Walking through a eucalypt forest, you expect to see the odd dead or sick-looking tree. But if you come upon a patch where most of the trees and understorey plants are dead or dying, you can be fairly sure that something is amiss.

A few patches like this were noticed in jarrah forest east of Perth in 1921 — the first indication of what came to be known as jarrah dieback disease. Now, less than 60 years later — a fraction of the lifetime of a jarrah tree — dieback has ravaged about 10% of the 1·8 million-ha forested portion of the south-west of Western Australia, and shows no sign of abating.

At first, the patches affected and the rate of spread were small, and there seemed little cause for concern. After World War II, however, it became clear that dieback was spreading at an increasing rate and that large areas of the forest were in danger.

Jarrah (*Eucalyptus marginata*) is a much sought-after hardwood. It is highly valued by furniture-makers, its resistance to white ants makes it a good flooring and house-frame timber, and jarrah railway sleepers have been exported since late last century to countries including the United Kingdom, India, and South Africa as well as being used widely in Australia. So, with the spread of dieback, concern grew at the threat to continued large-scale timber production.

A greater worry now is the possibility that dieback may spread widely in Perth's water supply catchments and cause unacceptable increases in the water's salt content (see *Ecos* 4). Of major concern from a conservation viewpoint is the fact that it is severely damaging a unique forest ecosystem. Much of the wildlife of the area occurs nowhere else, and the wildflowers are one of the West's main tourist attractions.

Mystery resolved

Up to the 1960s, the cause of jarrah dieback remained a mystery. In the absence of any sign of a pathogen, most speculation centred on the possibility that changes in the forest due to timber-getting — for example depletion of soil nutrients or raising of water tables — were doing the damage.

Then in 1962 Mr Frank Podger of the Forest Research Institute, now the CSIRO Division of Forest Research, noticed that trees were dying simultaneously in an area of jarrah forest and an adjacent shelter belt of pines on the Swan Coastal Plain. Professor Frank Newhook of the University of Auckland, New Zealand, had recently found that microscopic *Phytophthora* fungi were the cause of pine deaths in shelter belts in New Zealand, and Mr Podger found that the symptoms Professor Newhook described were identical with those in the Western Australian shelter belts. He surmised that *Phytophthora* might be killing both pine and jarrah.

This was soon confirmed. In 1964 Professor George Zentmyer, visiting Western Australia from the University of California, isolated a *Phytophthora* species implicated in many plant diseases, *P. cinnamomi*, from soil taken from an area of jarrah dieback. The following year, Mr Podger showed that the fungus could be introduced into the soil beneath healthy forest and then spread and cause dieback.

Since 1965, *P. cinnamomi* has been implicated in dieback problems in many parts of Australia. In Western Australia it is killing trees and other vegetation in the Stirling Range and Cape Le Grand National Parks as well as in the main south-western forest. In Victoria it is responsible for dieback in parts of Gippsland, the Brisbane Ranges, the Otways, the Grampians, and Wilsons Promontory National Park. It is causing dieback in some lowland forests in eastern Tasmania and in reserves south and east of Adelaide. It probably contributes to some forest dieback problems in New South Wales, and in central and northern Queensland it has recently been isolated from dead patches of rainforest.

