Managing the Risks of Phytophthora Root and Collar Rot During Bauxite Mining in the *Eucalyptus marginata* (Jarrah) Forest of Western Australia

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Western Australia is renowned as a region of exceptional plant species richness—more than 7,000 species of native vascular plants occur in the state (19), and of these, over 3,000 are endemic (30). The native plant communities in the southwestern part of the state are also the setting for what has been described as “a biological disaster of global significance for conservation of areas of great biodiversity and a major problem for wood based and extractive industries” (42). The cause of this “disaster” is *Phytophthora* root and collar rot (PRCR) disease, with *Phytophthora cinnamomi* being the predominant pathogen. This pathogen directly affects over 2,000 of the 7,000 native species (59), and its indirect effects are still to be elucidated.

P. cinnamomi is a water mold whose growth, reproduction and spread are favored by free water in the soil or ponding on the soil surface. Similar to other *Phytophthora* species, it has coenocytic mycelia with few septa and produces sporangia in free water (Fig. 1). The zoospores are biflagellate and are attracted to roots by chemical stimuli (25); their average diameter is 8.0 μm . Initially, zoospores are free swimming for hours before forming cysts. These encysted spores have thin walls but can survive for weeks in soil (13,33).

P. cinnamomi is heterothallic: oospores form when A1 and A2 mating types are paired. The A2 mating type is by far the most common throughout the world. In Western Australia, the A1 mating type is rare, so oospores are not considered to play an important role in reproduction or survival. Chlamydospores form abundantly in culture and in the host tissue. These thick-walled spores would be expected to be

more long-lived than encysted zoospores (34,55).

P. cinnamomi is believed to be exotic to Western Australia, and it has been speculated that this species has an Asian origin (60). The introduction of *P. cinnamomi* to Western Australia probably occurred in the nineteenth century with the importation of fruit trees and garden plants by European settlers. The pathogen eventually spread to native ecosystems, where many plant species had little natural resistance. Early reports of the disease focus on the impact on jarrah (*Eucalyptus marginata*) trees, a high-quality timber tree that was the backbone of an important export trade for the state. The original name of the disease was jarrah dieback, but this name is misleading because many native species are susceptible (59). Also, most species do not die back, but rather die suddenly when the root or collar rot deprives them of water.

The impact of PRCR is high in many native plant communities in southern Australia and particularly in Western Australia. Most of the long-term ecological studies of the impact of *P. cinnamomi* on plant communities have occurred in the state of Victoria, southeastern Australia. In the Grampians National Park, Victoria, 26% of the understory species disappeared, and an additional 28% were greatly reduced in number (31). The plant biomass was reduced by one-third, and the flora changed from one dominated by insect-, mammal-, and bird-pollinated plants to one that is dominated by wind-pollinated plants. It is likely that this change had major consequences for these animal populations. Many woody plants of Western Australian also are susceptible to *P. cinnamomi*, which suggests that this pathogen may have similar consequences on the community biodiversity in this region as well (59). This pathogen has been identified by the Australian government as one of only five threatening processes that are having a major impact on the biodiversity of the country (10).

P. cinnamomi has a very wide distribution in the jarrah forest. The impact varies from a “graveyard” (Fig. 2), where many of the susceptible plants die (including the jarrah trees), to subtle, where only the occasional understory plant dies.

The jarrah forest in Western Australia is also the location of one of the largest and most productive bauxite mining operations in the world. The bauxite mining and alumina refining company, Alcoa World Alumina Australia, supplies 16% of the world's alumina (Al_2O_3). It has two mines, Huntly and Willowdale (Fig. 3).

Managing the risks associated with mining in a forest where *P. cinnamomi* is widespread has been a major challenge to Alcoa since mining started in 1963. Although widespread, *P. cinnamomi* has been estimated to be present in approximately 14% of the forest (12); many areas of upland forest remain free of the disease. However, many ore bodies lie beneath PRCR-free forest. *P. cinnamomi* spreads in soil and water, so the challenge is daunting—to manage this pathogen during an operation that moves about six million cubic meters of soil a year, generates water runoff from minepits and haul roads, and disrupts natural drainage patterns.

Two of Alcoa's major environmental objectives are to minimize the spread of *P. cinnamomi* and to revegetate minepits to achieve a high botanical diversity composed of only species present in the forest surrounding the mine. These objectives have driven the environmental research and development (R&D) program to develop effective procedures to manage PRCR. To be endorsed by management, these procedures also needed to be economic and practicable. An intensive PRCR management program has now been operating since 1990 at Huntly, Alcoa's biggest mine. This article reviews the risk assessment process used, the R&D projects associated with this development, the management procedures being implemented, and the results of recent monitoring to assess

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the effectiveness of these procedures. To our knowledge, this is the first example of a large industry effectively implementing disease management procedures to minimize the impact of a major soil-borne plant pathogen on native ecosystems.

Introduction

The jarrah forest is only present in the southwestern corner of Western Australia, and the area of high-quality forest has been calculated to be 16,000 km² (1). Unlike most eucalypt forests, the tree component is principally comprised of only two species, jarrah and marri (*Corymbia calophylla*). The climate of the northern jarrah forest is Mediterranean, with long, hot, dry summers and cool, wet winters (48). The forest grows on an ancient plateau com-

posed of granite rocks intruded by dolerite dikes. Weathering of this rock has led to regolith profiles that may be deeper than 50 m. The soil consists of about 0.5 m of sandy gravel overlying a concretionary layer of laterite (the duricrust). The landscape is gently undulating, with the highest hill being 523 m.

There are approximately 780 species of vascular plants in the jarrah forest (2). Monitoring has found an average of 58 species per 80 m² quadrat in upland forest (J. Koch, *personal communication*). Ordination techniques were used to categorize the northern jarrah forest into 15 major site-vegetation types (24). This site-vegetation reflected the topography, moisture availability, and degree of leaching and fertility of the soil. The forest is a mosaic

of these site-vegetation types. More detailed information on the jarrah forest has been published in Dell et al. (15).

