships of plants in an area.
Fungistatic agent	Anti-fungal agents that inhibit the growth and reproduction of Phytophthora but do not kill it.
Hemispherical digital photographs	Photographs taken vertically upwards to measure the amount of leaf cover. The leaf cover, or leaf area index, is a measure of vegetation cover and a variable used to estimate biomass.
Hygiene protocol	A series of steps that people take to ensure that vehicles and equipment are clean of Phytophthora or any other pathogen before moving to an uninfected site.
Isohyet	A line drawn on a map showing areas of equal rainfall.
Microsatellite genotyping	Microsatellites are tracts of repetitive DNA that occur in an organism's genome. They have a higher mutation rate than other areas of DNA, so they can be used to measure genetic diversity.
Phytotoxic	Poisonous to plants.
Polymerase chain reaction (PCR)	A technique used in molecular biology to amplify a single copy or a few copies of a segment of DNA across several orders of magnitude, generating thousands to millions of copies of a particular DNA sequence.
Phloem	The vascular tissue in plants which conducts sugars and other metabolic products downwards from the leaves

RNA sequencing	RNA, ribonucleic acid, is present in all living cells. Its principal role is to act as a messenger carrying instructions from DNA for controlling the synthesis of proteins, although in some viruses RNA rather than DNA carries the genetic information. Sequencing of RNA reveals the presence and quantity of RNA in a biological sample.
Stereoscopic examination	A technique to create an illusion of depth (3D) from viewing two images offset by a small amount.
Sporulation	Formation of spores.
Xylem	The vascular tissue in plants which conducts water and dissolved nutrients upwards from the root and also helps to form the woody element in the stem.

References

Aberton MJ, Wilson BA, Hill J & Cahill DM (2001) Development of disease caused by *Phytophthora cinnamomi* in mature *Xanthorrhoea australis*. *Australian Journal of Botany* 49, 1-11.

Allan K & Gartenstein S (2010) *Keeping it clean—A Tasmanian field hygiene manual to prevent the spread of freshwater pests and pathogens*, NRM South, Hobart. Available at: dpipwe.tas.gov.au/invasive-species/weeds/weed- hygiene/keeping-it-clean-a-tasmanian-field-hygiene-manual. Accessed 8 May 2018.

Anderson P, Brundrett M, Grierson P & Robinson R (2010) Impact of severe forest dieback caused by *Phytophthora cinnamomi* on macrofungal diversity in the northern jarrah forest of Western Australia. *Forest Ecology and Management* 259, 1033-1040.

Annett K (2008) *Impacts of the plant pathogen P.cinnamomi (Cinnamon fungus) on fauna and ecosystem functions*. PhD thesis, Deakin University.

Australian Seed Bank Partnership (ASBP) (2017) Australian Seed Bank Partnership website. Available at: seedpartnership.org.au/associates/doe. Accessed 8 May 2018.

Australian Network for Plant Conservation (ANPC) (2009) *Plant germplasm conservation in Australia: Strategies and guidelines for developing, managing and utilising ex situ collections*, Offord CA & Meagher PF (Eds), p. 204.

Barrett S (2001) *Phytotoxic effects of phosphite in native plant communities in southern Western Australia*. PhD thesis, Murdoch University, Perth.

Barrett S & Rathbone D (2018) Long-term phosphite application maintains species assemblages, richness and structure of plant communities invaded by *Phytophthora cinnamomi*. *Austral Ecology*. Available at: doi.org/10.1111/aec.12574. Accessed 8 May 2018.

Barrett S, Shearer BL, Crane CE & Cochrane A (2008) An extinction-risk assessment tool for flora threatened by *Phytophthora cinnamomi*. *Australian Journal of Botany* 56, 6, 477-486.

Barrett S & Yates CJ (2015) Risks to a mountain summit ecosystem with endemic biota in southwestern Australia. *Austral Ecology* 40, 4, 423–432. Available at: doi.org/10.1111/aec.12199. Accessed 8 May 2018.

Bishop CL, Wardell-Johnson GW & Williams MR (2010) Community-level changes in Banksia woodland following plant pathogen invasion in the Southwest Australian Floristic Region. *Journal of Vegetation Science* 21, 5, 888-898. Available at: doi.org/10.1111/j.1654-1103.2010.01194.x. Accessed 8 May 2018.

Bunny FJ, Crombie DS & Williams MR (1995) Growth of lesions of *Phytophthora cinnamomi* in stems and roots of jarrah (*Eucalyptus marginata*) in relation to rainfall and stand density in Mediterranean forest of Western Australia. *Canadian Journal of Forest Research* 25, 6, 961-969.

Burgess TI, Scott JK, McDougall KL, Stukely MJC, Crane C, Dunstan WA, Brigg F, Andjic V, White D, Rudman T, Arentz F, Ota N & Hardy GEStJ (2017) Current and projected global distribution of *Phytophthora cinnamomi*, one of the world's worst plant pathogens. *Global Change Biology* 23, 1661-1674. Available at: onlinelibrary.wiley.com/doi/full/10.1111/gcb.13492. Accessed 8 May 2018.

Butcher TB, Stukely MJC & Chester GW (1984) Genetic variation in resistance of *Pinus radiata* to *Phytophthora cinnamomi*. *Forest Ecology and Management* 8, 197-220.

Cahill DM, Rookes JE, Wilson BA, Gibson L & McDougall KL (2008) *Phytophthora cinnamomi* and Australia's biodiversity: Impacts, predictions and progress towards control. Turner Review no. 17, *Australian Journal of Botany* 56, 4, 279-310.

Calver MC & Dell J (1998) Conservation status of mammals and birds in south-western Australian forests: Is there evidence of direct links between forestry practices and species decline and extinction? *Pacific Conservation Biology* 4, 296-314.

Centre for Phytophthora Science and Management (CPSM) (2005) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 4—Risk assessment models for species, ecological communities and areas*. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

Coates DJ, McArthur SL & Byrne M (2015) Significant genetic diversity loss following pathogen driven population extinction in the rare endemic *Banksia brownii* (Proteaceae). *Biological Conservation* 192, 353-360.

Cochrane A, Barrett S, Crane C, Dunne C, Hartley R & Freebury G (2011) Last chance to see: Banksias of the south coast of Western Australia. *Landscope* 26, 4, 17–22.

Cochrane A (2004) Western Australia's ex situ program for threatened species: A model integrated strategy for conservation, in Guerrant EO, Havens K & Maunder M (Eds), 2004, *Ex situ plant conservation: Supporting species survival in the wild*, 2004. Island Press, Washington DC, pp. 40-65.

Commonwealth Scientific and Industrial Research Organisation (CSIRO) & Australian Bureau of Meteorology (2015), *Climate Change in Australia Information for Australia's Natural Resource Management Regions: Technical Report*. Available at: www.climatechangeinaustralia.gov.au/en/publications-library/technical-report. Accessed 8 May 2018.

Conservation Commission of Western Australia (CCWA) (2013), *Forest Management Plan 2014–2023*. Available at: conservation.wa.gov.au/management-plans/forest-management-plan-2014-2023. Accessed 8 May 2018.