Far and wide

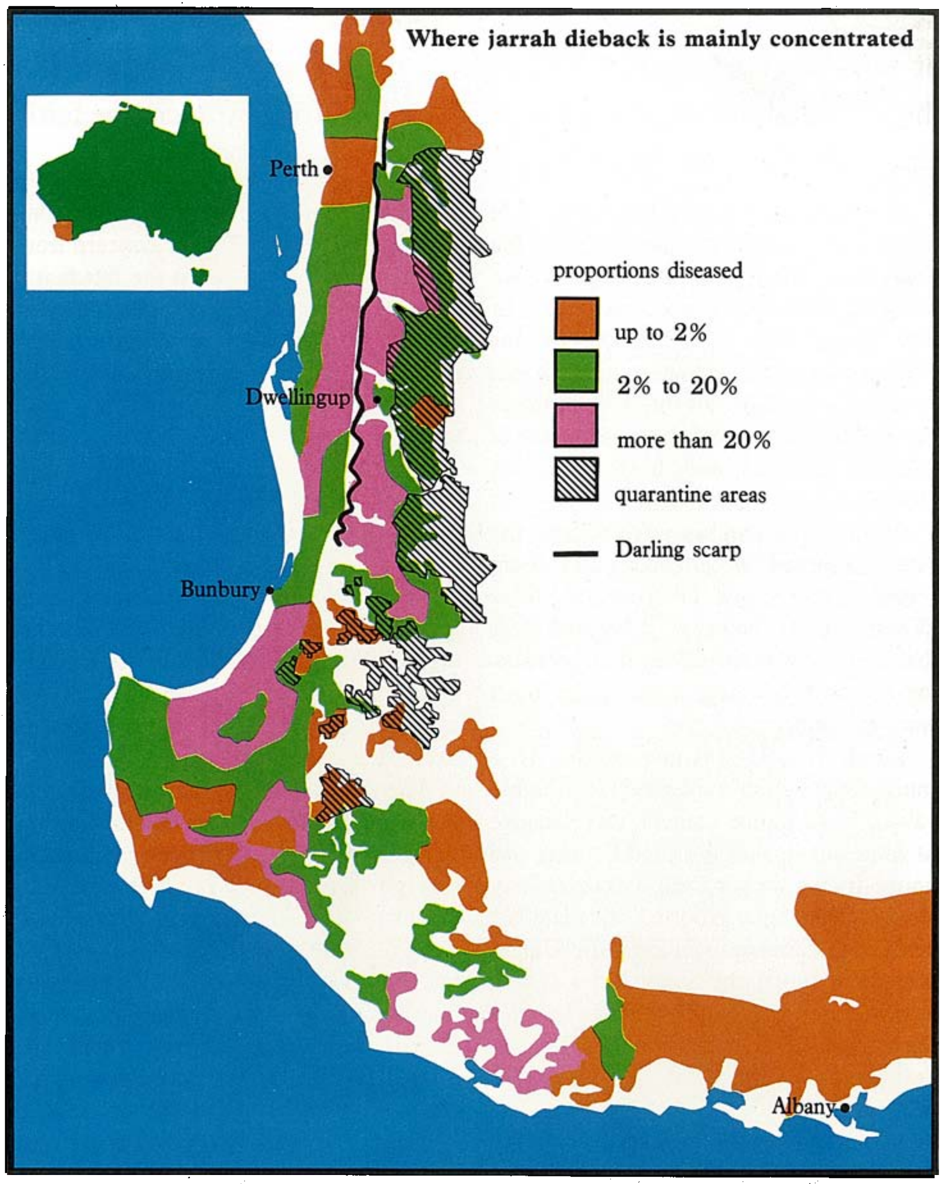
The fungus can also be a serious problem in heathlands, tree plantations, orchards, and gardens; in fact more than 400 plant species are now known to be susceptible

A destructive forest fungus

to it, including peach, plum, and avocado trees, in addition to forest species, and pineapples, azaleas, and camellias.

However, *P. cinnamomi* does not leave a trail of destruction wherever it goes. Between 1969 and 1972, Dr Bryan Pratt and Dr Bill Heather, of the Australian National University Forestry Department, in a joint project with Dr Jack Shepherd of the CSIRO Division of Plant Industry, tested thousands of soil samples collected mainly in the forest strip between Cairns and southern Tasmania. As well as finding the fungus in soils from dieback areas, they found it in soils from many areas of forest, notably near the New South Wales coast, that showed no sign of disease.

This fungus is far from the only cause of forest dieback in Australia.



Also, this fungus is far from the only cause of forest dieback in Australia. Others include *Armillaria* fungi (see the article on page 15), fungi that attack leaves, many types of insect, and tree parasites such as mistletoe. Some dieback problems have been attributed to attacks by a variety of organisms, and drought and fire can play important roles in increasing the susceptibility of trees and other forest plants. The causes of some diebacks remain unknown. Elsewhere in this issue we look at some serious dieback situations in Victoria and Tasmania for which *P. cinnamomi* cannot be blamed.

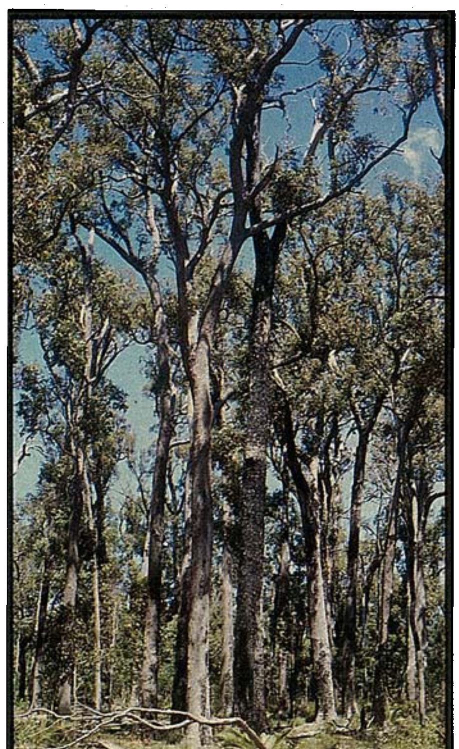
Although it is now known to be distributed widely around the world, *P. cinnamomi* was not discovered until 1922, when R.D. Rands found it attacking wild cinnamon in the mountains of western Sumatra. It was first identified in Australia 8 years later, as the cause of a pineapple disease in Queensland, and was first isolated in native Australian eucalypt forest in 1948, when Dr Lilian Fraser of the State Agriculture Department found it associated with some dead understorey plants in forest near Sydney.