PRCR has a patchy distribution, with most valley bottoms being infested. In the western, high-rainfall region of the forest, the disease is also present in many mid-slope and some upslope positions. Human activity is high in this western region; logging and establishment of towns led to the construction of many roads. Roads positioned high in the landscape appear to be an important avenue for spread of the pathogen.

Inoculum levels vary with depth in the soil profile. The pathogen is recovered most frequently from the surface of the duricrust (47). This pattern was found in both high-disease-impact sites and sites of

Fig. 1. Life cycle of *Phytophthora cinnamomi* in the *Eucalyptus marginata* forest.

Fig. 2. Graveyard *Eucalyptus marginata* (jarrah) forest as affected by *Phytophthora cinnamomi*.

Fig. 3. Location of Alcoa's two bauxite mines in Australia.

moderate to low impact. This layer is believed to impede drainage so it remains wetter for longer periods, which favors spore production and survival. Zones of water infiltration in the duricrust are also zones of root penetration. The co-occurrence of wet conditions, plant roots, and relatively high levels of *P. cinnamomi* inoculum may lead to infection. However, the infection process in jarrah in the native forest is not well understood. There have been observations of infected fine roots with little evidence of colonization of the larger roots (50). Vertical roots have been found to be girdled by *P. cinnamomi* with little damage to lateral roots (44). In contrast, the invasion of lateral roots led to growth of *P. cinnamomi* into the collar region of jarrah, and these trees die when the collar is girdled (3).

Mining and Rehabilitation Processes

Alcoa's mining operations clear about 550 ha of forest a year. The ore bodies tend to be 5 to 40 ha and are located on the flanks of hillslopes. These ore bodies are connected by 18-m-wide haul roads, which are used to transport the ore. The bauxitic

layer is usually 3 to 5 m thick, so the minepits are relatively shallow.

At the Huntly mine, 85% of the mining area is in PRCR-free forest, but many ore bodies have PRCR forest on the lower slopes. The presence of *P. cinnamomi* may also be associated with forest roads that dissect the ore bodies. After mining, the aim is to maintain the area of PRCR-free vegetation that existed prior to clearing for mining; that is, if the area of PRCR-free forest cleared for mining was 100 ha, then after mining the PRCR-free area should be at least 100 ha.

P. cinnamomi may also interfere with Alcoa's efforts to meet its biodiversity objective, which is to "re-establish the same plant species richness in the rehabilitated mined area as exists in nearby forest control sites." Only species endemic to the forest surrounding the mine are considered. Many vascular plants in the jarrah forest are susceptible to *P. cinnamomi* (45), so the pathogen has the potential to greatly reduce the number of plant species re-established in the rehabilitated areas.

The following section summarizes Alcoa's mining and rehabilitation processes. Understanding these processes will high-

light the magnitude of the risks of spreading *P. cinnamomi* during mining.

The first stage in the mining process is exploration drilling. Drill rigs mounted on tractors traverse about 2,500 ha a year to collect samples of the regolith (Fig. 4A). Over 60% of this forest is PRCR-free. Once the locations of the ore bodies have been mapped, the sequence of mining and rehabilitation is planned to minimize the financial cost of the operations while ensuring that rehabilitation operations are scheduled for the most appropriate time of year. It is important that the topsoil is moved in a manner, and at the time of year, that maintains the viability of the seeds it contains.

There are two timber extraction operations within the mines. The first operation removes all the large logs, with the follow-up operation removing all the material for fence posts and firewood (Fig. 4B). The remaining trees and stumps are bulldozed into heaps and burned. Scrapers remove the topsoil (0 to 10 cm) and usually transport it immediately to a recently rehabilitated minepit (Fig. 4C). The gravel layer (called overburden) below the topsoil is about 40 cm thick and contains very few

Fig. 4. (A) Exploration drill rig sampling in the forest. (B) An area cleared for mining showing timber removal. (C) Using scrapers to strip soil from the cleared area. (D) Blasting the duricrust. (E) Loading ore onto a dump truck. (F) Bulldozer pushing down the minepit face during the landscaping phase of rehabilitation. (G) Scrapers returning soil to a landscaped minepit. (H) Bulldozer showing the winged tine used to rip the rehabilitated area. (I) Helicopter fertilizing a rehabilitated minepit.

seeds. Scrapers and bucket excavators remove this layer and stockpile it nearby.

The hard duricrust layer is either blasted (Fig. 4D) or broken with a large bulldozer pulling a chisel tine. Front-end loaders or large bucket excavators fill dump trucks with the broken ore (Fig. 4E). Once mined, a typical pit will be a 10-ha depression with 3- to 5-m-high pit faces. Landscaping using large bulldozers first shatters the floor of the minepit and then creates a surface topography that blends with the adjacent landscape (Fig. 4F). Scrapers transfer and spread the overburden from the stockpiles onto the landscaped area (Fig. 4G). Topsoil is then placed on the gravel. A winged tine is pulled by a bulldozer to shatter the top 1.2 m of the new soil profile (Fig. 4H). It is carried out on the contour and produces a rippled surface with 20- to 30 -cm-high mounds that are 2 m apart. This procedure is called rehabilitation ripping. The aims of rehabilitation ripping are to (i) improve deep drainage; (ii) control surface water movement to reduce the risk of erosion; and (iii) provide vertical and horizontal cracks in the surface profile to enable roots to access the deeper preferred pathways below 1.2 m. The roots of jarrah and marri in the non-mined forest are very deep; some roots have been found at 55 m (14).

A mixture of seed from species endemic to the locality of the mine is spread on the topsoil by hand. Over 90 species are used at a rate of 2.8 kg/ha. This seed supplements the seed that is present in the topsoil. Plant species that do not establish well from seed are planted. The rehabilitated areas are fertilized in spring with 500 kg/ha of di-ammonium phosphate with added trace elements. A specialized hopper is attached under a helicopter to spread the fertilizer (Fig. 4I).

Throughout the entire mining and rehabilitation process, the only activity that does not affect the risk of spreading the pathogen is fertilizing. All other steps have risks of spreading *P. cinnamomi* or increasing the impact of the disease.