Crane CE & Shearer BL (2007) Hemispherical digital photographs offer advantages over conventional methods for quantifying pathogen-mediated changes caused by infestation of *Phytophthora cinnamomi*. *Australasian Plant Pathology* 36, 466-474. Available at: doi.org/10.1071/AP07052. Accessed 8 May 2018.

Crone M, McComb JA, O'Brien PA & Hardy GEStJ (2012) Annual and herbaceous perennial native Australian plant species are asymptomatic hosts of *Phytophthora cinnamomi* on black gravel sites in the *Eucalyptus marginata* (jarrah) forest of Western Australia. *Plant Pathology* 62(5), 1057-1062. Available at: onlinelibrary.wiley.com/doi/abs/10.1111/ppa.12016. Accessed 8 May 2018.

Crone M, McComb JA, O'Brien PA & Hardy GEStJ (2013a) Assessment of Australian native annual/herbaceous perennial plant species as asymptomatic or symptomatic hosts of *Phytophthora cinnamomi* under controlled conditions. *Forest Pathology* 43, 245–251.

Crone M, McComb JA, O'Brien PA & Hardy GEStJ (2013b) Survival of *Phytophthora cinnamomi* as oospores, stromata and thick walled chlamydospores in roots of symptomatic and asymptomatic annual and herbaceous perennial plant species. *Fungal Biology* 117, 2, 112-123.

Davison EM & Tay FCS (2003) *A sampling strategy for Phytophthora for 'difficult' sites*. Report no. 235, Minerals and Energy Research Institute of Western Australia, East Perth.

Davison EM & Tay FCS (2005) How many soil samples are needed to show that Phytophthora is absent from sites in the south-west of Western Australia? *Australasian Plant Pathology* 34, 293-297.

Department of Biodiversity, Conservation and Attractions (DBCA) (2017), *Phytophthora dieback management manual*, October 2017. Department of Biodiversity, Conservation and Attractions, Perth. Available on request.

Department of the Environment and Energy (DoEE) (2015) *Arrive clean, leave clean: Guidelines to help prevent the spread of invasive plant diseases and weeds threatening our native plants, animals and ecosystems*.
Commonwealth of Australia. Available at: www.environment.gov.au/biodiversity/invasive-species/publications/ arrive-clean-leave-clean. Accessed 8 May 2018.

Department of the Environment and Energy (DoEE) (2018) *Threat abatement plan for disease in natural ecosystems caused by* Phytophthora cinnamomi. Commonwealth of Australia, Canberra. Available at: environment.gov.au/approved-taps

Dieback Working Group (DWG) 2015, *Managing Phytophthora dieback in bushland—A guide for landholders and community conservation groups*, 7th edn. Available at: www.dwg.org.au. Accessed 8 May 2018.

Dixon K (2017) personal communication by email, 22 March 2017. Professor and Director, ARC Centre for Mine Site Restoration, Department of Environment and Agriculture, Curtin University.

Drenth A & Sendall B (2001) *Practical guide to detection and identification of Phytophthora*. Cooperative Research Centre for Tropical Plant Protection, Brisbane, Australia.

Dundas SJ, Fleming PA & Hardy GES (2013) Flower visitation by honey possums (*Tarsipes rostratus*) in a coastal banksia heathland infested with the plant pathogen *Phytophthora cinnamomi*. *Australian Mammalogy* 35, 166-174. Available at: doi.org/10.1071/AM12044. Accessed 8 May 2018.

Dundas SJ, Hardy GEStJ & Fleming PA (2016) The plant pathogen *Phytophthora cinnamomi* influences habitat use by the obligate nectarivore honey possum (*Tarsipes rostratus*). *Australian Journal of Zoology* 64, 122-131.

Dunne C, Crane CE, Lee M, Massenbauer T, Barrett S, Comer S, Freebury GJC, Utber DJ, Grant MJ & Shearer BL (2011) A review of the catchment approach techniques used to manage a *Phytophthora cinnamomi* infestation of native plant communities of the Fitzgerald River National Park on the south coast of Western Australia. *New Zealand Journal of Forestry Science* 41, S121-S132. Available at http://www.scionresearch.com/__data/assets/pdf_file/0004/35806/NZJFS-41S2011S121-S132_DUNNElr.pdf. Accessed 8 May 2018.

Dunstan WA, Howard K, Hardy, GES & Burgess TI (2016) An overview of Australia's *Phytophthora* species assemblage in natural ecosystems recovered from a survey in Victoria. *IMA Fungus* 7, 1, 47-58.

Dunstan WA, Rudman T, Shearer BL, Moore NA, Paap T, Calver MC, Dell B & Hardy GEStJ (2010) Containment and spot eradication of a highly destructive, invasive plant pathogen (*Phytophthora cinnamomi*) in natural ecosystems. *Biological Invasions* 12, 4, 913-925.

El-Tarabily KA, Sykes ML, Kurtböke ID, Hardy GEStJ, Barbosa AM & Dekker RFH (1996) Synergistic effects of a cellulase-producing *Micromonospora carbonacea* and an antibiotic-producing *Streptomyces violascens* on the suppression of *Phytophthora cinnamomi* root rot of *Banksia grandis*. *Canadian Journal of Botany* 74, 4, 618-624.

Environment Australia (2001) *Threat abatement plan for dieback caused by the root-rot fungus* Phytophthora cinnamomi. Environment Australia, Canberra.

European and Mediterranean Plant Protection Organisation (OEPP/EPPO) (2004) Diagnostic protocols for regulated pests. *Bulletin OEPP/EPPO* 34, 155-157. Available at: onlinelibrary.wiley.com/doi/10.1111/j.1365- 2338.2004.00720.x/full. Accessed 8 May 2018.

Friend JA (2004) *Dibbler recovery plan July 2003 – June 2013*. Western Australian Wildlife Management Program No 38, Department of Conservation and Land Management, Perth, p. 26. Available at: www.environment.gov.au/resource/dibbler-parantechinus-apicalis-recovery-plan.

Forest Protection Authority (FPA) (2012) Management of *Phytophthora cinnamomi* in production forest. Available at: www.fpa.tas.gov.au/ data/assets/pdf_file/0009/110223/Flora_technical_note_8_Phytophthora.pdf. Accessed 8 May 2018.

Gadek PA & Worboys S (2003) *Rainforest dieback mapping and assessment: Phytophthora species diversity and impacts of dieback on rainforest canopies*. Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland, p. 114.

Garkaklis, MJ, Calver, MC, Wilson, BA & Hardy, GEStJ (2004) Habitat alteration caused by an introduced plant disease, *Phytophthora cinnamomi*: A potential threat to the conservation of Australian forest fauna, in Lunney, D (Ed), *Conservation of Australia's forest fauna*, 2nd edition. Royal Zoological Society of New South Wales, Sydney, pp. 899-913.