Life of the fungus

The fact that it remained undiscovered for so long is scarcely surprising. Its dimensions are microscopic; the photos accompanying this article show it magnified many thousand times. Until the early 1960s when Dr Kheng Hoy Chee, a student of Professor Newhook's, developed a technique using lupin seedlings as baits, it was extremely difficult to detect.

Some details of its life in soil and roots, and of variation within the species, are still unknown and are being studied in Australia and other countries. Research by Dr Shepherd, for example, shows that populations of the fungus from different parts of this country differ widely in growth rate and in ability to reproduce sexually. The implications of these differences remain to be assessed.

Much evidence suggests that the fungus relies mainly on asexual reproduction to build its populations to destructive levels. Its asexual life cycle has a number of distinct stages. One stage, the chlamydospore, can apparently survive for considerable lengths of time in dead roots. When conditions in the soil are sufficiently wet and warm (above about 15° C), chlamydospores produce sporangia and tubular material known as mycelium, which in turn produces more



Healthy jarrah forest.

sporangia. When these ripen, they release another type of spore, the zoospore. Vast numbers of these are produced very rapidly when conditions are favourable.

Zoospores are attracted to roots by amino acids, sugars, and alcohols in chemicals that the roots exude. Then they produce mycelia that penetrate and destroy root cells, reducing the ability of the plants to take up water and nutrients.

Research in Australia and overseas shows that *P. cinnamomi* is generally most destructive when drought follows a period of warm wet weather. The warmth and moisture encourage rapid production of zoospores. Large-scale destruction of roots follows, and then the drought places the plants under stress that they cannot cope with because of their reduced root complement.

The destructiveness of the fungus varies greatly with soil conditions. In general, plants growing in poorly drained, infertile soil with a low organic matter content and small population of microorganisms are much more likely to succumb than their cousins growing in well-drained fertile soil. The fungus seems unable to survive in some soils. Several researchers, including Dr Patricia Broadbent and Professor Kenneth Baker, working with the New South Wales Department of Agriculture, Dr Dorothy Halsall of the CSIRO Division of Plant Industry, and Dr Nick Malajczuk of the Division of Land Resources Management, are trying to sort out the factors in these soils that limit the activity of *P. cinnamomi*. It is already clear that the size of the soil microorganism population is particularly important.

Only some succumb

Researchers are also trying to find out what makes some eucalypt trees and forest understorey plants much more susceptible to *Phytophthora* infection than others. Among eucalypts, stringybark species are usually particularly susceptible, for some unknown reason.

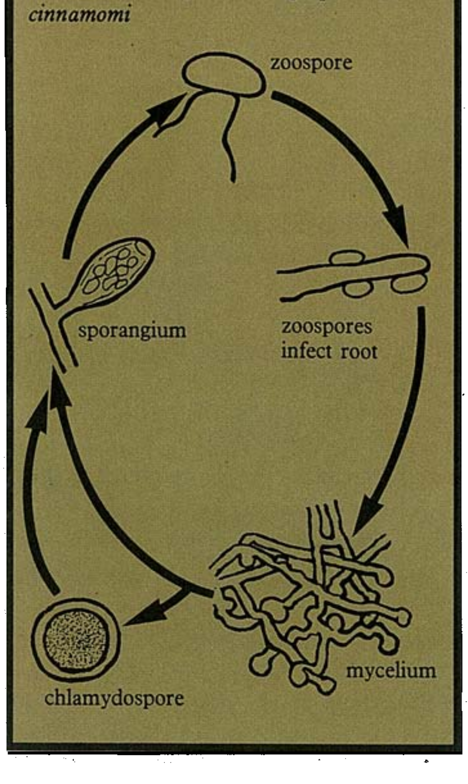
In Western Australia, the State hit hardest by the fungus, jarrah (a stringybark) is the only eucalypt being killed in large numbers. Marri (*E. calophylla*) trees, which are scattered throughout the jarrah forest, generally survive when the fungus moves through an area.