Risk Assessment

Some disease control procedures were in place soon after mining began in 1963. Most of these focused on selecting tree species resistant to *P. cinnamomi* to use in the rehabilitated areas. In 1978, scientists from state government departments and CSIRO (53) predicted that the spread of *P. cinnamomi* during mining was inevitable and would be high (1- to 4-ha spread for every hectare mined). From the 1960s to the early 1980s, the threat of PRCR strongly influenced the selection of tree species for the rehabilitated areas. It was always assumed that re-establishing jarrah trees would be unsuccessful because *P. cinnamomi* eventually would kill them.

From 1963 until 1989, mining was restricted to areas predominantly infested

with *P. cinnamomi*. More PRCR control procedures were introduced during this period to better control soil and water movement. The mid to late 1980s was a period of enlightenment in relation to PRCR in the forest and in rehabilitated bauxite minepits. It was realized that, in the forest, the impact of PRCR was variable, and in many sites the presence of the pathogen did not result in the death of jarrah trees. Also, no large areas of new infection were found adjacent to mining. In addition, jarrah trees planted in trial plots within the rehabilitated areas were surviving. Consequently, it was realized that bauxite mining would not necessarily lead to extensive spread of *P. cinnamomi* and associated mortality of jarrah, and that revegetation procedures could use entirely local tree and understory species with minimal risk of high mortality.

In 1989, the state government decided that Alcoa's mining at Huntly should move northeast into predominantly PRCR-free forest. This was a radical change from the previous mine envelopes, where much of the forest was infested. In this new mine envelope, virtually all vegetation communities adjacent to streams were infested, but most of the mid and upper slopes were free of *P. cinnamomi*. By 1989, considerable scientific and environmental knowledge was available that favored this shift. It was known that *P. cinnamomi* had a relatively low impact on many site vegetation types in the forest. Methods were available to reliably map the presence of *P. cinnamomi* throughout the mine envelope. Some intrusive PRCR control procedures, such as washing vehicles and marking disease fronts, had been in place for the previous 5 years without significant opposition from mining staff. These procedures were perceived to be successful at minimizing spread of *P. cinnamomi*. Alcoa accepted the challenge of making this move, knowing that the potential risk of spreading *P. cinnamomi* was high but also that the quantity and quality of ore in this region of the forest was high.

Alcoa's approach was to establish a team of mining practitioners and environmental scientists from within the company to develop practicable PRCR management procedures for each stage of mining. The first challenge was to develop a broad disease control strategy for the new mining envelope. The existing strategy had been based on the assumption that gravel haul roads were infested with *P. cinnamomi*. In all areas, apart from active minepits, vehicles were required to be cleaned before moving from a PRCR area into a PRCR-free area. Previously, the frequency of vehicle cleaning was relatively low because there were relatively few PRCR-free areas. In contrast, the new mining envelope, which was predominantly PRCR-free, required a much greater frequency of cleaning, especially when moving from the

haul road to the forest. Cleaning vehicles was expensive due to lost production while the vehicles were being cleaned. In addition, the effectiveness of cleaning a large muddy vehicle on a wet day was assessed to be low. Minimizing the need for cleaning earthmoving machinery would decrease the cost and minimize the risk of spreading *P. cinnamomi*. Consequently, the "PRCR-free" or "green" strategy was developed. This strategy was based on all haul roads being built of uninfested material, with strict hygiene procedures being used during construction, and all vehicles being cleaned before entering the mine from public roads and forest tracks. Vehicles could now travel from the haul roads to uninfested areas without cleaning; this greatly decreased the time spent cleaning vehicles. The next stage was to identify the major risks during each stage of mining that could spread *P. cinnamomi*. Because all team members had been exposed to existing PRCR control procedures, this task was relatively easy. The major risks were thought to be:

- contaminating *P. cinnamomi*-free soil with *P. cinnamomi*-infested soil,
- *P. cinnamomi* spores in drainage water spreading along many kilometers of haul roads and from there into the forest,
- introducing *P. cinnamomi* from infested soil clinging to vehicles,
- surface water draining from cleared areas into the forest,
- operators not understanding or ignoring the rules, and
- errors in mapping the PRCR boundaries.

The risk to the health and survival of vegetation in the rehabilitated minepits from the presence of *P. cinnamomi* was difficult to quantify. There was little understanding of what effect changes to the host and the environment would have on the severity of the disease symptoms. The presence of *P. cinnamomi* could continually kill a range of plant species, thereby preventing the site being self sustaining and decreasing species richness. The pathogen could also cause high mortality of the keystone tree species, jarrah. To assess the potential impact of *P. cinnamomi* on revegetated minepits, monitoring programs were upgraded and a research program was commissioned by Alcoa at Murdoch University, Perth, Western Australia.

R&D Program to Minimize Spread and Impact of Pathogen

Monitoring projects. *Where is P. cinnamomi around the mines?* Gravel from haul road surfaces and minepit floors was monitored monthly for 3 years using a soil baiting method. Briefly, this involved flooding soil samples and baiting with *Eucalyptus sieberi* cotyledons; these cotyledons were plated onto *Phytophthora*-selective agar (35). The water in sumps that receive runoff from haul roads also was monitored monthly. The monthly haul

road and minepit sampling found less than 1% of the samples to be infested by *Phytophthora* species. *P. cinnamomi* was never isolated from water in haul road sumps. However, *P. cinnamomi* was found in water in the Huntly dam, which is used to suppress dust on the haul roads. Well-formed forest roads and forest tracks formed in situ have also been screened for the presence of *Phytophthora* spp. *Phytophthora* spp. were rarely found on the well-formed roads but were more common on the tracks where water ponded frequently in ruts. *P. citricola* and *P. cinnamomi* were found on tracks, but *P. citricola* was the more common (isolated from 26% of the 170 samples).

Our conclusion from the monitoring programs, which were limited considering the length of haul roads and the frequency of monitoring, was that inoculum levels of *P. cinnamomi* are low but the pathogen could be present. Therefore, the presence of *P. cinnamomi* on the haul roads and in the dam that supplies water to suppress dust on the haul roads reinforced the need to clean vehicles before they entered PRCR-free forest and the need to chlorinate the water supply.