Gates JA (2011) *Recovery plan for the Kangaroo Island Dunnart (Sminthopsis atkeni)*. Department of Environment and Natural Resources, South Australia, p. 23. Available at: www.environment.gov.au/resource/recovery-plan- kangaroo-island-dunnart-sminthopsis-aitkeni. Accessed 8 May 2018.

Global Invasive Species Database, www.issg.org/database/welcome/.

Grant M & Barrett S (2003) The distribution and impact of *Phytophthora cinnamomi* (Rands) in the south coast region of Western Australia, in McComb JA, Hardy GEStJ & Tommerup I (Eds), *Phytophthora in forests and natural ecosystems: Proceedings of the 2nd International Union of Forest Research Organizations (IUFRO) working party 7.02.09 meeting, Albany, Western Australia, 30 September – 5 October 2001*. Murdoch University Print, Murdoch, Western Australia.

Grose M, Abbs D, Bhend J, Chiew F, Church J, Ekström M, Kirono D, Lenton A, Lucas C, McInnes K, Moise A, Monselesan D, Mpelasoka F, Webb L & Whetton P (2015) *Southern Slopes cluster report, Climate change in Australia projections for Australia's natural resource management regions: Cluster reports*, Ekström M et al. (Eds), CISRO and Bureau of Meteorology, Australia. Available at: www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/ cms_page_media/172/SOUTHERN_SLOPES_CLUSTER_REPORT_1.pdf. Accessed 31 August 2017.

Groves E, Hardy GEStJ & McComb J (2009a) *Native garden plants resistant to dieback (*Phytophthora cinnamomi*)*. Murdoch University, Perth, Western Australia. Available at: www.cpsm-Phytophthora.org/downloads/CPSM_ resistanceBrochures.pdf. 8 May 2018.

Groves E, Hardy GEStJ & McComb J (2009b) *Western Australian natives resistant to* Phytophthora cinnamomi. Murdoch University, Perth, Western Australia. Available at: www.cpsm-Phytophthora.org/downloads/natives_ resistant.pdf. 8 May 2018.

Guest DI & Bompeix G (1990) The complex mode of action of phosphonates as antifungal agents. *Australasian Plant Pathology* 19, 113-115.

Guest DI & Grant B (1991) The complex action of phosphonates as antifungal agents, *Biological Reviews* 66, 159-187.

Hardham AR (1999) Cell biology of *Phytophthora cinnamomi*, in Gadek PA (Ed), *Patch deaths in tropical Queensland rainforests: Association and impact of* Phytophthora cinnamomi *and other soil borne organisms*. Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland, 27-31.

Hardham AR (2005) Phytophthora cinnamomi. *Molecular Plant Pathology* 6, 589–604.

Hardy GEStJ, Barrett S & Shearer BL (2001) The future of phosphite as a fungicide to control the soil borne plant pathogen *Phytophthora cinnamomi* in natural ecosystems. *Australasian Plant Pathology* 30, 133-139.

Hill TCJ, Tippett JT & Shearer BL (1995) Evaluation of three treatments for eradication of *Phytophthora cinnamomi* from deep, leached sands in southwest Australia. *Plant Disease* 79, 122-127.

Hill RJ, Wilson BA, Rookes JE & Cahill DM (2009) Use of high resolution digital multi-spectral imagery to assess the distribution of disease caused by *Phytophthora cinnamomi* on heathland at Anglesea, Victoria. *Australasian Plant Pathology* 38, 110-119.

Hope P, Abbs D, Bhend J, Chiew F, Church J, Ekström M, Kirono D, Lenton A, Lucas C, McInnes K, Moise A, Monselesan D, Mpelasoka F, Timbal B, Webb L & Whetton P (2015) *Southern and South-Western Flatlands cluster report, Climate change in Australia projections for Australia's natural resource management regions: Cluster reports*, Ekström, M et al. (Eds), CSIRO and Bureau of Meteorology, Australia. Available at: www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/172/SSWFLATLANDS_CLUSTER_REPORT.pdf. Accessed 31 August 2017.

Howard CG (2008) *A contemporary study of the genetic variation of* Phytophthora cinnamomi *recovered from natural ecosystems of New South Wales.* PhD thesis, University of Sydney, Sydney, New South Wales.

Islam MT, Rookes JE & Cahill DM (2017) Active defence by an Australian native host, *Lomandra longifolia*, provides resistance against *Phytophthora cinnamomi*. *Functional Plant Biology* 44, 4, 386-399. Available at: doi.org/10.1071/FP16266. Accessed 8 May 2018.

Keith DA, McDougall KL, Simpson CC & Walsh J (2011) Spatial analysis of risks posed by root-rot pathogen, *Phytophthora cinnamomi*: Implications for disease management. *Proceedings of the Linnean Society of New South Wales* 134, 147-179.

Keith D, McDougall K, Simpson C & Walsh J (2011) *Are there spatial patterns in threats posed by root rot disease,* Phytophthora cinnamomi*, in Royal National Park?*, Linnaean Society of NSW. Available at: linneansocietynsw. org.au/symposia/First%20National%20Park/9%20Keith%20Phytophthora.pdf. Accessed 8 May 2018.

Kliejunas JT & Ko WH (1976) Dispersal of *Phytophthora cinnamomi* on the island of Hawaii. *Phytopathology* 66, 4, 457-460.

Krull CR, Waipara NW, Choquenot D, Burns BR, Gormley AM, Stanley MC (2013) Absence of evidence is not evidence of absence: Feral pigs as vectors of soil-borne pathogens. *Austral Ecology* 38, 534-542.

Kueh KH, McKay SF, Facelli E, Facelli JM, Velzeboer RMA, Able AJ & Scott ES (2012) Response of selected South Australian native plant species to *Phytophthora cinnamomi*. *Plant Pathology* 61, 1165-1178.

Laidlaw WS and Wilson BA (2003) Floristic and structural characteristics of a coastal heathland exhibiting symptoms of *Phytophthora cinnamomi* infection in the eastern Otway Ranges, Victoria. *Australian Journal of Botany* 51, 283-93.

Laidlaw WS & Wilson BA (2006) Habitat utilisation by small mammals in a coastal heathland exhibiting symptoms of *Phytophthora cinnamomi* infestations. *Wildlife Research* 33, 639-649.

Lambers H, Ahmedi I, Berkowitz O, Dunne C, Finnegan PM, Hardy GEStJ, Jost R, Laliberté E, Pearse SJ & Teste FP (2013) Phosphorus nutrition of phosphorus-sensitive Australian native plants: Threats to plant communities in a global biodiversity hotspot. *Conservation Physiology* 1(1): doi.org/10.1093/conphys/cot010. Accessed 8 May 2018.

Li AY, Williams N, Fenwick SG, Hardy GEStJ, Adams PJ (2014) Potential for dissemination of *Phytophthora cinnamomi* by feral pigs via ingestion of infected plant material. *Biological Invasions* 16(4), 765-774 Available at: doi.org/10.1007/s10530-013-0535-7. Accessed 8 May 2018.