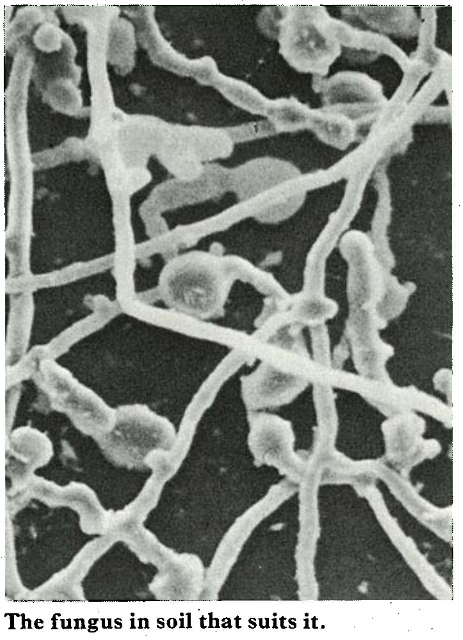
Experiments by Dr Malajczuk in Perth indicate that differences in microbe populations around roots of the two species in the forest soil, caused by differences in the chemicals the roots exude, make jarrah trees more susceptible than marri. He found that the species were equally susceptible when grown in the laboratory in microbe-free soil.

The roots of karri (*E. diversicolor*), after jarrah Western Australia's most important timber species, can also be attacked by the fungus. However, work at the Western Australian Regional Station of the Forest Research Institute by Dr Chris Palzer, who is now with the Tasmanian Forestry Commission, indicates that this fast-growing tree can replace lost roots rapidly enough to avoid obvious damage. Karri is largely restricted to about 140 000 hectares of the wettest and most fertile portion of the south-western forest.

Hosing down heavy vehicles is one of the 'hygiene' measures used to limit fungus spread.

Asexual life cycle of *Phytophthora cinnamomi*





The fungus in soil that suits it.

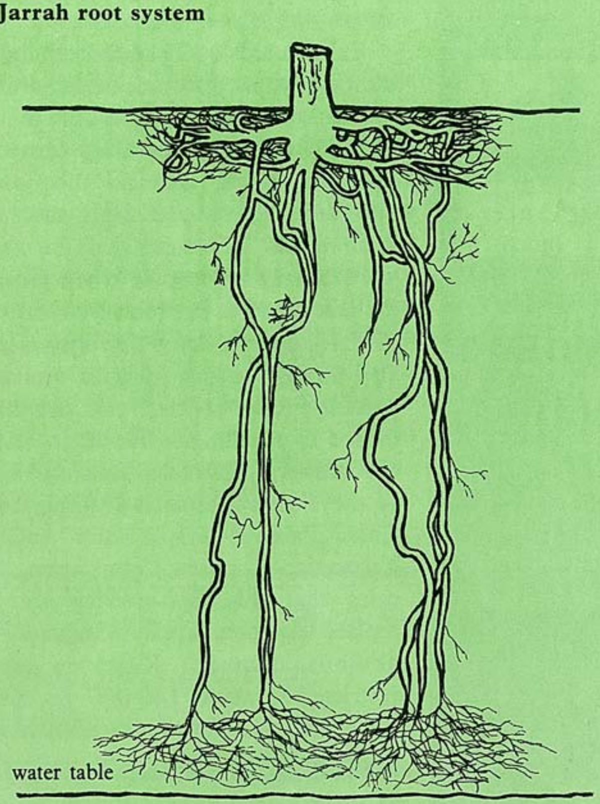
When conditions favour the fungus, both chlamydospores (the thick-walled resting spores) and mycelium produce sporangia. These release the zoospores that infect roots.

If only . . .