Vegetation monitoring. An intensive program in 1995 monitored the survival of jarrah in 5- to 16-year-old rehabilitated minepits. Generally, survival was high (Table 1). Mortality in a rehabilitated minepit tended to be patchy, with patches coinciding with the areas where water ponded in ripples. The minepits with the lowest survival tended to have the greatest occurrence of water ponding in ripples. Areas where water ponded could be scattered throughout the minepit.

We had predicted that the presence of *P. cinnamomi* would decrease the species richness in rehabilitated minepits. Recent

monitoring has indicated that this is not the case. Each year, the species richness in 50 plots (comprising five 4 × 4 m quadrats) is monitored at each mine. Monitoring is done 15 months after revegetation. The treatment of the topsoil had the biggest impact on species richness. Directly returning topsoil resulted in significantly greater species richness than using stockpiled topsoil. Surprisingly, using soil infested with *P. cinnamomi* did not significantly decrease species richness (Table 2).

The outcome of the vegetation monitoring program and opportunistic sampling of recently dead plants suggested that *P. cinnamomi* was killing some susceptible plants from a range of species, but not as many as we expected based on knowledge of the pathogen in the nonmined forest. This was an encouraging outcome, but we needed to determine how *P. cinnamomi* was killing the plants and why plant survival was so high.

How *P. cinnamomi* kills jarrah in rehabilitated minepits. In the past, only dead trees had been sampled for the presence of *P. cinnamomi*. A new approach was taken to screen stems and roots of 1- to 6-year-old trees showing very early stress symptoms (slight yellowing and purpling of the foliage [Fig. 5]). Unexpectedly, all trees had lesions at or just above the soil line (Fig. 6). At no time were roots necrotic in the absence of necrotic collars or lignotubers. In addition, lignotubers appeared to be more resistant to the pathogen than the stems or roots (23). These results are in contrast to those from the jarrah forest, which clearly show that it is the roots of jarrah that become infected, and where extensive lesions have often been observed in both large lateral and vertical taproots (48).

A study was conducted to determine

whether *P. cinnamomi* could infect trees through the lower stem periderm tissue under conditions of temporary ponding in rehabilitated areas. Glasshouse and field trials were conducted that involved mimicking ponding or temporary inundation by placing inoculum receptacles (Fig. 7) around the stems of trees, into which motile zoospore suspensions of *P. cinnamomi* were placed. These trials (38,39) clearly showed that 100% of the trees inoculated in this fashion became infected, wounding was not required for infection to occur, and zoospores were able to penetrate suberized stem tissue. Short periods of ponding (2 days) resulted in infection, and temporary ponding was not required to predispose trees to infection. Another study (4) showed that these types of ponds were never hypoxic. Therefore, trees were not being exposed to waterlogging conditions. It was also shown that, despite 100% infection, only 7% of trees died as a result of inoculation; this is consistent with the percentage of deaths normally observed in rehabilitated minepits (see Table 1).

Recovery of the pathogen declined with time after infection, especially over the hot, dry summer months (38). However, we observed that over time the pathogen in the plant becomes dormant or is exposed to fungistatic processes. Continued washing and leaching of phenolic compounds from lesioned or apparently healthy tissue in the region of inoculation resulted in recovery of *P. cinnamomi*, despite the initial plating of this tissue (lesioned or apparently healthy) onto *Phytophthora*-selective agar being unsuccessful (38). This has important implications in terms of survival and dissemination of the pathogen, since only small amounts of viable inoculum are required to initiate massive sporangium and zoospore production of this polycyclic

Table 1. Survival of jarrah trees growing in 5- to 16-year-old rehabilitated minepits at Huntly, monitored in 1995

Year rehabilitated	No. of minepits	Total no. of trees monitored	Survival (%)
1979	2	193	83
1986	2	208	94
1988	3	356	90
1989	3	284	89
1990	3	325	91

Table 2. Mean plant species richness (species per 80 m²) of 15-month-old rehabilitated bauxite minepits with varying topsoil history and presence of *Phytophthora cinnamomi*

Topsoil history	Infested by <i>P. cinnamomi</i>	Mean richness ± standard error (species per 80 m ²)	No. of plots
Directly returned to minepit	No	51.7 ± 1.6	56
	Yes	51.0 ± 2.1	26
Stockpiled topsoil	No	39.5 ± 0.9	112
	Yes	39.8 ± 0.9	110

Fig. 5. Chlorotic *Eucalyptus marginata* showing early symptoms of *Phytophthora* root and collar rot.

pathogen under ideal conditions. The studies also showed that the pathogen can extensively colonize host tissue (up to 10 cm up the stem) during winter months as a hemibiotroph with no observable lesions being present (38).

***P. cinnamomi*-resistant clonal jarrah.** In the 1980s, a program was established by Alcoa, the Department of Conservation and Land Management, and Murdoch University to identify and propagate jarrah plants with a high resistance to *P. cinnamomi*. Seed was collected from jarrah trees surviving in sites where most jarrahs had been killed by *P. cinnamomi*. The resulting seedlings were screened for resistance against isolates of the pathogen (52).

The most resistant seedlings were propagated using tissue culture methods (36,37). Ninety-eight clones of jarrah that demonstrated higher than average resistance to *P. cinnamomi* in the glasshouse, and the capability to be propagated easily using tissue culture, have been selected. Large field trials have been established to check the field resistance of the clones. Propagation of jarrah clones using tissue culture is expensive but necessary, because it is not possible to propagate jarrah by cuttings. Resistance to *P. cinnamomi* is a highly heritable trait (52), so seed orchards have been established to produce plants of high resistance for a lower cost.

Recently, concerns about the long-term establishment of these clones in PRCR sites have been raised. Firstly, recent work in our laboratory has shown that there is a large variation in the pathogenicity of isolates of *P. cinnamomi*, some being significantly more pathogenic than the isolates used in the initial screening for resistance (D. Hüberli, *unpublished*). In addition, concern was also raised about the possible effects of waterlogging or temporary hypoxia on the resistant clones because temporary ponding in rehabilitated minepits was associated with jarrah deaths; the clones had never been screened for resistance under these conditions. It was also necessary to determine whether older plants (5 to 6 years old) remained resistant to the pathogen, since all previous screening had been conducted on approximately 1-year-old plants. Finally, we wanted to confirm earlier observations that the method of inoculation, stem versus root inoculation, did not affect the overall ranking of resistance.

