

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

March 2017

DRAFT FOR COMMENT

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1. Introduction

Australia's native plants and ecological communities are threatened by the soil-borne plant pathogen, *Phytophthora cinnamomi*, for which it is estimated there are over 2000 potential host species (Shearer *et al.*, 2004).

Phytophthora cinnamomi is known to be present in all states and territories of Australia except the Northern Territory. It causes disease in an extremely diverse range of native, ornamental, forestry and horticultural plants. Described as a 'biological bulldozer', *P. cinnamomi* is destroying bushlands, heathlands, woodlands and forests, which are the habitat for rare and endangered flora and fauna species. 'Dieback caused by the root-rot fungus *Phytophthora cinnamomi*' is listed as a key threatening process under the *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* (TAP) (Department of the Environment and Energy, 2017). The TAP outlines the actions proposed to abate the threat and addresses statutory requirements. This document provides supporting information on matters such as the biology of the pathogen, its population dynamics, spread, diagnosis and impacts on biodiversity and management measures.

2. Background

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

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.

P. cinnamomi is thought to have entered Australia with early settlers from Europe. Since the mid 1960s this exotic pathogen has been recognised as a cause of serious disease in native ecosystems of Australia. In the 1960s, *P. cinnamomi* was recognised as the cause of 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 are known to cause disease in Australian flora species, *P. cinnamomi* has had the greatest effect and poses the greatest threat. At least 32 species of *Phytophthora* occur in various parts of Australia. 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 species can reproduce sexually; however, for this to occur, two mating strains (A1 and A2) of the pathogen need to be present. The major evidence for the pathogen being non-endemic to Australia is:

1. The A2 strain of *P. cinnamomi* predominates 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 species of plant which suggests that the plants did not evolve with the pathogen.

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

P. cinnamomi can parasitise a wide range of life stages across the taxonomic spectrum of Australian flora. 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 ecological community will usually be the following:

- extinction of populations of some flora species
- a modification of the structure and composition of ecological communities
- a massive reduction in primary productivity
- a reduction in the genetic diversity of a plant species
- habitat loss and degradation for dependent flora and fauna.

After the pathogen's effects on an ecological community have taken their course, the smaller number of resistant species that remain, with time, 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.

A threat of an epidemic exists where dominant species of particular plant communities are

inherently susceptible to disease caused by *P. cinnamomi* 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. If an interaction that is sufficiently destructive to be considered a threatening process is to develop, both these conditions need to be present.

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 visual 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 vegetation communities and several plant species are at risk of extinction (see tables at Appendix A and B in the TAP). In vegetation communities where most dominant plants are resistant to *P. cinnamomi*, it is 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 sometimes called a water mould. Its taxonomic nomenclature is: 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. Two types of spores are produced asexually by the mycelium: zoospores, that are produced within structures called sporangia and chlamydospores. A third type of spore, termed an oospore, is produced through sexual recombination of A1 and A2 mating strains of the pathogen.

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

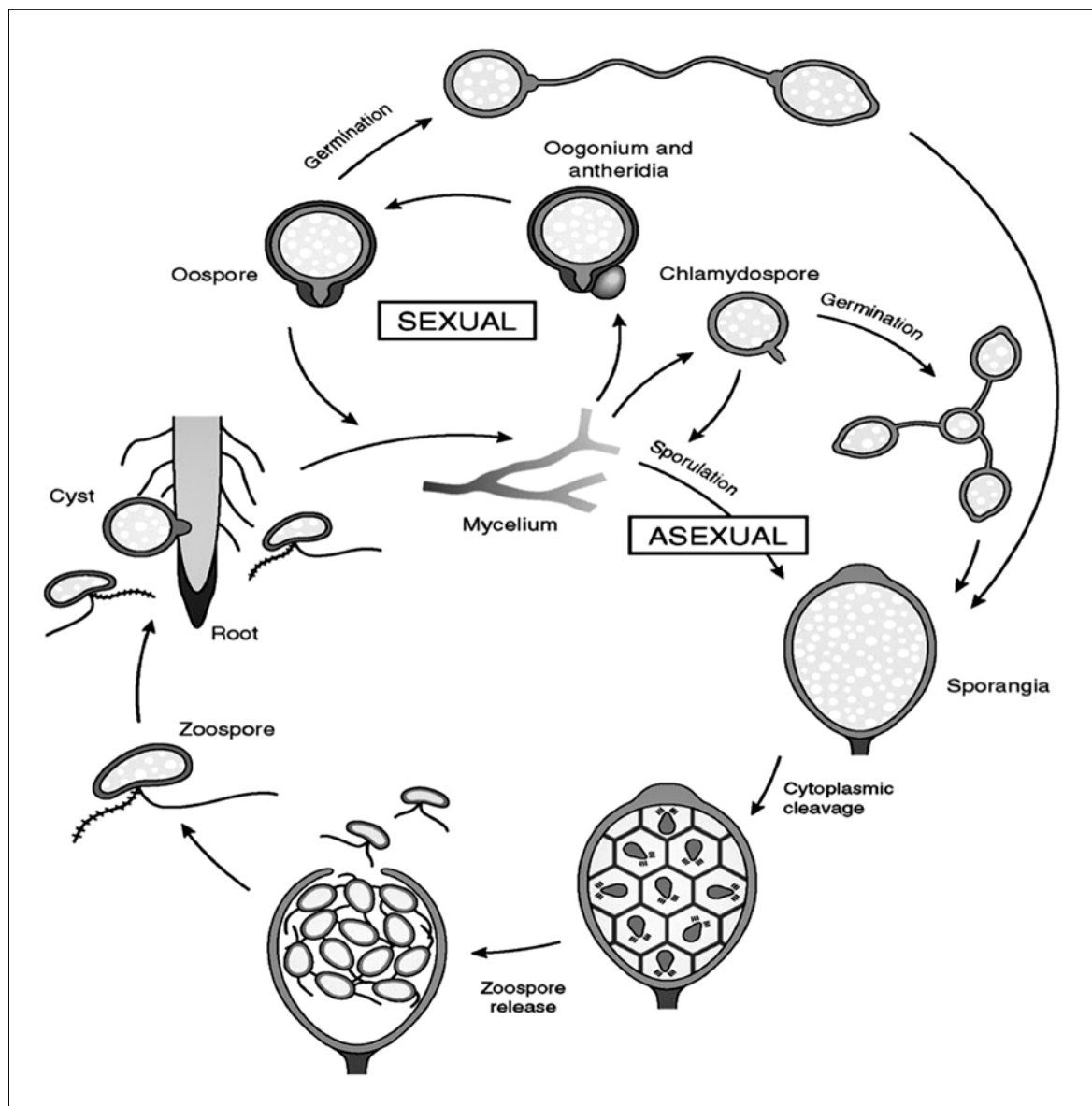
Up to 30 zoospores, each less than 10 microns in diameter, are produced within each sporangium. Zoospores are short-lived (2 to 3 days) and have two flagella which enable them to swim for short distances through water (25 to 30 millimetres, with soil porosity a factor in how far they will travel). At 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 shows the generalised life cycle of *P. cinnamomi*.