Lucas A (2003) *Water stress and disease development in Eucalyptus marginata (jarrah) infected with* Phytophthora cinnamomi. PhD thesis, Department of Biological Sciences, Murdoch University, Perth, Western Australia, p. 235. Available at: researchrepository.murdoch.edu.au/167/3/02Whole.pdf. Accessed 8 May 2018.

Marks GC & Smith IW (1991) The cinnamon fungus in Victorian forests; History, distribution, management and control. *Lands and Forests Bulletin* no 31, Department of Conservation and Environment, Melbourne, p. 33.

Massenbauer T 2017, personal communication by email, 6 September 2017. Dieback Spatial Information Officer, South Coast NRM, Western Australia.

Menkhorst P & Broome L 2006, *National recovery plan for the smoky mouse Pseudomys fumeus*. State of Victoria Department of Sustainability and Environment, Melbourne, p. 19. Available at: www.environment.gov.au/resource/smoky-mouse-pseudomys-fumeus. Accessed 8 May 2018.

Moir ML, Vesk PA, Brennan KEC, Hughes L, Keith DA, McCarthy MA, Coates DJ, & Barrett S (2011) A preliminary assessment of changes in plant-dwelling insects when threatened plants are translocated. *Journal of Insect Conservation* 16, 367-377.

Moir ML, Vesk PA, Brennan KEC, Poulin R, Hughes L, Keith DA, McCarthy MA, & Coates DJ (2012) Avoiding coextinction of dependent species during ex situ conservation and assisted migrations of threatened hosts. *Conservation Biology* 26, 199-207.

Moir ML, Coates DJ, Kennington J, Barrett S, & Taylor G (2016) Concordance in evolutionary history of threatened plant and insect populations warrant unified conservation management approaches. *Biological Conservation* 198, 135-144.

Moore NA (2005) *Role of fire on* Phytophthora cinnamomi *in the Stirling Range National Park, Western Australia*. Honours thesis, Murdoch University, Perth, Western Australia.

Moore N, Barrett S, Howard K, Craig MD, Bowen B, Shearer B & Hardy G (2014) Time since fire and average fire interval are the best predictors of *Phytophthora cinnamomi* activity in heathlands of south-western Australia. *Australian Journal of Botany* 62, 587-593.

Natural Values Atlas (NVA). State of Tasmania. Available at: www.naturalvaluesatlas.tas.gov.au.

Newby Z 2014, *Quantification of the risk of Phytophthora dieback in the Greater Blue Mountains World Heritage Area*. PhD thesis, University of Sydney Faculty of Agriculture and Environment.

Newell GR & Wilson BA (1993) The relationship between Cinnamon fungus (*Phytophthora cinnamomi*) and the abundance of *Antechinus stuartii* (Dasyurida: Marsupialia) in the Brisbane Ranges, Victoria. *Wildlife Research* 20, 251-259.

NRM South (2018) web resources, www.nrmsouth.org.au/biosecurity/.

O'Brien PA (2008) PCA primers for specific detection of *Phytophthora cinnamomi*. *Australasian Plant Pathology* 37, 69-71.

O'Brien PA & Hardy GEStJ (2014) *Phytophthora cinnamomi* in Western Australia. *Journal of the Royal Society of Western Australia* 97, 47-55.

O'Gara E, Howard K, Wilson B & Hardy GEStJ (2005a) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 1—A review of current management*. Report funded by the Commonwealth

Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia. Available at: www.environment.gov.au/biodiversity/invasive- species/publications/management-Phytophthora-cinnamomi-biodiversity-conservation. Accessed 8 May 2018.

O'Gara E, Howard K, Wilson B & Hardy GEStJ (2005b) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 2—National best practice guidelines*. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia. Available at: www.environment.gov.au/ biodiversity/invasive-species/publications/management-Phytophthora-cinnamomi-biodiversity-conservation. Accessed 8 May 2018.

Ouimette DG & Coffey MD (1990) Symplastic entry and phloem translocation of phosphonate. *Pesticide Biochemistry and Physiology* 38, 18-25.

Pegg K, Forsberg L, Cooke T & Coates L (2014) Phytophthora diseases—Problematic in the nursery and beyond. Available at: www.ngia.com.au/Attachment?Action=Download&Attachment_id=1833. Accessed 8 May 2018.

Pegg K & Manners A (2014) Soilborne root pathogens in production nurseries. Available at: www.ngia.com.au/Attachment?Action=Download&Attachment_id=1848. Accessed 8 May 2018.

Petit S & Dickson C (2005) Grass-tree (*Xanthorrhoea semiplana*, Liliaceae) facilitation of the endangered pink-lip spider orchid (*Caladenia* syn. *Arachnorchis behrii*, Orchidaceae) varies in South Australia. *Australian Journal of Botany* 53, 5, 455-464.

Pilbeam RA, Colquhoun IJ, Shearer B & Hardy GEStJ (2000) Phosphite concentration: Its effect on phytotoxicity symptoms and colonisation by *Phytophthora cinnamomi* in three understorey species of *Eucalyptus marginata* forest. *Australian Plant Pathology* 29, 86-95.

Podger FD, James SH & Mulcahy MJ (1996) *Review of dieback in Western Australia, Vol. 1, Report and recommendations*. Report to the Western Australian Minister for the Environment, Perth, Western Australia.

Phytophthora Technical Group (2006) *Phytophthora management guidelines*, 2nd edn. Government of South Australia.

Pryce J, Edwards W & Gadek P (2001) Detecting *Phytophthora cinnamomi* in rainforest soils: The effect of spatial scale on sampling strategy, in Gadek PA, Gillieson D, Edwards W, Landsberg J & Pryce J (Eds), *Rainforest dieback mapping and assessment in the Wet Tropics World Heritage Area*. James Cook University (Cairns campus) and Cooperative Research Centre for Tropical Rainforest Ecology and Management.

Project Dieback (2014) State Phytophthora dieback Management and Investment Framework. Available at: www.dieback.net.au/about/state-dieback-management-and-investment-framework.html. Accessed 8 May 2018.

Puno VI, Laurence MH, Guest DI & Liew ECY (2015) Detection of *Phytophthora multivora* in the Wollemi Pine site and pathogenicity to *Wollemia nobilis*. *Australasian Plant Pathology* 44, 2, 205-215. Available at: doi.org/10.1007/s13313-014-0344-1. Accessed 8 May 2018.

Rands R (1922) *Streepkanker van kaneel, veroorzaakt door* Phytophthora cinnamomi *n. sp*. (Stripe canker of cinnamon, caused by *Phytophthora cinnamomi* n. sp). Mededelingen van het Instituut voor Plantenziekten 54, Ruygrok, Batavia (Jakarta).

Rathbone D & Barrett S (2017) Vertebrate browsing impacts in a threatened montane plant community and implications for management. *Ecological Management and Restoration* 18, 2, 164-171.

Schahinger R, Rudman T & Wardlaw T (2003) *Conservation of Tasmanian plant species and communities threatened by* Phytophthora cinnamomi: *Strategic regional plan for Tasmania*. Technical Report 03/03, Nature Conservation Branch, Department of Primary Industries, Water and Environment, Hobart, p. 38. Available at: dpipwe.tas.gov.au/ Documents/Conservation-of-Tas-Plant-Species-Threatened-by-Phytophthora.pdf. Accessed 8 May 2018.