Three studies were set up to determine (i) whether resistant clones still expressed resistance to our most pathogenic isolates of *P. cinnamomi*, (ii) whether the ranking of resistance was affected by the inoculation method, and (iii) if waterlogging could predispose resistant clonal plants to PRCR. In the last study, the biochemical mechanisms of resistance to the pathogen were also examined.

The results of studies in growth chambers indicated that some resistant clones

are killed by the most pathogenic isolates, while others are not. This was irrespective of plant age. The studies also indicated that the resistance mechanisms in the resistant clones broke down at 25°C or above, whereas at 20°C, the susceptible clones died significantly sooner than the resistant clones (D. Hüberli, *unpublished*). Pathogenicity ratings based on under-bark inoculations maintained these ratings after inoculation by zoospores. In the field trial, some of the resistant clones were as susceptible to *P. cinnamomi* as the susceptible clones and seedlings (D. Hüberli, *unpublished*). Ponding was not found to predispose resistant or susceptible clones to infection by zoospores (6,39). However, once the plants were infected, the duration of hypoxia or anoxia influenced their biochemical defense responses. Overall, plants subjected to hypoxia were less able to switch on rapid defense responses against the pathogen. This was irrespective of whether the plants were resistant or susceptible clones (4,5,7).

Control of *P. cinnamomi* during mining. "Can't we just soak this bug with a chemical to kill it in the soil?" was a frequent question from the miners during team meetings to develop PRCR management procedures. Their frustration was not with the procedures to manage big PRCR-free areas, but with the big areas of PRCR-free forest where there were small infestations or where infested tracks crossed the PRCR-free forest. They could foresee the problems of how to remove soil from small areas with big machines, where to store the infested soil, and how often vehicles would need to be cleaned during mining to ensure the PRCR-free area was not compromised.

Fig. 6. Collar lesion caused by *Phytophthora cinnamomi* in a 4-year-old *Eucalyptus marginata* tree growing in a rehabilitated minepit.

A research program examined potential methods to eradicate the pathogen from the soil.

High soil temperatures. Ambient air temperatures above 35°C are common during summer and are usually associated with cloudless skies. Haul roads and other cleared mining areas are exposed to the sun, and surface soil temperatures reach 60°C. We did not know the effect of these relatively high soil temperatures on the survival of the pathogen. Laboratory studies showed that *P. cinnamomi* was killed in colonized millet seed when a temperature of 50°C was maintained for 0.5 h or 40°C for 24 h (8). We believe that the high soil temperatures on the haul road surface will kill *P. cinnamomi* inoculum in the surface layer during summer.

There was also the opportunity to generate heat by burning the residue wood left after logging operations; these piles could be burned on forest tracks crossing uninhabited areas. Previous research had shown that burning log piles increased soil temperatures to a depth of 80 cm (54). We established two large field trials to monitor the soil temperature and survival of *P. cinnamomi* in wood plugs below burning piles of residue logs (8). The soil temperatures reached 40°C at 64 cm below the fire, and this temperature was maintained for days (Fig. 8). The wood plugs were retrieved 9 days after the fire was lit. *P. cinnamomi* could not be reisolated from the wood plugs to a depth of 80 cm directly below the fire.

The depth of soil above the duricrust is usually less than 50 cm, so it was concluded that this procedure would be effective for tracks where the soil was less than

Fig. 7. Experimental design used to expose collar periderm tissue to inundation and zoospores of *Phytophthora cinnamomi*.

50 cm deep. The procedure is now available as part of the disease management procedures.

Disinfectants. To be successful at the operational level, a chemical treatment needs to be cheap and effective, have low toxicity to humans, and have a low risk of polluting the water resource. With these constraints in mind, quaternary ammonium and substituted phenol compounds were assessed for their value in eradicating *P. cinnamomi* in mine soils. Laboratory experiments examined the concentration and duration of treatment required to eradicate *P. cinnamomi* and the adsorptive behavior of these chemicals in the mine soils. Millet seed and wooden plugs colonized by *P. cinnamomi* were used as the inoculum source.

In gravel, the recommended dosage rates for both chemicals eradicated *P. cinnamomi* after 7 days. In the other, more organic soil types, both chemicals were ineffective. It was concluded that the need to eradicate *P. cinnamomi* in soils was not sufficiently critical to justify the financial cost of the chemical and the associated procedures needed to minimize the pollution risk to the water resource.

At relatively low concentrations, the copper ion kills *Phytophthora* species (49). It is cheap and readily binds to organic material in mine soils, thereby reducing the risk of polluting the water resource. Vermiculite infested with two isolates of *P. cinnamomi* was added to topsoil and gravel treated with concentrations up to 5 g of CuSO₄ per kg of soil. Direct plating of vermiculite and baiting of soils with leaves of *Pimelia ferruginea* and cotyledons of *Eucalyptus sieberi* were used to assess the PRCR-suppressing capability of CuSO₄. The pathogen was not eliminated from any of the treatments after 2 h of exposure. However, infection of baits in gravel did not occur after 5 days exposure at 2 g of CuSO₄ per kg of soil (26). This trial indicated that copper sulfate could minimize the risk of spreading the pathogen from a

small volume of gravel (<60 m³). Unfortunately, it does not meet the needs of many operations to totally eliminate the pathogen rapidly from the soil. To date, there is still no disinfectant that is capable of meeting the needs of mining operations while overcoming economic and environmental concerns.

Systemic chemical treatments for *P. cinnamomi*. Spot infections (<1 ha) in the forest to be mined cause operational problems for the miners. In addition, new spot infections in the forest caused by mining and other forest users are a threat to adjacent uninfested forest. These spots may be as small as one or two individual plants. These infections offer the opportunity to use systemic fungicides to decrease these problems, minimize the risk of spreading the fungus, and conserve the trees and understory plants in the infested areas. The development of a method to contain or eradicate *P. cinnamomi* in such sites will help Alcoa meet its environmental objectives of minimizing the spread of the pathogen and also help financially by reducing costs associated with hygiene measures.