Figure 1 Generalised life cycle of *Phytophthora cinnamomi*

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



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 mycelium and grows between, and into, the plant cells. The pathogen may exit the infected root at some point, starting new infections.

The plant becomes visibly diseased when infection results in the impairment of the plant's physiological and biochemical functions. Uptake of water is one of the functions affected, and this is why symptoms of *P. cinnamomi* infection have similarities, at least initially, with those of water-stress.

As the A2 mating strain predominates in the Australian environment, it is unlikely that sexual recombination, and thus oospore production, occurs to any large degree in the natural environment.

2.2.2 Pathogen survival

There are still significant gaps in our knowledge of the exact mechanisms of long-term pathogen survival. Of the asexual spores, chlamydospores are thought to be the most resistant to

degradation and have, therefore, been implicated in the ability of *P. cinnamomi* to survive for long periods of time under unfavourable conditions. They potentially provide a source for re-infection of seedlings or long distance spread via soil movement.

Crone et al. (2013) claim that their recent study has shown, for the first time, the importance of selfed oospores—thick walled chlamydospores and stromata produced by *P. cinnamomi* in asymptomatic annual and herbaceous perennial species—for the long term survival of *P. cinnamomi*. They also claim it has increased our understanding of a biotrophic and/or endophytic lifestyle of *P. cinnamomi* in these plant species not previously recognised as hosts of the pathogen.

2.2.3 Geographic and climatic occurrence

The magnitude of the impact of *P. cinnamomi* in a native vegetation community is determined by a combination of factors including temperature, rainfall and soil types. The area of native vegetation affected by *P. cinnamomi* 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 disease caused by *P. cinnamomi*, there are many other factors that influence disease expression (i.e. conducive temperature, geology and soil conditions co-occurring with susceptible plant hosts, including pH, fertility, moisture and texture).

The areas of Australia vulnerable to disease caused by *P. cinnamomi* can be separated into five broad climatic zones:

- north Queensland in elevations above 750 metres with notophyll dominant vegetation and acid-igneous geology
- 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 Victoria and New South Wales border
- winter-dominant rainfall areas, in maritime climates of coastal and sub-montane Tasmania.

Recent work by Newby (2013) on vulnerable areas in the Greater Blue Mountains World Heritage Area has considered the climate and/or landscape suitability for *P. cinnamomi* via species distribution models. It was found that *P. cinnamomi* was most likely to be found where rainfall was 1300 millimetres per annum and would not be found below 550 millimetres per annum. It was also most likely to occur where minimum temperatures were between 11 to 13°C and not found where the minimum temperature did not drop below 18°C. *P. cinnamomi* was best suited to soils with ~6-8 per cent clay, but past ~37 per cent, it was unlikely to occur. Many of the most conducive areas were, but not limited to, high altitudes in the range of 900 to 1000 metres.

Although rainfall is clearly sufficient for the establishment of *P. cinnamomi* in the wet/dry, tropical and sub-tropical 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 is known to occur in coastal Queensland. Although 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*, is also considered a problem that will need to be addressed.