Scott J, Burgess T, Hardy G, Dunne C & Cahill D (2013) Climate modelling to determine the impacts of *Phytophthora cinnamomi* under future climate scenarios. Prepared for the Commonwealth Government Department of Sustainability, Environment, Water, Population and Communities by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia. Available at: www.environment.gov.au/biodiversity/invasive- species/publications/climate-modelling-determine-impacts-Phytophthora-cinnamomi. Accessed 1 September 2017.

Scott PM, Barber PA & Hardy GES (2015) Novel phosphite and nutrient application to control *Phytophthora cinnamomi* disease. *Australasian Plant Pathology* 44, 4, 431-436, Available at: doi.org/10.1007/s13313-015-0365-4. Accessed 8 May 2018.

Shearer BL, Crane CE, Barrett S & Cochrane A (2007) Assessment of threatened flora susceptibility to *Phytophthora cinnamomi* by analysis of disease progress curves in shadehouse and natural environments. *Australian Plant Pathology* 36, 609-20.

Shearer BL, Crane CE & Cochrane A (2004) Quantification of the susceptibility of the native flora of the South West Botanical Province, Western Australia, to Phytophthora cinnamomi. *Australian Journal of Botany* 52, 4, 435-443.

Shearer BL, Crane CE & Cochrane JA (2010) Variation in susceptibility to *Phytophthora cinnamomi* infection within the genus Lambertia. *Australian Journal of Botany* 58, 7, 575-585 Available at: doi.org/10.1071/BT10154. Accessed 8 May 2018.

Shearer BL, Crane CE & Cochrane JA (2013) Variation in susceptibility of Banksia (including Dryandra) to *Phytophthora cinnamomi*. *Australian Plant Pathology* 42, 351-361.

Shearer BL, Crane CE & Dunne CP (2012) Variation in vegetation cover between shrubland, woodland and forest biomes invaded by *Phytophthora cinnamomi*. *Australian Plant Pathology* 41, 413-424.

Shearer BL, Crane CE & Fairman RG (2004) Phosphite reduces disease extension of a *Phytophthora cinnamomi* front in Banksia woodland, even after fire. *Australasian Plant Pathology* 33, 249-254.

Shearer BL & Fairman RG (2007) A stem injection of phosphite protects Banksia species and *Eucalyptus marginata* from *Phytophthora cinnamomi* for at least four years. *Australasian Plant Pathology* 36, 78-86.

Shearer BL, Crane CE, Fairman RG, & Dunne CP (2009) Ecosystem dynamics altered by pathogen-mediated changes following invasion of Banksia woodland and *Eucalyptus marginata* forest biomes of south-western Australia by *Phytophthora cinnamomi*. *Australasian Plant Pathology* 38, 417-436. Available at: doi.org/10.1071/AP09018. Accessed 8 May 2018.

Strelein GJ, Sage LW & Blankendaal PA (2006) Rates of disease extension of *Phytophthora cinnamomi* in the jarrah forest bioregion of southwestern Australia, in Brasier C, Jung T & Oswald W (Eds), *Progress in research on Phytophthora diseases of forest trees: Proceedings of the 3rd International Union of Forest Research Organizations (IUFRO) working party S07.02.09 meeting*, Freising, Germany, 11-18 September 2004. Forest Research, Farnham, UK, pp. 49-52.

Stukely MJC & Crane CE (1994) Genetically based resistance of *Eucalyptus marginata* to *Phytophthora cinnamomi*. *Phytopathology* 84, 650-656.

Vallee L, Hogbin T, Monks L, Makinson B, Matthes M & Rossetto M (2004) *Guidelines for the translocation of threatened plants in Australia*, 2nd edn. Australian Network for Plant Conservation, Canberra, p. 80. Available at: www.anpc.asn.au/translocation.

Velzeboer R, Stubbs W, West A & Bond A (2005) *Threatened plant species at risk from Phytophthora in South Australia*, Department for Environment and Heritage, Adelaide, p. 35.

Weste G & Ashton DH (1994) Regeneration and survival of indigenous dry sclerophyll species in the Brisbane Ranges, Victoria, after a *Phytophthora cinnamomi* epidemic. *Australian Journal of Botany* 42, 239-253.

Weste G, Brown K, Kennedy J & Walshe T (2002) *Phytophthora cinnamomi* infestation—A 24 year study of vegetation change in forests and woodlands of the Grampians, Western Victoria. *Australian Journal of Botany* 50, 247-274.

Williams N, Hardy GEStJ & O'Brien PA (2009) Analysis of the distribution of *Phytophthora cinnamomi* in soil at a disease site in Western Australia using nested PCR. *Forest Pathology* 39, 2, 95-109.

Wills RT (1993) The ecological impact of *Phytophthora cinnamomi* in the Stirling Range National Park, Western Australia. *Australian Journal of Ecology* 18, 145-159.

Wilson BA, Aberton J and Cahill D (2000) The relationship between site factors and distribution of *Phytophthora cinnamomi* in the Eastern Otway Ranges, Victoria. *Australian Journal of Botany* 48, 247-60.

Wilson BA, Howard K, O'Gara E & Hardy GEStJ (2005) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 3—Risk assessment for threats to ecosystems, species and communities:*
A review. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

Wilson BA & Laidlaw WS (2001) Impact of *Phytophthora cinnamomi* on mammals in southern Australia, *Phytophthora in forests and natural ecosystems: Proceedings of the 2nd International Union of Forest Research Organizations (IUFRO) working party 7.02.09 meeting, Albany, Western Australia, 30 September* – 5 October 2001. Murdoch University Print, Murdoch, Western Australia.

Wilson BA, Lewis A & Aberton J (1997) *Conservation of national estate communities threatened by cinnamon fungus at Anglesea, Victoria*. Report for the Victorian Government Department of Natural Resources and Environment, Melbourne. p. 93.

Wilson BA, Newell G, Laidlaw WS & Friend G (1994) Impact of plant diseases on faunal communities. *Journal of the Royal Society of Western Australia*, 77, 139-143.

Worboys SJ & Gadek PA (2004) *Rainforest dieback: Risks associated with roads and walking track access in the Wet Tropics World Heritage Area*. School of Tropical Biology James Cook University Cairns Campus and Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns. Available at: www.wettropics.gov.au/ site/user-assets/docs/rainforestDiebackRoads%26WalkingTracks.pdf. Accessed 20 September 2017.

Yeatman GJ & Groom CJ (2012) *National recovery plan for the woylie (Bettongia penicillata ogilbyi)*. Wildlife Management Program No 51, Department of Environment and Conservation, Perth.

Zhuang-Griffin L (2015) *Assessment of the status of the endangered Swamp Antechinus (Antechinus minimus maritimus) in the eastern Otways: Factors influencing decline*. Honours thesis, School of Life and Environmental Sciences, Deakin University, Burwood, Australia.