The phosphite (phosphonate) fungicides control many plant diseases caused by *Phytophthora*, even at concentrations in planta that only partially inhibit pathogen growth in vitro (20,21). They are unique among fungicides, in that they are translocated in both the xylem and the phloem (40). Phosphite treatment induces a strong and rapid defense response in the challenged plant (22). These defense responses stop pathogen spread in a large number of hosts. Phosphite has also been shown to inhibit in vitro sporulation of *Phytophthora* spp. at low concentrations (18). If resistance of plants to *Phytophthora* spp. is increased and the pathogen in the phosphite-treated tissue cannot reproduce, then potentially the pathogen could be eradicated from the treated areas.

In Western Australia, early work conducted by the Department of Conservation

and Land Management showed that phosphite could control *Phytophthora* spp. in *Banksia grandis*, *E. marginata*, and rare and endangered *Banksia* spp. (32,46). They applied the fungicide as trunk injection, foliar spray to runoff, and from aircraft as ultra-low-volume sprays. As a result of this early success, we initiated a number of studies to examine the potential of phosphite to control *P. cinnamomi* in native plant communities in and adjacent to mining. These studies aimed to determine if phosphite could prevent multiple deaths in a range of native plant species and could minimize the spread of *P. cinnamomi* from infested into uninfested areas. We are also examining whether long-term plant health and reproductive fitness, and mycorrhizal associations could be detrimentally influenced by phosphite.

The outcomes of these studies will provide us with a set of practicable and economic procedures for the application of phosphite under field conditions. These will include information on rate, frequency, and season of application, plus a description of the expected benefits.

To date, our research has shown that phosphite sprayed on plants can contain the spread of *P. cinnamomi* in many native shrubs from a range of susceptible families (41,58). The pathogen disappears from the "walled off" lesions over time. However, when plants are inoculated 6 to 18 months after being sprayed with phosphite, the effectiveness of the fungicide declines in some (G. E. St. J. Hardy, unpublished data). Consequently, it is likely that phosphite will need to be sprayed every 1 to 2 years.

In glasshouse studies (56) and in field studies (57), we have shown that phosphite, when applied as a foliar spray, does not prevent the pathogen from sporulating in diseased tissue. Zoospores from this tissue were able to infect *Pimelia ferruginea* cotyledons, indicating that zoospores are capable of causing disease—this is despite the pathogen being effectively contained within the plant. Treatment of infested sites may prevent deaths of plants but may not prevent the spread of inoculum downslope.

Preliminary work on ectomycorrhizal fungi (27) indicates that phosphite has no detrimental effects in vitro or in planta on these symbiotic associations.

Pollen tube development and seed viability are definitely affected in the short term by treatment with phosphite at recommended rates (0.5% a.i. foliar application to runoff; 20 to 40% a.i. ultra-low-volume foliar application) (16,17). However, the long-term effects still need to be determined, especially on annual species.

Biochemical studies have shown that phosphite induces host defense in jarrah (29). The effect on the pathogen was either direct or indirect, depending on whether the levels of phosphite were high or low in

Fig. 8. Time course of temperature in the soil at a range of depths below a windrow fire at Huntly.

the roots, respectively. This indicates that the phosphite concentration at the site of pathogen invasion influences the mode of phosphite action in controlling the pathogen in the host.

The phosphite research is continuing. The next major phase in the project is to develop practicable and efficient techniques to apply phosphite. Once these are developed, a range of infested sites will be treated as part of operational trials.

Control Measures

A detailed manual of dieback management procedures for each stage of mining was produced by the risk assessment team. This document is reviewed annually and is revised to take account of findings from the R&D program, feedback from the operators on how practicable the procedures are, and any changes in mining procedures. The procedures make use of the following strategic approach.

1. Know where the pathogen is present (Fig. 9A). Reliable, up-to-date maps and field demarcation of diseased sites are the backbone of the control measures. Before commencing mining at the new mine at Huntly, the presence of *P. cinnamomi* was mapped within the entire envelope (about 10,000 ha) using standard methods developed by the Department of Conservation and Land Management (51). These methods used the presence of PRCR symptoms and screening of plants and soil to establish PRCR boundaries in the field. Alcoa requires that the PRCR boundaries be rechecked within a 12-month period prior to a major mining operation in the forest. All the data on PRCR boundaries are stored on a Geographical Information System. This information is updated frequently to ensure that mine planners and environmental scientists have the best maps for their planning tasks.

2. Schedule high-risk operations during low-risk periods of the year. Appropriate scheduling of operations can greatly decrease the risk of spreading *P. cinnamomi*. The risk of infested soil adhering to vehicles and mine machinery is low when the soil is dry. High-risk operations can be scheduled for the hot, dry months from November to May. For example, haul roads are usually built during this dry soil period. This decreases the risk of inadvertently spreading infested soil on machinery and the risk of infested water draining into adjacent PRCR-free forest. Exploration drilling operations in PRCR-free forest also occur when the risk of tires moving soil is very low. Mining is a year-round operation, so only some stages and some areas can be scheduled for the low-risk period of the year. The control measure of scheduling high-risk operations during low-risk periods is seen as an extremely valuable tool. Therefore, detailed planning occurs to ensure that high-risk operations, and operations in areas where

the consequences of ineffective control are assessed to be high, are undertaken when the soil is dry.

Other planning issues are also addressed to reduce the risks of spreading the pathogen; these include: the location of roads, the duration that a minepit is left active, the sequence of mining a large minepit, and the location of stockpiles. The mine planner and mine environmental scientist work as a team to develop plans to ensure that mining is economic but the risk of spreading *P. cinnamomi* is low.