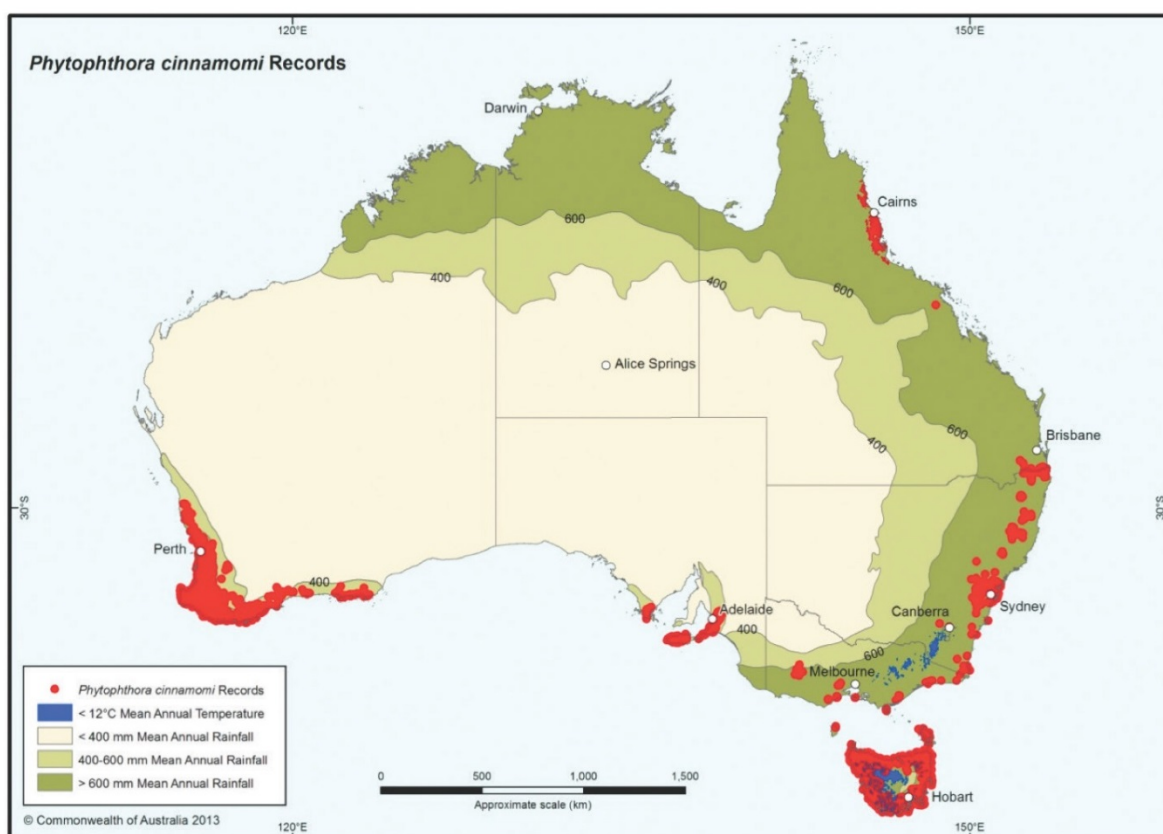
Additionally, *P. cinnamomi* is a serious concern in the Wet Tropics World Heritage region of far northern Queensland, where the syndrome is complex, differs considerably from that in the temperate south of the continent and appears to be related to prior significant disturbance of sites (Gadek and Worboys, 2003, cited in O'Gara et al., 2005a).

Speculation still exists over the role of *P. cinnamomi* 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.

P. cinnamomi isolations, records of impact and the broad climatic envelope of *P. cinnamomi* susceptibility in Australia are depicted in Figure 2.

Figure 2 *P. cinnamomi* isolations, records of impact and broad climatic envelope of *P. cinnamomi* susceptibility in Australia.

Based on O'Gara et al. (2005b) and occurrence data supplied to DSEWPaC between 2010 and 2012 (contributors are listed at Appendix A). This figure does not represent the precise distribution of the pathogen in Australia and is for general information only. It is not intended to be used for management purposes.



Areas of susceptibility and distribution

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).

Western Australia

In Western Australia the vulnerable zone was defined by the Department of Conservation and Land Management (2003) as:

- the parts of the South West Land Division and areas adjoining it to the north-west and south-east that receive an average annual rainfall greater than 400 millimetres
- those areas receiving rainfall above 400 millimetres that do not have a calcareous substrate and in which susceptible native plants occur in conjunction with the environmental factors required for *P. cinnamomi* to establish and persist.

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 communities of plants occur, the areas in Victoria that are considered vulnerable to the threat of *P. cinnamomi* are:

- all elevations in those 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 the foot hills of Wilsons Promontory
- south of the border between Victoria and New South Wales.

South Australia

In South Australia, any site with susceptible vegetation growing on neutral to acid soils and an average annual rainfall 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 and National Parks, Forest Reserves and many roadside reserves in the Mount Lofty Ranges, 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, i.e. 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 is

known to occur 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 is rarely limiting for the establishment of *P. cinnamomi*. As with 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 and Gadek, 2004, cited in O’Gara et al., 2005a).

Although dieback related to *P. cinnamomi* 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 *P. cinnamomi* being associated with disease in undisturbed native vegetation in the Northern Territory. It is generally accepted that the environmental conditions are not conducive to the establishment and persistence of *P. cinnamomi* in susceptible native plant communities.

Cahill et al. (2008) provides a comprehensive review of the regional impact of *P. cinnamomi*.

2.2.4 Potential impacts of climate change

Climate change-induced fluctuations in average rainfall may change the future distribution of *P. cinnamomi* and the manifestation of the disease it causes. For example, by 2030 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 runoff and pathogen dispersal (Cahill et al., 2008). Furthermore, stress in native plant communities resulting from altered climatic conditions could interact with the disease caused by *P. cinnamomi*.