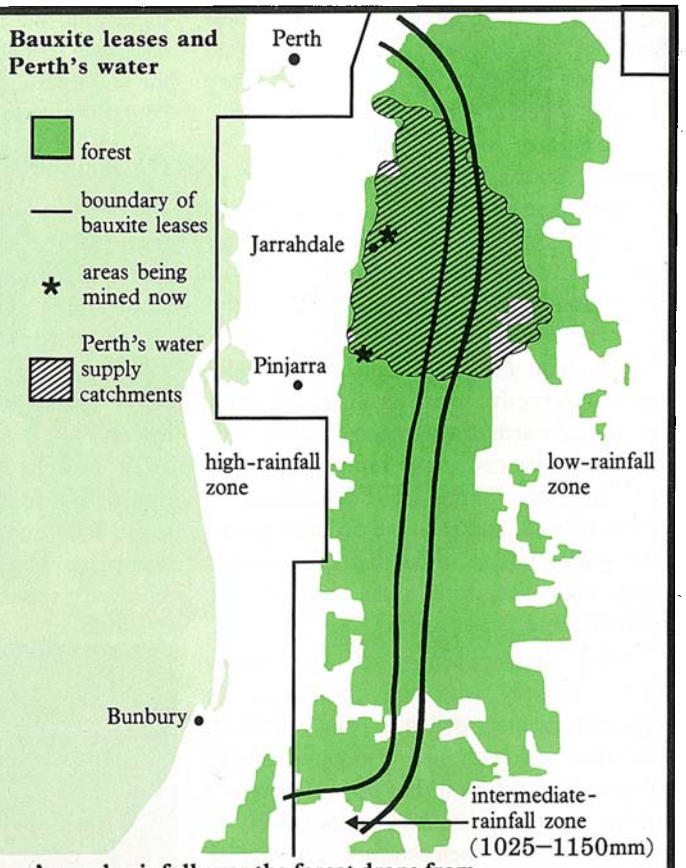
If *P. cinnamomi* had been identified as the cause of jarrah dieback in 1945 rather than in 1965, probably much less of the forest would be diseased now. Unfortunately there was no reason to guess, when bulldozers, low-loaders, and other heavy equipment were brought into the forest for road-making and logging operations after World War II, that these machines would spread dieback by moving soil infested with the fungus to healthy areas. Since 1965, the Western Australian Forests Department has introduced 'forest hygiene' measures aimed at stopping this man-made spread, including restrictions on the movement of machinery from diseased to healthy areas and thorough washing of the machinery when it has to be moved.

Observations indicate that, without human assistance, the fungus spreads slowly uphill — perhaps less than a metre a year on average. The main mechanism appears to be mycelial growth through the root systems of highly susceptible plants. Downhill spread can be much more rapid, as water flowing over and filtering through the soil carries zoospores with it.

The first sign that *Phytophthora* has arrived in an area of jarrah forest is the rapid death, usually in autumn, of most understorey plants, including wildflower species, banksias, blackboys (*Xanthorrhoea preissii*), and zamia palms (*Macrozamia riedlei*). Jarrah trees can also die quickly, especially when young.



Jarrah 'sinker' roots can penetrate to depths of at least 20 m to tap groundwater. The fine feeder roots are concentrated in about the top metre of soil.



Annual rainfall over the forest drops from about 1300 to 600 mm with distance east from the Darling scarp.

But sometimes they take many years to succumb, often after several attempts to regenerate by producing clumps of new foliage along bared branches.

The climate of the Western Australian south-west provides the conditions under which *P. cinnamomi* is most destructive. Most rain falls in the winter, and virtually none in the hottest months — December to March. Fungus populations can build up and attack susceptible roots when conditions are warm and wet in spring (sometimes in autumn as well). Then the weakened trees are faced with the stresses of the summer drought.

The last 2 years have been particularly dry, and forest plants (notably banksias) have been dying in much larger numbers than usual, giving the impression that dieback is leaping ahead. The real explanation is almost certainly the increased stress being placed on infected plants.

Deep roots

Healthy jarrah trees have a remarkable ability to tap underground water and continue growing during the hot dry months. In their first years, their growth is mainly downwards; only after their 'sinker' roots reach the water table do they begin vigorous tree development. Interestingly, it is mainly the trees' fine feeder roots near the surface rather than their deep water-gathering roots that *Phytophthora* attacks. Inability to take up nutrients may be the main direct cause of their decline.

The laterite soils in most parts of the jarrah forests are extremely infertile. But over a small proportion of the forest area, where rivers have cut through the laterite, rich red soils confer resistance to the fungus on the jarrah growing in them.

The areas of forest most at risk are valleys with poor soil. Measurements of soil moisture and temperature by Dr Syd Shea of the Forests Department show that, in these water-accumulating areas, conditions are conducive to *Phytophthora* infection for long periods in the spring, summer, and autumn. In higher areas, which are generally freely drained, consistent rainfall is needed to keep conditions suitable for spread of the fungus, and favourable temperature and moisture conditions usually coincide for relatively short periods, mainly in spring.

From the point of view of Perth's water supply, it is fortunate that the dieback is mainly concentrated in the wetter portion of the Range.

A wide distribution

Diseased areas are now scattered through most parts of the forest, but by far the worst-affected area is the western section of the Darling Range, within 8-12 km of the scarp (see the map). This higher-rainfall portion (annual rainfall drops sharply with distance east from the scarp, from about 1300 to 600 mm) has been the site of most road-making and timber-getting activity since World War II. Since 1963, it has also been the site of a growing bauxite-mining industry, which has contributed to the spread of dieback (see the box).

From the point of view of Perth's water supply, it is fortunate that the dieback is mainly concentrated in the wetter portion of the Range. Here, the main effect of removing forest vegetation is to increase the amount of water flowing into the reservoirs. This is a positive benefit in these times of water shortage.