3. Restrict vehicle movement from PRCR-infested to PRCR-free areas (Fig. 9B). Success of the PRCR-free strategy is reliant on the PRCR-free areas remaining free of *P. cinnamomi*. The unknown presence of *P. cinnamomi* on a wet haul road has the potential to introduce *P. cinnamomi* to every PRCR-free area that vehicles visit. Controlling access to all PRCR-free areas is essential. This is achieved by blocking tracks so they cannot be used, using signs and bunting to limit access and inform users of access conditions, putting gates on all entry points to the mine, and constructing "bridges" across infested areas using gravel and rocks from uninfested sites.

4. Clean vehicles before entering PRCR-free areas (Fig. 9C). Operations occur in both PRCR and PRCR-free sites, so procedures need to be in place to minimize the risk of spreading infested soil across boundaries. Before any vehicle or mobile equipment moves from PRCR to PRCR-free sites, as much soil as possible needs to be removed. The most effective cleaning occurs in the workshop, so scheduling is optimized to exploit workshop cleaning. For example, after ripping an infested area, the bulldozer is transported back to the workshop, where it is cleaned. It is then sent to rip uninfested areas, and then it can move directly into an infested area. It is finally cleaned at the workshop again, ready for its next task.

Cleaning occurs at all stages of mining where vehicles are required to cross PRCR boundaries. Large trailer-mounted high-pressure water pumps are used in the field. Effective cleaning of vehicles in the field is difficult, so the need for this task is reduced as much as possible by detailed planning.

5. Don't mix infested and uninfested soils (Fig. 9D). The location of boundaries between infested and uninfested areas is known at all times during mining and is marked in the field. In some cases, the marked boundary needs to be moved further into the uninfested area for practical reasons, e.g., the PRCR area may be too small to enable a large mining vehicle to turn. However, this boundary change is marked in the field. The uninfested soil is moved and stored separately from the infested soil. All overburden and soil stockpiles are distinctively marked to show if they are overburden (OB) or topsoil (T)

and if they are infested (red) or uninfested (green).

6. Prevent water draining from infested to uninfested areas (Fig. 9E). Zoospores of *P. cinnamomi* are easily transported in water, so surface water

Fig. 9. (A) Painted trees in the forest show the disease boundary. (B) Access control gate at Huntly. (C) Cleaning the tires of a scraper before it drives into an uninfested area. (D) A sign to show that this stockpile is composed of uninfested (dieback-free) topsoil. (E) A bulldozer ripping a drainage slot adjacent to *Phytophthora* root and collar rot-free forest.

movement from infested to uninfested areas needs to be controlled. Surface water is never allowed to drain freely into the forest. Irrespective of the PRCR status of the water or forest, discharge is always controlled. The haul roads shed a lot of water. A system of drainage channels and high bunds prevents surface water from flowing directly into the forest. Instead, the water is directed into sumps. In the rehabilitated minepits, the ripping pattern directs all surface water back into the mine-pit, away from the forest. If an infested ore body site is located above an uninfested site, then the duricrust in the lowest part of the boundary is disrupted by ripping with a bulldozer or blasting. This “drainage slot,” as it is termed, intercepts and prevents water running into the forest downslope.

7. Train all field staff and planners. PRCR control measures for each stage of mining and rehabilitation were documented during the risk assessment team meetings. There is a strong commitment to implement these procedures because most managers and field supervisors were directly involved in their preparation. All operators are trained in the control procedures relevant to their duties. There is strong senior management commitment to the procedures, so any breach of the rules is regarded as important and requiring disciplinary action. Contractors are also trained in the procedures. Any breach by contractors could lead to the canceling of a contract.

Every 3 years, a major PRCR management audit is performed. Compliance with the critical procedures by operators, field supervisors, and planners is assessed. These audits have also identified opportunities to improve the procedures to increase their effectiveness or decrease the cost. Some procedures have been discontinued because the risk was assessed to be minimal for the high cost of the control procedure.

Effectiveness of PRCR Management

The economic cost of implementing PRCR management procedures at Huntly is difficult to calculate, but it is high—probably well over \$1.5 M US per year. Most costs are indirect and result from inefficiencies imposed at the mine planning stage and the need for extra staff and machines throughout the rest of the operations (9). So, the important question is “How effective are these PRCR management procedures?”

We identified the need for three monitoring projects to address this question. First, we needed to find out if *P. cinnamomi* was spreading from our operations into the adjacent uninfested forest. Secondly, we needed to find out if the soil stripped from uninfested forest sites remained uninfested throughout the various mining stages leading up to revegetation. Finally, we needed to quantify the area that

had been “rationalized” from uninfested to infested during the mining operations. Rationalization occurs when operational constraints prevent uninfested soils from being handled separately from infested soils, e.g., when a large scraper (articulated vehicle 24 m long) is unable to turn without driving across a PRCR boundary. Rationalization also occurs if there has been a breach in dieback management procedures and we believe the area is no longer free of *P. cinnamomi*. The opportunity is also taken during rehabilitation to spread uninfested soil over a larger area than it came from. In this case, we believe we have changed an infested area into an uninfested one.

In the first two projects, the success of monitoring was dependent on observing deaths of PRCR-susceptible species. These species are present in the forest and in rehabilitated minepits. Although fewer individuals are present in minepits, there are sufficient individuals to monitor. The third project was a desktop exercise. The location of the PRCR boundary is known before mining, and the location of the new PRCR boundary line in the minepit is known after mining. The minepit PRCR boundary line is determined by the location of the uninfested soil that is returned during rehabilitation.

Spread to uninfested forest. Determining the rate of spread of *P. cinnamomi* in the forest cannot be regarded as a direct measure of the effectiveness of PRCR management procedures. Infested soil could be transferred from mined areas into uninfested forest without the pathogen getting established and infecting susceptible plants. Instead, we use the results of this monitoring project as an indicator of effectiveness; if there were large areas of spread throughout the mine, then this would be a strong indicator that the procedures were ineffective. In the past, scientists and foresters predicted that the spread of *P. cinnamomi* from mining would be high; rates from 1 to 4 ha of spread for every hectare mined were proposed (53).

A 50-m-wide strip of forest abutting mining areas (includes minepits and roads) within uninfested forest was interpreted for the presence of PRCR symptoms. New infestations were marked in the field, their location surveyed, and the data transferred to Alcoa's Geographical Information System.