A study (CPSM, 2013) used existing datasets on *P. cinnamomi* distribution together with strategic soil surveys from regions outside the pathogen’s known distribution range. It used CLIMEX modeling to determine its likely distribution in 2070 based on the CSIRO-Mk3.0 global climate model. The modeling demonstrates that in the future, areas with previously unfavourable conditions, particularly at altitudes above 700 m, may lead to 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. This is the most comprehensive study of *P. cinnamomi* distribution undertaken to date. The information will be useful to managers and policy makers involved in ensuring the spread and impact of *P. cinnamomi* is contained in the future.

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 reducing winter rainfall could be offset by increasing soil temperatures becoming more conducive to pathogen activity. Lucas (2003) found in glasshouse experiments that simulating a drought over summer increases the resistance of *E. marginata* (jarrah) to *P. cinnamomi*.

Physiological changes in host plants and in the pathogen could also be factors involved 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).

For a midrange emission scenario, CSIRO and Bureau of Meteorology (2007; 2012) predict a best estimate of annual warming over Australia by 2030 of around 1°C. There are likely to be regionally different responses across Australia. For most locations the mean warming is predicted to be 0.7 to 0.9°C in coastal areas and 1 to 1.2°C inland. In winter, warming is projected to be a little smaller than in the other seasons, as low as 0.5°C in the far south. Warming is typically predicted to be smaller near the coasts than further inland. Annually, predicted results have a similar predicted pattern to the seasons, with the warming being largest in the interior and the north-west.

For the south-west of Western Australia, where many threatened *P. cinnamomi* susceptible species occur, there is a high level of consistency amongst climate prediction models for 2050. All suggest a total precipitation decline in south-western Australia from the coast (between three per cent and 22 per cent in Cape Naturaliste and King River) to the inland wheat belt (between zero per cent and 36 per cent in Corrigin) (CSIRO and Bureau of Meteorology, 2007; 2012). For both temperature and precipitation, projected change can vary significantly at fine spatial scales, particularly in coastal and mountainous areas.

Under these predicted climate scenarios, the frequency of both drought and fire are likely to increase, 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 grass tree woodland) will provide an indication of the impact of the pathogen on priority native species and communities in a changing climate.

2.2.5 Transmission and spread

P. cinnamomi can be spread either actively or passively. Active or autonomous dispersal occurs as a result of actions on the part of the pathogen—predominantly by zoospores and mycelial growth. Passive dispersal of the pathogen is dependent upon propagules of the pathogen being passively carried or vectored by an independent party or object.

Active spread by zoospores is favoured by coarse-textured soils with large pores, and water-filled root channels through which zoospores are able to swim for around 25 to 30 millimetres. Mycelia can grow through roots and spread to adjacent healthy plants where root-to-root contact occurs. Root-to-root movement of the pathogen is thought to be one of the major ways in which the pathogen spreads up and across slopes from a disease centre.

P. cinnamomi can be carried passively in overland and subsurface water flow. Animals may also act as vectors of infested soil and have been implicated in spreading *P. cinnamomi*, 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.

Among the numerous *P. cinnamomi* vectors, human-induced transport of soil is the most important. 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 southern 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.

2.2.6 Rates of spread

The time-scale 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 down slope in incised water courses or gullies. Surveys in Western Australia have shown the *P. cinnamomi* upslope disease extension on the Darling Plateau (East) was 0.37 metres/year, compared to 2.15 metres/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 *E. marginata* (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).

2.3 The disease

2.3.1 Effects on susceptible plant species

Disease symptoms 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 discoloration may extend up into the wood of the lower stem. Severely affected plants may wilt permanently and their leaves 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.

A number of flora species which are nationally listed as being threatened and which may be susceptible to *P. cinnamomi* are listed in Appendix A of the TAP.

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* (grass tree) 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 *Xanthorrhoea* species such as *X. australis*, *X. quadrangulata* and *X. semiplana* often decline rapidly and the plant may collapse (R Velzeboer 2012, pers. comm.).

The families from which the pathogen is most frequently isolated are Myrtaceae, Proteaceae,

Fabaceae, Epacridaceae and Dilleniaceae. With the exception of the Dilleniaceae, this reflects the dominance of these families in the woody flora of Australia and their importance as structural components in the affected communities. However, there is considerable variation in susceptibility within families, genera and species (Cahill et al., 2008).

In Western Australia, 300 plant species have been listed as susceptible to infection by *P. cinnamomi* (O’Gara et al., 2005b) although it has been estimated that as many as 2000 plant species of the south-west are susceptible (Wills, 1993). Shearer et al. (2004) has estimated a mean 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.

A list of over 1000 native plant species known to be susceptible to disease by *P. cinnamomi* in Australia is contained in the *National Best Practice Guidelines* (O’Gara et al., 2005b). The list has been compiled from published material, unpublished records and observations of individual researchers.

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. For example, 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* is highly susceptible to infection on the Swan Coastal Plain of Western Australia but rarely affected in the adjoining *E. marginata* (jarrah) forest). It has also been recognised that there can be variability in susceptibility within a species, resulting in the same species being ascribed different levels of susceptibility in different areas.

At best, records of host species suggest only that *P. cinnamomi* is able to infect some part of some plants in populations of the listed species. They provide no indication of the extent of invasion or of the severity of the consequences in terms of the health and survival of individual plants, plant populations or species. As a result they are not very useful for predicting the possible fate of a particular species.