Further east, however, as clearing for farming has shown in catchments south of those that supply Perth, removal of the forest can greatly increase the salt content

continued on page 8

Catchments in the 784 000 -ha region known as the Northern Jarrah Forest (see the map) provide all of Perth's water, except about 20% that comes from underground sources. This entire region, together with large areas around it, is covered by bauxite-mining leases held by Alcoa, Alwest, and Pacminex. So a potential conflict exists between mining and the maintenance of water quality. Removal of forest, the first step when mining operations begin in an area, increases the amount of water flowing into streams, but can also greatly increase its salinity.

Mining is going ahead now in water supply catchments near Jarrahdale and Pinjarra. These areas are in the high-rainfall western section of the forest, where clearing has little effect on stream salinity. But if operations move east — as expected some time in the future, probably within 20 years — some salinity increases seem inevitable. Clearly it will be important to be able to estimate potential effects before mining proceeds in any area.

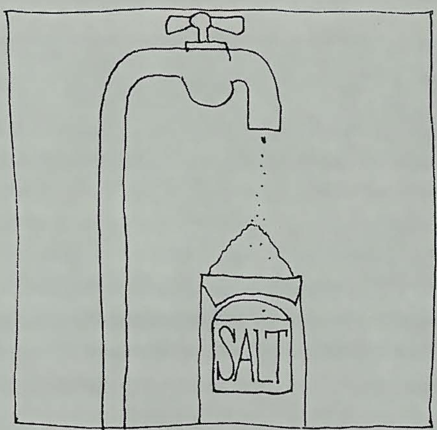
Experience in the existing mining areas has left the Western Australian Forests Department with no doubt that bauxite-mining contributes to the spread of dieback. The heavy equipment used for road-building around the mines and for mining and carting ore can move infested soil. Also, disruption of drainage by mining operations and the practice of watering roads to keep them serviceable in summer can create favourable conditions for the fungus. So the effects of dieback initiated by mining have to be added to those of the mining itself.

Unfortunately from the point of view of the impact of mining on the spread of dieback, most of the bauxite in the forest is on ridges and the upper parts of slopes. If the forest around a mining area becomes infected, drainage will carry the infection downslope. According to the Forests Department, a conservative estimate is that, for every hectare mined, three more will be devastated by dieback.

This ratio was adopted by Dr Adrian Peck of the CSIRO Division of Land Resources Management, Mr Bob Hewer of the Western Australian Public Works Department, and Mr Graham Slessar of Alcoa in a recently completed study of the link between mining and salinity. The scientists produced a mathematical model of the mining–salinity relation, and used it to estimate the effects of a possible mining operation in one of Perth's water supply catchments, that of the South Dandalup Dam near Dwellingup.

They assumed, in line with current practice, that trees would be planted in the pits after mining. They also assumed that, within 5 years of planting, these would be taking up as much water as the original forest; hence there would be a sudden increase in input to groundwater, followed by a decline over 5 years to the original level. The validity of this assumption depends to a large degree on whether the planted trees prove to have the same hydrological effect as the original jarrah.

The dieback downslope was assumed to gradually reduce the forest leaf area so the rate of groundwater input would increase to a maximum 10 years after mining began.



The scientists looked at what would happen if no attempt was made to reforest the dieback areas, and at the effects of a replanting effort that took a further 10 years to reduce the groundwater input to the level under the original forest.

To take account of the variation in groundwater salinity between different parts of the South Dandalup catchment, they divided the catchment into 10 zones. They estimated rates of movement of groundwater through the soil using existing data from bore tests. This movement is rather slow, and many years can pass before increased input shows up in the outflow of groundwater to streams.

The mining program assumed in the study involves steady increases in the areas affected until the year 2004, and then a rapid decline until mining stops in 2009. Mining is assumed to gradually move east as the bauxite in western areas is exhausted, and the maximum area mined in a year is taken as 352 ha. This program approximately follows current plans up to 1985, but beyond that is purely conceptual.

The scientists assumed that the growing quantities of bauxite expected to be treated at the Pinjarra alumina refinery would all come from the South Dandalup catchment. In practice, according to the mining companies, some of this bauxite will come from other catchments, and mining in the more-saline eastern areas will proceed at a much slower rate than assumed.

On the basis of the assumptions used, however, the model predicts that, if dieback areas are replanted, the average salinity of water flowing into the South Dandalup reservoir will rise from the present level of 185 mg per l to a maximum of 270 mg per l in about the year 2015. Then it will decline. Without replanting, the predicted maximum salinity, reached some time after 2025, is 330 mg per l. Significantly, all but about 10 mg of the increase comes, in both cases, from the effects of dieback.