Appendix A

Suggested reading

O'Gara E, Howard K, Wilson B & Hardy GEStJ (2005a) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 1—A review of current management*. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

O'Gara E, Howard K, Wilson B & Hardy GEStJ (2005b) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 2—National best practice guidelines*. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

Wilson B, Howard K, O'Gara E & Hardy GEStJ (2005) *Management of* Phytophthora cinnamomi *for biodiversity conservation in Australia: Part 3—Risk assessment for threats to ecosystems, species and communities: A review*. Report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

Note: the full reports can be downloaded from www.environment.gov.au/biodiversity/invasive/publications/p-cinnamomi.html

Further reading

Aberton M, Wilson BA & Cahill DM (1999) The use of phosphite as a control for *Phytophthora cinnamomi* in native vegetation at Anglesea, Victoria. *Australasian Plant Pathology* 28, 225-234.

Barker PCJ, Wardlaw TJ & Brown MJ (1996) Selection and design of Phytophthora management areas for the conservation of threatened flora in Tasmania. *Biological Conservation* 76, 187-193.

Barrett S, Shearer BL, Crane CE & Cochrane A (2008) An extinction-risk assessment tool for flora threatened by *Phytophthora cinnamomi*. *Australian Journal of Botany* 56, 477-486.

Brasier C (2003) Phytophthoras in European forests: Their rising significance. *Sudden Oak Death Online Symposium*, 21 April – 12 May 2003.

Brown BN (1998) Occurrence and impact of *Phytophthora cinnamomi* and other *Phytophthora* species in rainforests of the Wet Tropics World Heritage Area, and of the Mackay region, Queensland, in Gadek PA (Ed), *Patch deaths in tropical Queensland rainforests: Association and impact of* Phytophthora cinnamomi *and other soil borne pathogens*. Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland, pp. 41-76.

Burgess TI, White D, McDougall KM, Garnas J, Dunstan WA, Català S, Carnegie AJ, Worboys S, Cahill D, Vettraino AM, Stukely MJC, Liew ECY, Paap T, Bose T, Migliorini D, Williams B, Brigg F, Crane C, Rudman T & Hardy GEStJ (2017) Distribution and diversity of Phytophthora across Australia. *Pacific Conservation Biology* 23, 2, 150-162. Available at: doi.org/10.1071/PC16032.

Centre for Phytophthora Science and Management (CPSM) (2013) *Climate modelling to determine the impacts of* Phytophthora cinnamomi *under future climate scenarios*. Report funded by the Commonwealth Government Department of Sustainability, Environment, Water, Population and Communities by the Centre for Phytophthora Science and Management, Murdoch University, Western Australia.

Centre for Phytophthora Science and Management website, Murdoch University, Western Australia. Available at: www.cpsm.murdoch.edu.au.

Colquhoun I & Hardy GEStJ (2000) Managing the risks of Phytophthora root and collar rot during bauxite mining in the *Eucalyptus marginata* (Jarrah) forest of Western Australia. *Plant Disease* 84, 2, 116-127.

Dell B, Hardy G & Vear K (2005) History of *Phytophthora cinnamomi* management in Western Australia, in Calver MC, Bigler-Cole H, Bolton G, Dargavel J, Gaynor A, Horwitz P, Mills J & Wardell-Johnson G (Eds), *A forest consciousness: Proceedings of the 6th Australian Forest History Society Conference*, Millpress Science Publishers, Rotterdam, Netherlands.

Department for Environment and Heritage (2002) *Phytophthora threat management procedure: Standard operating procedures 2002*, Adelaide, South Australia.

Department for Environment and Heritage (2004) *Dieback in native vegetation in the Mount Lofty Ranges: A guide to causes and symptoms*, Adelaide, South Australia, p. 22.

Department of Biodiversity, Conservation and Attractions (2017) *Phytophthora dieback management manual, October 2017*. Department of Biodiversity, Conservation and Attractions, Perth.

Department of Conservation and Land Management (WA) (2003) Phytophthora cinnamomi *and disease caused by it*. Department of Conservation and Land Management, Government of Western Australia, Perth.
Available at: www.dpaw.wa.gov.au/images/documents/conservation-management/pests-diseases/disease-risk-areas/ Phytophthora_cinnamomi_and_disease_caused_by_it-_Vol._1_Management_Guidelines_.pdf.

Department of Sustainability and Environment (2008) Victoria's Public Land *Phytophthora cinnamomi* management strategy. Department of Sustainability and Environment, Melbourne. Available at: forestphytophthoras.org/ references/victoria%E2%80%99s-public-land-phytophthora-cinnamomi-management-strategy.

Dieback Working Group (DWG) (2000) *Managing Phytophthora dieback: Guidelines for local government*. Dieback Working Group, Western Australia, p. 95, Available at: www.dwg.org.au.

Dieback Working Group (DWG) (2004) *Environmental code of practice for the management of Phytophthora dieback in extractive industries*. Dieback Working Group, Western Australia, p. 46. Available at: www.dwg.org.au.

Dieback Working Group (DWG) (2015) *Managing Phytophthora dieback in bushland—A guide for landholders and community conservation groups*, 7th edn. Available at: www.dwg.org.au.

Dunne C, Crane CE, Lee M, Massenbauer T, Barrett S, Comer S, Freebury GJC, Utber DJ, Grant MJ & Shearer BL (2011) A review of the catchment approach techniques used to manage a *Phytophthora cinnamomi* infestation of native plant communities of the Fitzgerald River National Park on the south coast of Western Australia. *New Zealand Journal of Forestry Science* 41, S121-S132, Available at: www.scionresearch.com/__data/ assets/pdf_file/0004/35806/NZJFS-41S2011S121-S132_DUNNElr.pdf.

Dunstan WA, Rudman T, Shearer BL, Moore NA, Paap T, Calver MC, Dell B & Hardy GEStJ (2010) Containment and spot eradication of a highly destructive, invasive plant pathogen (*Phytophthora cinnamomi*) in natural ecosystems. *Biological Invasions* 12, 4, 913-925.

Forest Practices Authority (2012) *Flora technical note no 8: Management of* Phytophthora cinnamomi *in production forest*. Forest Practices Authority, Hobart, Tasmania, p. 16. Available at: www.fpa.tas.gov.au/_data/ assets/pdf_file/0009/110223/Flora_technical_note_8_Phytophthora.pdf.

Grant M & Barrett S (2003) The distribution and impact of *Phytophthora cinnamomi* (Rands) in the south coast region of Western Australia, in McComb JA, Hardy GEStJ & Tommerup I (Eds), *Phytophthora in forests and natural ecosystems: Proceedings of the 2nd International Union of Forest Research Organizations (IUFRO) working party 7.02.09 meeting, Albany, Western Australia, 30 September* – 5 October 2001. Murdoch University Print, Murdoch, Western Australia.

Hardham AR (1999) Cell biology of *Phytophthora cinnamomi*, in Gadek PA (Ed), *Patch deaths in tropical Queensland rainforests: Association and impact of* Phytophthora cinnamomi *and other soil borne organisms*. Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland, pp. 27-31.