Field interpreters assessed 141 km of the boundary between uninfested forest and 1,950 ha of land cleared for mining operations. The total area of new infestations was 6.55 ha; this equates to 0.003 ha for every hectare cleared for mining. If the pathogen moves downslope from these new infestations, the area would increase to 28 ha; this equates to 0.014 ha for every hectare cleared for mining. The main causes of spread were thought to be water draining from stockpiles, transfer of infested soil during vehicle movement, and

drainage from mining and rehabilitated areas (11).

Spread within rehabilitated mined areas. If PRCR management procedures are effective, then uninfested soil removed before mining should be returned to the minepit during rehabilitation in the same uninfested condition. To test this, every 1-year-old rehabilitated area with uninfested soil was surveyed for dead or dying PRCR-susceptible plants. This age of vegetation was selected because the major susceptible plants are easily seen (15 to 50 cm tall), and their mortality tends to be highest at this age. The plants and soil surrounding the roots were screened in the laboratory for the presence of *P. cinnamomi*.

Of the 29 rehabilitated minepits monitored, only four were found to have *P. cinnamomi* present. We believe that this is an encouraging result, which indicates that, in most cases, the PRCR management procedures have been effective. Opportunities for improvement were also identified.

Rationalization of infested and uninfested areas. Three large areas at Huntly were selected for this study. The area of uninfested forest within the minepit boundaries before mining was calculated. This area was then compared with the area where uninfested soil was returned to the rehabilitated mined areas.

The area cleared for mining was 450 ha, of which 359 ha were dieback-free prior to mining. The total area of dieback-free rationalized to dieback within clearing was 13.6 ha. Most of this increase was caused by an error in soil handling procedures.

Conclusion. The results of all three monitoring projects indicate that the PRCR management procedures are effective. A major outcome of this work is the identification of opportunities to improve the procedures. These projects will be repeated every 3 years.

Outlook

The hard work has been done—the procedures are in place, and so far they appear to be successful. A period of refining the procedures is now underway. Expensive and impracticable procedures will be addressed to seek improvements and cost reduction. Instances of breaches to procedures and evidence of mining spreading the pathogen will be investigated. Many of these investigations will identify deficiencies in the present system, which may spawn new research projects. The most worthwhile feedback on opportunities for improvement will come from field supervisors and operators. Their concerns and frustration with PRCR control procedures need to be voiced, and there needs to be a response to assess their feedback. This is happening, and procedures have changed after reviewing concerns from field personnel.

The new challenge for mine management and environmental supervisors is to

maintain the impetus and commitment given to the PRCR management program. When introduced, the program was new, challenging, had ownership by field supervisors, prominent support from senior managers, and had won a prestigious environmental award from Alcoa's worldwide operations. New employees are now in field positions and in mine management. A team with a similar composition to the original one has been established to regularly review each procedure. This team provides the ideal forum for concerns to be raised and provides the miners with the opportunity to query us on the rationale for particular hygiene measures. This review procedure is designed to improve the procedures and to lift the ownership and commitment to a similar level as before.

The future is also a period of opportunity. Seed from seed orchards of PRCR-resistant clones of jarrah will be available soon. These can then be incorporated into the seed mix for revegetating PRCR-susceptible minepits. Alternatively, much of the seed may be more valuable in the program to revegetate forest areas where the impact of PRCR is very high. In these sites, it is difficult to regenerate a tree canopy using local tree seed; this resistant seed may help overcome this shortcoming.

Another focus area will be the development of production seed orchards of PRCR-resistant clones of jarrah. Jarrah flowers profusely only every 6 to 8 years in the wild (2). The challenge is to develop orchards that will produce abundant seed every year. Part of this research will focus on the basics of jarrah reproduction. Jarrah reproduction has never been studied in detail despite it being a species of high commercial value. Breeding individuals of higher PRCR resistance is also possible and will demand attention when the disease resistance mechanisms are better understood.

Phosphite is recognized to be one discovery that could significantly aid in the management of PRCR disease in Australia. Research has shown that it will increase the resistance of many plants to *P. cinnamomi*. The present need is to develop prescriptions to use phosphite in and around the mines. Its potential use to prevent sporulation in infected vegetation and hence decrease downhill spread may be optimistic, but in cases of very localized infections, it may be successful, and *P. cinnamomi* may become undetectable in these areas.

There are also opportunities to inform and educate other mining companies and all other companies or groups who access native vegetation communities that are susceptible to PRCR. This disease is widespread throughout the southwestern corner of Western Australia, and in the past, its management has been viewed as too difficult. Our success can be combined with recent successes of the Department of

Conservation and Land Management to show that something practical can be done to combat the disease.

We believe that the research direction in the future should be more focused to answer specific questions related to the sustainability of the rehabilitated mined areas, for example: "Why are there so few deaths of susceptible species in the rehabilitated areas?" and "Could predicted change to weather patterns, such as wetter summers, lead to higher mortality rates?" These questions are being addressed by examining the effect of summer drought stress on the pathogenicity of *P. cinnamomi*. It could be that low stem water potentials in summer enable 93% of infested jarrah seedlings to survive infection (38). The presence of a dense cover of native legumes around the trees may also inhibit *P. cinna-*

*mom*i when present in the soil. Previous research indicated that this could occur (43). We will test these hypotheses in the laboratory and in a large irrigated field trial.

Being responsive to the needs of the mine operations is critical to the success of the PRCR management program. The need for R&D projects will flow from the operations. The challenges are to identify the projects with a significant likelihood of success that make a significant contribution to environmental objectives when implemented. The impetus to continually improve the procedures will ensure that the R&D continues to keep us busy with stimulating work.

In conclusion, we have shown that it is possible for a large mining operation to manage and contain a devastating soil-

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Giles Hardy

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borne pathogen when mining and rehabilitating in a native forest environment. This has been made possible firstly, by taking an integrated approach to ensure our objectives are well defined, secondly, by actively involving practitioners and researchers in the development of management procedures to ensure that our R&D program is well targeted to the present and future needs of the operations. Finally, regular monitoring of the effectiveness of the procedures has allowed us to assess the benefits and identify opportunities for improvement.

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