2.3.2 Effects on ecological communities

Infection by *P. cinnamomi* in susceptible ecological communities will often result in major disruption and decline of 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) 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 little 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 chronosequential changes in the floristic composition (Weste and Ashton, 1994; Weste et al., 2002).

Crone et al. (2012) showed, for the first time, the importance of annual and herbaceous perennial plants, with and without symptoms, as hosts of *P. cinnamomi*. These are important but previously overlooked groups of plants that can allow the pathogen to persist on sites after susceptible species have disappeared or have substantially reduced in numbers.

2.3.3 Impacts on animals

There has been little work investigating the impact of Phytophthora dieback on faunal populations and communities. Despite this, there is a concern that the dramatic impact of *P. cinnamomi* infections on plant communities can result in major declines in some animal species due to the loss of shelter and nesting sites or food sources. The greatest impact is likely to be to those species that require relatively dense species-rich shrublands or have restricted diets.

There are very susceptible plant species in most of the habitats on the south coast of Western Australia in which the EPBC Act listed *Parantechinus apicalis* (dibbler) has been recorded. The effect of disease-induced changes to the habitats of dibblers is unknown but disease caused by *P. cinnamomi* needs to be considered as a potential threat (Friend, 2004).

Also in Western Australia, the conservation status of *Tarsipes rostratus* (honey possum) has been speculatively connected to Phytophthora dieback (Calver and Dell, 1998). The density and distribution of the honey possum is governed by the availability of nectar and pollen for food, predominantly from proteaceous plants (Garavanta et al., 2000; Wooller et al., 2000), many species of which are known to be susceptible to *P. cinnamomi*.

An analysis of mammals that occur in Victoria found that for 22 species, more than 20 per cent of their range occurs in *P. cinnamomi*-affected areas (Wilson and Laidlaw, 2001). Five rare or threatened species; *Pseudomys fumeus* (smoky mouse), *P. shortridgei* (heath mouse), *P. novaehollandiae* (New Holland mouse), *Potorous longipes* (long-footed potoroo) and *Petrogale penicillata* (brush-tailed rock-wallaby), have greater than 20 per cent of their distributions in areas susceptible to Phytophthora dieback (Cahill et al., 2008).

In New South Wales *P. cinnamomi* invasion is considered to be a process threatening the conservation of endemic populations of *Isodon obesulus* (southern brown bandicoot) and *P. fumeus* (smoky mouse). *P. longipes* (long-footed potoroo) is also considered to be at risk from Phytophthora impact due to the proximity of infections to suitable habitat for this marsupial.

In South Australia, the endemic and endangered *Sminthopsis aitkeni* (Kangaroo Island dunnart) is regarded to be threatened by *P. cinnamomi* due to the loss of susceptible plants from its habitat (Gates, 2011).

Wilson et al. (1994) found that *P. cinnamomi* 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.

For example, 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 cm above ground level (Newell and Wilson, 1993). *A. agilis* (agile antechinus), *Rattus fuscipes* (bush rat), *R. lutreolus* (swamp rat) and *S. leucopus* (white footed dunnart) were captured more frequently in non-diseased areas as compared to diseased areas. This shows that the pathogen may affect the community structure of small mammals, which may lead to a decline in species' richness as a consequence of the disease proceeding through the habitat (Laidlaw and Wilson, 2006).

Menkhorst and Broome (2006) found that *P. cinnamomi* has the potential to have a very large

impact on populations of the EPBC Act listed Endangered *P. fumeus* (smoky mouse). Many of the plant families and genera characteristic of smoky mouse habitat are particularly susceptible to the pathogen.

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.

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.

3. Dealing with the problem

The limited management options currently 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 *P. cinnamomi* in the landscape. Currently, the two major objectives of *P. cinnamomi* management are:

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

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

Active interventions that reduce transmission of *P. cinnamomi* 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 use of the fungistatic agent phosphite directly applied to the host plant is difficult and expensive to apply in remote areas, but is useful in localised populations of high conservation value. However, there is much still unknown about the effects of the agent on non-target species and animals (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 *P. cinnamomi* 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.

The expected take-up of improvements in detection techniques using polymerase chain reaction (PCR) (O'Brien, 2008) will 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. 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.

3.1.2 Diagnosis

There is widespread confusion between the disease and death caused by *P. cinnamomi* 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, 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 disease caused by *P. cinnamomi*. This problem is exacerbated by the cryptic nature of *P. cinnamomi*. The organism can be seen only by microscopic examination in laboratories; while it sometimes produces reliable visible symptoms in a number of hosts, in many other hosts it is not reliably detected.

Until recently, the diagnosis of *P. cinnamomi* as the causative agent of disease required laboratory analysis of samples of soil and tissues from affected plants. 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 and Sendall, 2001, cited in O'Gara et al., 2005a).

PCR-based methods should help to facilitate the identification of further vulnerable plant species and are expected to improve the economic feasibility of both the sampling to detect, or confirm visible evidence of infection. This should assist in the subsequent mapping of infested sites and the continued monitoring of disease fronts.

3.1.3 Mapping

The current distribution of *P. cinnamomi* in Australia is not well known. 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 both determining where the pathogen is and where it may go. 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. 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) provides a recent and comprehensive review discussing the potential for employing predictive mapping for *P. cinnamomi*.

Various attempts at mapping have been made using technological 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. 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.