Leave No Trace Australia website, Leave No Trace Australia, Swanbourne, Western Australia. www.LNT.org.au.

McDougall KL & Summerell BA (2003) The impact of *Phytophthora cinnamomi* on the flora and vegetation of New South Wales—A re-appraisal, in McComb JA, Hardy GEStJ & Tommerup I (Eds), *Phytophthora in forests and natural ecosystems: Proceedings of the 2nd International Union of Forest Research Organizations (IUFRO) working party 7.02.09 meeting, Albany, Western Australia, 30 September* – 5 October 2001. Murdoch University Print, Murdoch, Western Australia.

Nursery Industry Accreditation Scheme Australia (2016) *Best management practice guidelines* 6th edn. Nursery and Garden Industry Australia, Sydney.

Pilbeam RA, Colquhoun IJ, Shearer B & Hardy GEStJ (2000) Phosphite concentration: Its effect on phytotoxicity symptoms and colonisation by *Phytophthora cinnamomi* in three understorey species of *Eucalyptus marginata* forest. *Australasian Plant Pathology* 29, 86-95.

Podger FD (1972) *Phytophthora cinnamomi*, a cause of lethal disease in indigenous plant communities in Western Australia. *Phytopathology* 62, 972-981.

Possingham H, Ryan S, Baxter J & Morton S (2002) Setting biodiversity priorities: A paper prepared as part of the activities of the working group producing the report Sustaining our Natural Systems and Biodiversity for the Prime Minister's Science, Engineering and Innovation Council in 2002. Prime Minister's Science, Engineering and Innovation Council, Canberra.

Reiter N, Weste G & Guest D (2004) The risk of extinction resulting from disease caused by *Phytophthora cinnamomi* to endangered, vulnerable or rare species endemic to the Grampians, western Victoria. *Australian Journal of Botany* 52, 425-433.

Rudman T (2004) *Interim* Phytophthora cinnamomi *management guidelines*. Department of Primary Industries, Water and Environment, Government of Tasmania, Hobart. Available at: dpipwe.tas.gov.au/conservation/ publications-forms-and-permits/publications/interim-Phytophthora-cinnamomi-management-guidelines.

Shearer BL & Dillon M (1995) Susceptibility of plant species in *Eucalyptus marginata* forest to infection by *Phytophthora cinnamomi*. *Australian Journal of Botany* 43, 113-134.

Shearer BL & Dillon M (1996) Susceptibility of plant species in Banksia woodlands on the Swan Coastal Plain, Western Australia, to infection by *Phytophthora cinnamomi*. *Australian Journal of Botany* 44, 433-445.

Shearer BL & Tippett JT (1989) Jarrah dieback: The dynamics and management of *Phytophthora cinnamomi* in the Jarrah (*Eucalyptus marginata*) forest of south-western Australia. *Research Bulletin no. 3*, Department of Conservation and Land Management, Government of Western Australia, Como, Western Australia, p. 76.

Smith I (2002) *Guidelines for reducing the spread of* Phytophthora cinnamomi *during earth moving operations*. Department of Natural Resources and Environment, Government of Victoria, Melbourne.

Weste G (1974) *Phytophthora cinnamomi*—the cause of severe disease in certain native communities in Victoria. *Australian Journal of Botany* 22, 1-8.

Weste G (1997) The changing status of disease caused by *Phytophthora cinnamomi* in Victorian open forests, woodlands and heathlands. *Australasian Plant Pathology* 26, 1-9.

Williams N, O'Gara E, Hardy GEStJ & O'Brien PA (2009) Development of molecular diagnostic tools for the detection of *Phytophthora cinnamomi* from cryptic soil samples in southern Australia, in *Phytophthoras in forests and natural ecosystems: Proceedings of the 4th meeting of the International Union of Forest Research Organizations (IUFRO) working party S07.02.09*, 26–31 August 2007, Monterey, California, p. 348.
Available at: researchrepository.murdoch.edu.au/3531/1/molecular_diagnostic_tools.pdf.

Wills RT & Keighery GJ (1994) Ecological impact of plant disease on plant communities. *Journal of the Royal Society of Western Australia* 77, 127-131.

World Wildlife Fund & Dieback Consultative Council (2004) *Arresting Phytophthora dieback: The biological bulldozer*. Report by the World Wildlife Fund (Gland, Switzerland) and the WA Dieback Consultative Council, Western Australia, p. 22.

Information on other Phytophthora species

Aghighi S, Hardy GEStJ, Scott JK & Burgess TI (2012) *Phytophthora bilorbang* sp. nov., a new species associated with the decline of *Rubus anglocandicans* (European blackberry) in Western Australia. *European Journal of Plant Pathology* 133, 4, 841-855.

Burgess TI, Webster JL, Ciampini JA, White D, Hardy GEStJ & Stukely MJC (2009) Re-evaluation of *Phytophthora* species isolated during 30 years of vegetation health surveys in Western Australia using molecular techniques. *Plant Disease* 93, 3, 215-223.

Burgess TI, White D, McDougall KM, Garnas J, Dunstan WA, Català S, Carnegie AJ, Worboys S, Cahill D, Vettraino AM, Stukely MJC, Liew ECY, Paap T, Bose T, Migliorini D, Williams B, Brigg F, Crane C, Rudman T & Hardy GEStJ (2017) Distribution and Diversity of Phytophthora across Australia. *Pacific Conservation Biology* 23, 2, 150-162. Available at: doi.org/10.1071/PC16032. Accessed 8 May 2018.

Crous PW, Summerell BA, Shivas RG, Burgess TI, Decock CA, Dreyer LL, Granke LL, Guest DI, Hardy GEStJ, Hausbeck MK, Hüberli D, Jung T, Koukol O, Lennox CL, Liew ECY, Lombard L, McTaggart AR, Pryke JS, Roets F, Saude C, Shuttleworth LA, Stukely MJC, Vánky K, Webster BJ, Windstam ST & Groenewald JZ (2012) Fungal planet description sheets 107–127. *Persoonia: Molecular Phylogeny and Evolution of Fungi* 28, 138-182.

Jung T, Stukely MJC, Hardy GEStJ, White D, Paap T, Dunstan WA & Burgess TI (2011) Multiple new *Phytophthora* species from ITS clade 6 associated with natural ecosystems in Australia: Evolutionary and ecological implications. *Persoonia: Molecular Phylogeny and Evolution of Fungi* 26, 13-39.

Nagel JH, Gryzenhout M, Slippers B, Wingfield MJ, Hardy GEStJ, Stukely MJC & Burgess TI (2013) Characterization of *Phytophthora* hybrids from ITS clade 6 associated with riparian ecosystems in South Africa and Australia. *Fungal Biology* 117, 5, 329-347.

Rea AJ, Jung T, Burgess TI, Stukely MJC & Hardy GEStJ (2010) *Phytophthora elongata* sp. nov., a novel pathogen from the *Eucalyptus marginata* forest of Western Australia. *Australasian Plant Pathology* 39, 6, 477-491.