Although the predicted salinities are well below the accepted limit for drinking water of 500 mg per l, they represent substantial increases that would restrict the possible use of South Dandalup water to dilute water from other reservoirs. The scientists advise caution in interpreting the results of the study, partly because of the lack of field data to test the accuracy of the method and also because of uncertainties in the input data and the degree of abstraction of the model. But the results clearly show the potential importance of dieback spread by bauxite-mining.

Simulation of the effects of bauxite-mining and dieback disease on river salinity. A.J. Peck, R.A. Hewer, and G.C. Slessar. *CSIRO (Australia) Division of Land Resources Management Technical Paper* No. 3, 1977, 1–18.

Stream and groundwater salinity levels in the South Dandalup catchment of Western Australia. S.R. Shea and A.B. Hatch. *Forests Department of Western Australia Research Paper* No. 22, 1976.

Managing jarrah forest catchments. S.R. Shea and E. Herbert. *Forest Focus* No. 19, 1977.

This sign is on a road leading into a quarantined portion of the jarrah forest.

of streams as well as increasing their flow. Already, in a few localized areas, clearing by dieback disease has caused streams to turn saline.

In a move partly aimed at preventing new *Phytophthora* infections in the eastern forest area, during the past 3 years the Western Australian government has placed about 500 000 ha in quarantine. Entry is permitted only in special circumstances. After 3 years, in which it is hoped no new infections will be initiated, the Forests Department plans to use close-up aerial photography to make a precise map of dieback distribution. The 3 years are expected to give all *Phytophthora* in the area time to make its presence visible in the plant cover. This will give the Department the best possible basis for devising control measures for particular areas.

Can it be stopped?

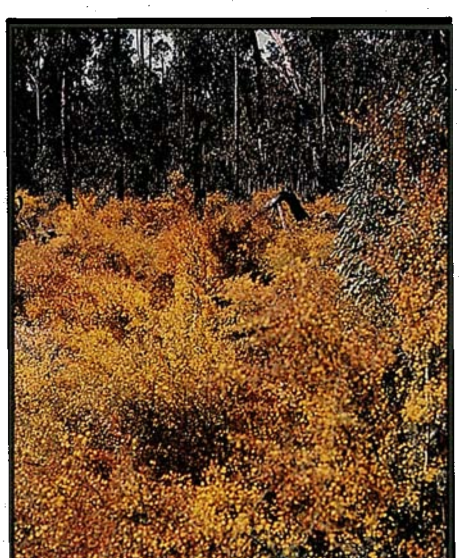
What are the prospects for control? Dr Shea estimates that, without stringent hygiene and quarantine, almost the entire forest could be affected by the fungus within 20 years. The measures being taken to minimize man-made spread should slow the process down significantly, but will not stop it.

If most of the jarrah forest is to have a long-term future, the march of dieback has to be stopped. Direct control methods, such as the use of fungicides, would almost certainly be uneconomic on the scale required, and are not being researched. Control by seeding the forest with microorganisms antagonistic to *Phytophthora* or with less-virulent strains of the fungus, if such strains exist or can be created, is another approach for which no great hopes are held, but which may be worth investigating further.

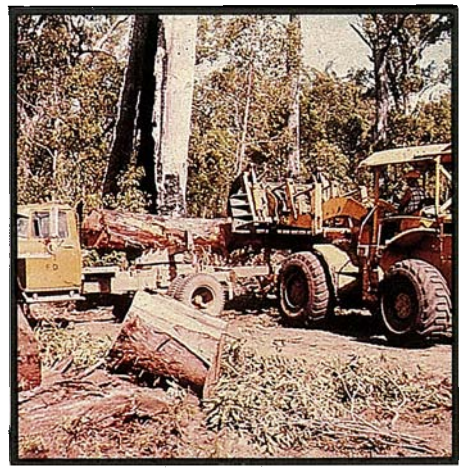
At the CSIRO Division of Forest Research in Perth, Mr Jan Titze has begun looking at the possibility that control could be achieved in some areas by adding lime to the forest soil. This follows observations by Dr Heather and Australian National University colleagues that the rate of spread of the fungus in lupin roots in nutrient culture is reduced in the presence of higher calcium levels. If useful results can be achieved with relatively small amounts of lime, it may prove feasible to use aerial spreading techniques over parts of the forest. Much research remains to be done on this possibility, and it is not regarded as better than a long shot.

In another set of experiments, Mr Titze is examining with Forests Department researchers the possibility of controlling the spread of dieback by planting casuarinas. He has found that some casuarina species appear to suppress activity of the fungus on the roots of susceptible plants growing nearby, probably by building up the soil microbe population. Casuarinas have other advantages — they add nitrogen to the soil, and

A bauxite-mine pit, with jarrah behind.