To improve the chance of finding *P. cinnamomi* in the Greater Blue Mountains World Heritage Area, species distribution modelling using information about *P. cinnamomi* ecology was undertaken. This was then used to identify the parts of the landscape where *P. cinnamomi* was most likely to be, prior to conducting sampling. New models to predict the distribution of

P. cinnamomi with a very high level of accuracy were developed. This also allowed the identification of environmental variables (for example rainfall, temperature etc.) that significantly influence the distribution of the organism. This approach can reduce the area to be sampled and increase the chances of successfully finding the pathogen (Newby, 2013).

3.2 Minimising the spread of *Phytophthora cinnamomi*

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 which, in the long term, are at risk from dieback caused by *P. cinnamomi*. 'Protectable areas' are defined as uninfected areas, occurring in the vulnerable zone, that have good prospects of remaining uninfected over the next two to three decades.

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

3.2.1 Access prohibition or restriction

Prohibiting access or quarantining an area is generally used to protect biodiversity assets of high conservation value from *P. cinnamomi*. Prohibition of access may be enforceable under legislation, for example, the Western Australian *Conservation and Land Management Act 1984*, the South Australian *National Parks and Wildlife Act 1972*, the Tasmanian *Plant Quarantine Act 1997* and the New South Wales *National Parks and Wildlife Act 1974*.

As *P. cinnamomi* can be readily spread in infected soil, plant material and water, access to specified areas may be restricted to periods when soils are not likely to adhere to vehicles and pedestrians or when the likelihood of pathogen transmission is low. Land managers may choose to restrict all access or just vehicular traffic. Recreational activities such as bushwalking, cycling and horse-riding are perceived in some areas and under some circumstances to pose a low risk and may be allowable under specific conditions.

For sound management of access to uninfected areas, it is necessary to delineate the boundaries between infected and uninfected areas. A number of 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 processes.

3.2.2 Hygiene

Where access is permitted, hygiene refers to specific procedures designed to prevent the spread of *P. cinnamomi* by ensuring that infected soil, water and/or plant material are removed 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 area 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. Portable wash-down systems enable machinery, vehicles and any item that comes into contact with the ground, to be cleaned at the point of risk for activities that do not have a fixed location.

Where high conservation values are at stake, activities such as bushwalking, horse riding and cycling may pose a risk of introduction and may also be subject to hygiene. Disinfection of footwear, small tools and equipment against *P. cinnamomi* is required to maintain disease-free status in these instances.

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

- access to suppress wildfires and for 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 bush walking, apiarian, drilling, wildflower collecting.

The Dieback Working Group (WA) has produced *Managing Phytophthora dieback in bushland—a guide for landholders and community conservation groups (Edition 4, 2008)*. In addition, the Tasmanian Government publication *Keeping it clean* (Allan and Gartenstein 2010) provides thorough hygiene related 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; fire fighting; movement of infected gravel, sand, soil or water during road construction and maintenance. As an example of the implementation of such hygiene prescriptions, 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 Frenchman's Cap track. While they are a useful tool to minimise risks to priority areas, there are difficulties associated with the implementation of hygiene measures to ensure the optimal uptake of and compliance with these measures.

3.2.3 Potential further introductions through revegetation

P. cinnamomi occurs in the nursery and garden industry, where the pathogen 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 plants and plant medium and introducing *P. cinnamomi* into the natural environment.

Consumers are also unaware that this threat can be minimised by purchasing these from certified sources.

Revegetation of much of the landscape is occurring on a broad scale across the vulnerable envelope for *P. cinnamomi* and the threat of continued spread of *P. cinnamomi* 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 *P. cinnamomi* 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 *P. cinnamomi* via infected stock. The Nursery and Garden Industry of 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 small infestations of *P. cinnamomi* has been developed and could be applied 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 increasingly robust treatments including vegetation (host) destruction, fungicides, fumigation and physical root barriers at two *P. cinnamomi* infested sites with differing climate and vegetation types. *P. cinnamomi* was not recovered at three assessments of treated plots 6 to 9 months after treatments.

3.2.5 Monitoring and surveillance

Effective monitoring and surveillance for the presence of *P. cinnamomi* 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 *P. cinnamomi*. It also provides information necessary for evaluating the risk *P. cinnamomi* 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 if 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.

Currently there are scant data 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 cinnamomi*

Options for the mitigation of impact to biodiversity at infected sites are currently limited to the use

of the fungistatic agent phosphite. *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 and 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 *E. marginata* (jarrah), while expensive, is another option for the rehabilitation of high priority infected sites (see section 3.3.4).

3.3.1 Phosphite

The autonomous spread of *P. cinnamomi* is currently impossible to control. However, phosphite (also referred to as phosphonate), the anionic form of phosphonic acid (HPO_3^{2-}), has been shown in Western Australia and Victoria to slow the spread and reduce the impact of *P. cinnamomi* in susceptible vegetation. Phosphite exhibits a complex mode of action, both acting directly on the pathogen and indirectly by stimulating host defence responses to inhibit pathogen growth.

Phosphite is currently used in Western Australia to protect areas of high conservation value and critically endangered species from the threat of *P. cinnamomi*.

Phosphite is potentially applicable in a national context and, given limited management options, provides states and territories with an important tool. It should however, 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 and Bompeix, 1990)
- its mobility in phloem and xylem (enabling application by stem injection to trees and large shrubs)
- its uptake through foliage which enables it to be applied as a foliar spray, either manually or by broad scale aerial application
- its quick break down in the soil (Guest and Grant, 1991, cited in O’Gara et al., 2005a).