Rea AJ, Burgess TI, Hardy GEStJ, Stukely MJC & Jung T (2011) Two novel and potentially endemic species of Phytophthora associated with episodic dieback of Kwongan vegetation in the south-west of Western Australia. *Plant Pathology* 60, 6, 1055-1068.

Scott PM, Burgess TI, Barber PA, Shearer BL, Stukely MJC, Hardy GEStJ & Jung T (2009) *Phytophthora multivora* sp. nov., a new species recovered from declining Eucalyptus, Banksia, Agonis and other plant species in Western Australia. *Persoonia: Molecular Phylogeny and Evolution of Fungi* 22, 1-13.

Appendix B

Phytophthora dieback resources

Table 1: Phytophthora dieback resources, by state

State	Resource
Western Australia	Dieback Working Group resources (many of these documents have national applicability)
	Department of Biodiversity, Conservation and Attractions, 2017, Phytophthora dieback management manual, October 2017, Department of Biodiversity, Conservation and Attractions, Perth. Available on request
	Best practice guidelines: Management of Phytophthora dieback in extractive industries
	Managing Phytophthora dieback: Guidelines for local government
	Managing Phytophthora dieback in bushland: A guide for landholders and community conservation groups
	DIDMS GRID (Dieback Information and Delivery Management System Geographic Reporting Information Database) and Dieback Public Map
	Flyers relating to phosphite use: • Phosphite injection using Chemjet syringes • Dieback treatment spraying
	Native garden plants resistant to dieback (*Phytophthora cinnamomi*)
	Western Australian natives resistant to *Phytophthora cinnamomi*, compiled by Groves E, Hollick P, Hardy G & McComb J, Murdoch University
	Western Australian natives susceptible to *Phytophthora cinnamomi*, compiled by Groves E, Hollick P, Hardy G & McComb J, Murdoch University
	Project Dieback resources
	State Phytophthora dieback Management and Investment Framework
	Forest management plan 2014–2023 Conservation Commission of Western Australia

State	Resource
Tasmania	Keeping it clean—a Tasmanian field hygiene manual to prevent the spread of freshwater pests and pathogens. This manual provides information on how to prevent the spread of freshwater pests and pathogens in Tasmanian waterways, wetlands, swamps and boggy areas. It is intended primarily for people who work in these areas, but also will help recreational visitors to understand the risks and act accordingly.
	NRM South website—biosecurity resources
	How to identify *Phytophthora cinnamomi* infection in Tasmania, Biosecurity Tasmania
	Conservation of Tasmanian plant species & communities threatened by *Phytophthora cinnamomi*: Strategic regional plan for Tasmania, Technical Report 03/03, Schahinger R, Rudman T & Wardlaw TJ, 2003, Nature Conservation Branch, Department of Primary Industries, Water and Environment, Hobart
	Quarry Code of Practice 3rd Edition, Environment Protection Authority (2017)
	Natural Values Atlas
	Weed and Disease Planning and Hygiene Guidelines
	Interim *Phytophthora cinnamomi* management guidelines, Nature Conservation Report 05/7, Rudman T, 2005, Biodiversity Conservation Branch, Department of Primary Industries, Water and Environment, Hobart
Queensland	Patch deaths in tropical Queensland rainforests: Association and impact of *Phytophthora cinnamomi* and other soil borne organisms, Gadek PA (Ed), 1999, Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland
	Rainforest dieback: Risks associated with roads and walking track access in the Wet Tropics World Heritage Area, Worboys SJ & Gadek PA, 2004, School of Tropical Biology, James Cook University Cairns Campus and Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland
	Rainforest dieback mapping and assessment, 2004 monitoring report including an assessment of dieback in high altitude rainforests, Worboys SJ, 2006, Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland
	Guide to monitoring Phytophthora-related dieback in the Wet Tropics of North Queensland, Worboys SJ, 2006, Cooperative Research Centre for Tropical Rainforest Ecology and Management. Rainforest CRC, Cairns, Queensland
Victoria	Victoria's public land *Phytophthora cinnamomi* management strategy, State of Victoria, Department of Sustainability and Environment, 2008

State	Resource
New South Wales	Infection of native plants by *Phytophthora cinnamomi*—key threatening process listing, NSW Scientific Committee—final determination
	Statement of Intent 1: Infection of native plants by *Phytophthora cinnamomi*, Department of Environment and Climate Change, NSW
	Best practice management guidelines for *Phytophthora cinnamomi* within the Sydney Metropolitan Catchment Management Authority Area (2008)
	Royal Botanic Gardens Sydney website—Phytophthora dieback resources
South Australia	Phytophthora (dieback) control operational instruction 21.3, Transport SA—Statewide Operational Coordination Group 2000
	Phytophthora management guidelines 2006, Phytophthora Technical Group, Government of South Australia
	Bushwalking guidelines to prevent *Phytophthora cinnamomi* 2017, Natural Resources Kangaroo Island
General	Arrive clean, leave clean, Australian Government Skills and ethics series, Leave No Trace Australia

Appendix C

Data contributions for Figure 2, *Phytophthora cinnamomi* records

Map produced by Environmental Resources Information Network, Department of the Environment and

Energy CSIRO Atlas of Living Australia (2018)

Dryad Digital Repository (2018)

Burgess T, Scott JK, McDougall KL, Stukely MJC, Crane C, Dunstan WA, Brigg F, Andjic V, White D, Rudman T, Arentz F, Ota N, Hardy GESJ (2016) Current and projected global distribution of *Phytophthora cinnamomi*, one of the world's worst plant pathogens. Global Change Biology 23(4), 1661–1674. doi.org/10.1111/gcb.13492

Burgess T, Scott JK, McDougall KL, Stukely MJC, Crane C, Dunstan WA, Brigg F, Andjic V, White D, Rudman T, Arentz F, Ota N, Hardy GESJ (2016) Data from: Current and projected global distribution of *Phytophthora cinnamomi*, one of the world's worst plant pathogens. Dryad Digital Repository. doi.org/10.5061/dryad.v1jr7

Natural Values Atlas Database, Department of Primary Industries, Parks, Water and Environment, Tasmania. naturalvaluesatlas.tas.gov.au © State of Tasmania. Accessed 18 June 2018

NatureMap Database, Department of Biodiversity, Conservation and Attractions, Western Australia (2007–) NatureMap: Mapping Western Australia's Biodiversity. naturemap.dpaw.wa.gov.au. Accessed 18 June 2018

NatureMaps Database, Department for Environment and Water, South Australia. data.environment.sa.gov.au/NatureMaps. Accessed 18 June 2018

Australian Government Department of the Environment and Energy, Australian Natural Heritage Assessment Tool. Accessed 18 June 2018

Department of Environment and Science, Queensland

Department of Environment, Land, Water and Planning,

Victoria

Environment, Planning and Sustainable Development Directorate, Australian Capital

Territory Office of Environment and Heritage, New South Wales

Commonwealth of Australia, Bureau of Meteorology (2003) Mean annual rainfall data

Contextual data sources: Geoscience Australia and PSMA Australia environment.gov.au

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