Phosphite has a 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 (Hardy et al., 2001).

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. Moreover, there is emerging research that indicates that long term phosphite application may cause the accumulation of phosphate levels in the soil. This might cause the decline or modification of plant communities. Due to these unknown factors, a considered approach needs to be adopted when using phosphite for the management of *P. cinnamomi* in natural ecosystems.

The Australian Pesticides and Veterinary Medicines Authority (APVMA) administer 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 and therefore 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 APVMA state/territory co-ordinator is 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. Foliar application using backpack or trailer-mounted sprayers is usually restricted to small areas such as small reserves, remnant bushland or 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; techniques need to be further developed for this method.

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.

Case study: Prevention of spread in the Fitzgerald River National Park, WA

In Western Australia, the then Department of Environment and Conservation (WA DEC) (now the Department of Parks and Wildlife) conducted a large scale containment project on an infestation within an internally draining catchment in Fitzgerald River National Park. A Bayesian Belief Network model was developed for the range of management strategies and their effect on containment of the *P. cinnamomi* infestation. WA DEC constructed a 12 kilometre fence around the entire Bell Track infestation to prevent people and animals spreading the disease. In 2008, a three-kilometre-long plastic membrane to prevent plants spreading *P. cinnamomi* through root-to-root transmission was installed. The fungicide metham sodium was applied through a subterranean irrigation system at the location of the root-imperious membrane to increase the potential to contain the pathogen. The fungicide phosphite was aerially and ground applied to part of the 375 hectares of the Fitzgerald River National Park within the Bell Track project area. WA DEC contained this infestation, protecting the largely disease free status of the rest of Fitzgerald River National Park. The process has been published in the *New Zealand Journal of Forestry Science* and could be used as the basis for similar work in appropriate locations (Dunne et al., 2011).

3.3.2 Ex situ conservation

Ex situ conservation of germplasm in seed banks is a well established technique and with no definitive solution to the threat of *P. cinnamomi*, it may be the last hope in conserving some susceptible species. Compared to other types of germplasm, seed conservation 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).

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).

3.3.3 In situ conservation

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 where it 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.

3.3.4 Breeding for resistance

There may be considerable variation in the expression of disease within a species. It has been observed that remaining and apparently healthy *Eucalyptus marginata* (jarrah) in diseased jarrah forest are often the resistant component. Intra-specific resistance has been demonstrated using clones of susceptible *E. marginata* (Stukely and Crane, 1994) and the resistant individuals are the basis of a plant breeding program in Western Australia selecting for resistance of *E. marginata* to *P. cinnamomi*. This breeding program has particular but limited application for forestry and rehabilitation of infected sites in the *E. marginata* forest.

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 and 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.

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 spread and impact of *Phytophthora* could present as a more sustainable and effective approach to managing this threat in the long term.

3.4 Wide scale detection, diagnosis and demarcation protocols

In order to survey and map the distribution of *P. cinnamomi* on a wide scale, a uniform and consistent sampling standard for application across the country is required. The presence of *P. cinnamomi* at a site can be confirmed from a single positive sample but a site cannot be deemed 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 and Tay 2003, cited in O’Gara et al., 2005a).

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 1256m² 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 the 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.

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 for 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 (i.e. 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 enabled a ranking of assets according to the risk posed by *P. cinnamomi* and the perceived ability to manage the risks. Indicative assessments are produced when the models are run. The decision flow chart contained in the model terminates with the determination of disease status of the site, with three possible options: infected, uninfected or 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 (C Dunne [WA DEC] 2011, pers. comm.).

Within the Wet Tropics, a preliminary risk assessment methodology has been developed that guides decisions concerning implementation of hygiene measures during operational works. Studies have identified high, moderate and low risk zones within the World Heritage Area (Worboys and 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 areas most manageable (considering factors such as disease proximity, landscape features and ease of access etc.) were selected for priority management. A regional plan for the management of *P. cinnamomi* in the Tasmanian Wilderness World Heritage Area has been developed which addresses biodiversity assets at risk and identifies large disease-free areas.

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. This data provided maps showing the risk of plant diversity loss to *P. cinnamomi*.

Information regarding the susceptibility of threatened plant species in South Australia is very limited. A risk assessment based on status and proximity to *P. cinnamomi* infestations was developed to prioritise threatened plant species for research and management options (Velzeboer et al., 2005).

The risk assessment process developed should be viewed as iterative, and improvements and reviews undertaken as new data and knowledge become available.

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Appendix A

Data contributions for figure 2

Organisations

ACT Parks, Conservation and Lands, Australian Capital Territory (2011)

Deakin University, Melbourne, Victoria

Department of Environment and Primary Industry, Victoria (2011)

Department of Primary Industries, Parks, Water and Environment, Tasmania (2010)

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Royal Botanic Gardens and Domain Trust Sydney, New South Wales (2011)

Wet Tropic Management Authority (2011)

Papers

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Appendix B

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*, a report funded by the Commonwealth Government Department of the Environment and Heritage by the Centre for *Phytophthora* Science and Management (CPSM), Murdoch University, Western Australia.
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Please Note: The full reports can be downloaded from:

www.environment.gov.au/biodiversity/invasive/publications/p-cinnamomi.html

Further Reading

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Appendix C

State documents relevant to *Phytophthora cinnamomi*

State	Document
WESTERN AUSTRALIA	Dieback working group publications (many of these documents have national applicability)
	Best practice guidelines: Management of <i>Phytophthora</i> dieback in extractive industries
	Managing <i>Phytophthora</i> dieback: Guidelines for local government
	Managing <i>Phytophthora</i> dieback in bushland: A guide for landholders and community conservation groups
	Flyers relating to phosphite use: <ul style="list-style-type: none"> • <i>Phosphite injection using Chemjet Syringes</i> • <i>Dieback Treatment Spraying</i>
	Native garden plants resistant to dieback (<i>Phytophthora cinnamomi</i>)
	Western Australian natives resistant to <i>Phytophthora cinnamomi</i> , compiled by Groves E, Hardy G & McComb J, Murdoch University
	Western Australian natives susceptible to <i>Phytophthora cinnamomi</i> , compiled by Groves E, Hardy G & McComb J, Murdoch University
TASMANIA	Phytophthora dieback management plan for the South Coast Region 2010–2017 (draft), < southcoastnrm.com.au/images/user-images/documents/Phytophthora_Dieback_Management_Plan_for_the_South_Coast_Region_2010-2017.pdf >.
	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.
	Tasmanian Wilderness World Heritage Area <i>Phytophthora cinnamomi</i> Management Plan 2008–2017, unpublished, Tasmanian Parks and

State	Document
	<p>Wildlife Service.</p> <p>Conservation of Tasmanian plant species & communities threatened by <i>Phytophthora cinnamomi</i>: 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.</p> <p>Interim <i>Phytophthora cinnamomi</i> management guidelines, Nature Conservation Report 05/7, Rudman T (2005), Biodiversity Conservation Branch, Department of Primary Industries, Water and Environment, Hobart.</p>
QUEENSLAND	<p>Patch deaths in tropical Queensland rainforests: association and impact of <i>Phytophthora cinnamomi</i> and other soil borne organisms, Gadek PA (ed) 1999, Cooperative Research Centre for Tropical Rainforest Ecology and Management, Cairns, Queensland.</p> <p>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.</p> <p>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.</p> <p>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.</p>
VICTORIA	<p>Victoria's public land <i>Phytophthora cinnamomi</i> management strategy, the State of Victoria, Department of Sustainability and Environment, 2008.</p>
NEW SOUTH WALES	<p>Infection of native plants by <i>Phytophthora cinnamomi</i>—key threatening process listing.</p> <p>NSW Scientific Committee - final determination</p> <p>Statement of Intent 1: Infection of native plants by <i>Phytophthora cinnamomi</i> Department of Environment and Climate Change, NSW</p>

State	Document
	Best practice management guidelines for <i>Phytophthora cinnamomi</i> within the Sydney Metropolitan Catchment Management Authority Area. (2008).
	Facts about Phytophthora (brochure), Plant Disease Diagnostic Unit, Royal Botanic Gardens, Sydney.
	Phytophthora management in natural bushland—five strategies approach (brochure), Royal Botanic Gardens, Sydney
SOUTH AUSTRALIA	Phytophthora (dieback) control operational instruction 21.3, Transport SA - Statewide Operational Coordination Group 2000
	Phytophthora management guidelines 2006, <i>Phytophthora</i> Technical Group, Government of South Australia.

Appendix D

Site variables that influence whether eradication or containment of *Phytophthora cinnamomi* is possible

Table prepared by the Western Australian Department of Environment and Conservation. Note: This assessment is based on Western Australian land systems and is not directly transferable to other land systems.

	Eradication Level High probability of success	Eradication Level Medium probability of success	Containment	Impact Reduction
Size	< 1 ha	< 5 ha	5–500 ha	Any size
Soil type	Deep sand	Clay or rocky soils	–	–
Vegetation condition for high confidence occurrence mapping	High	High–moderate	High–moderate	Low
Level of infestation in surrounding native vegetation	Low	Low	Low	Moderate–high
Hydrological characteristics of the site	Limited surface or subsurface runoff	Moderate surface runoff and limited subsurface runoff	Moderate surface runoff and limited subsurface runoff	Moderate – high surface and subsurface runoff
Main mode of disease centre expansion	Root-to-root	Mix of root-to-root and movement in surface runoff	Mix of root-to-root and movement in surface run off	Movement in surface and subsurface run off
Topography	Flat	Flat–moderate slopes	Flat–moderate slopes	Moderate–steep slopes
Animal vectoring risk	Low	Low–moderate	Low–moderate	High
Presence of declared rare flora or threatened	No	No	No	Yes

	Eradication Level High probability of success	Eradication Level Medium probability of success	Containment	Impact Reduction
ecological communities				
Presence of other values (e.g. aboriginal heritage sites, rare fauna)	No	No	Yes	Yes
Proposed Methodology	Vegetation destruction, herbicide treatment, phosphite treatment, fumigation	Fencing, vegetation destruction, herbicide treatment, phosphite treatment, fumigation, root membranes, geo-textiles, hydrological engineering controls	Fencing, root impervious membranes, phosphite treatment, hydrological engineering controls	Phosphite treatment, seed collection, translocation
Estimated cost per hectare	\$50 000–\$100 000	\$100 000–\$500 000	\$20 000–\$100 000	\$1000–\$100 000+