Acacia pulchella **gives a dense ground cover.**



Logging can spread *Phytophthora* infection.

some can be used for timber production. The scientists are testing species from Western Australia and the eastern States for suppressive ability and resistance to attack by the fungus.

Fighting fungus with fire

However, even if some casuarinas prove highly effective at protecting trees and shrubs around them, the fact that they would have to be planted must limit their potential usefulness. What is really wanted is an inexpensive means of altering the vegetation cover over large areas in a manner that makes soil conditions unfavourable for the fungus. The Forests Department, which initiated research on the possibility of controlling dieback by manipulating the understorey vegetation, has for some years been examining the feasibility of using fire as the manipulator.

Fire is a natural part of the jarrah forest environment, and the trees and smaller plants are adapted to survive it or regenerate rapidly after it. The Forests Department runs a prescribed-burning program, involving fires of low to moderate intensity every 5 to 7 years, to reduce the risk of summer wildfires by removing the litter layer (see *Ecos* 7).

Dr Shea and colleagues in the Forests Department are looking at the possibility of changing the managed-burning routine to produce a *Phytophthora*-inhibiting understorey.

A devastating bushfire in 1961 near Dwellingup, south-east of Perth in the heart of the jarrah forest, provided the inspiration for this research. After that fire, wattles and other legume shrubs regenerated over most of the burnt area, forming a dense and continuous understorey. Before it, they had been minor components of the understorey, and now have again become minor components. The area is included in the prescribed-burning program; among the plants that regenerate most profusely after these comparatively gentle fires is one that appears to play a major role in the spread of dieback, bull banksia (*Banksia grandis*).

The scientists are attempting to develop a burning regime that would favour regeneration of legumes and reduce the density of proteaceous plants such as banksias. Hopefully, this would prevent further spread of the fungus in the well-drained upland areas that make up most of the forest. Also, as legumes add nitrogen to the soil, an understorey containing large numbers of them may increase the vigour of the forest and possibly, as a result, increase the resistance of plants to *Phytophthora* attack.

Resistant legumes

Part of the reason for expecting that life would become much more difficult for the fungus is the likely greater density of a mainly legume shrub layer, resulting in lower soil temperatures. Probably more important is the fact that most of the legume species show strong resistance to attack by the fungus. Bull banksia, on the other hand, is highly susceptible. Its spreading matted roots, well suited to extracting nutrients from infertile soil, are eagerly attacked by *Phytophthora*. They provide the fungus with a food base that enables it to mass-produce the zoospores that spread dieback.

Many questions remain to be answered. One is whether seeds of legume species that would regenerate after hotter fires are present in the soil throughout the forest. An experimental hot fire set off by the Forests Department in March 1975 produced a dense legume cover, and this extended to some areas where nobody could remember having seen such species in the understorey. The Department has begun a project, involving hot burns at 10 sites scattered through the forest, to find out how widely the responsive seeds are distributed.

One piece of evidence suggests good prospects of finding them in most areas; where seeds are present, bulldozing the soil can bring up the legumes, and it is common to find them growing along newly made roads. If they are present throughout the forest, of course, the legumes must have been part of the forest understorey in all areas in the past.

Interestingly, Dr Shea has found that the present prescribed burns would provide enough heat to germinate seeds of one of the main legume species, *Acacia pulchella*, a prickly wattle, if the seeds stayed near the soil surface. But apparently most don't; in a clump of seedlings that Dr Shea examined, the average depth of germination was 4–6 cm. The highest concentration of seeds was in ants' nests. So it seems that seed-burying by ants may be the reason why hot fires are needed to bring up more than the odd specimen of this legume.

This photo shows the big impact soil type can have on the effects of *P. cinnamomi*. Both soils contain the fungus. The sapling in red kraznosem soil (left) appears healthy while that in grey soil from a Gippsland dieback site is dying.

After the March 1975 fire, forest animals rapidly ate back the legumes that came up. Hopefully, this would not happen if hot burns were conducted on a large scale, because the animals would then have much larger legume-covered areas to graze.

A protective effect

Replacement of an understorey dominated by banksias with one largely made up of legumes should reduce the ability of *P. cinnamomi* to survive and spread by greatly reducing the quantity of highly susceptible roots in the soil. Also, in laboratory tests some legumes, notably *A. pulchella*, have displayed an ability to actively protect susceptible plants from the fungus.

If most of the jarrah forest is to have a long-term future, the march of dieback has to be stopped.

Exactly how this happens is not known, but experiments by Dr Malajczuk indicate that the microbe populations around roots play an important role. He has found, for example, that the proportion of bacteria antagonistic to the fungus around the roots of *A. pulchella* far exceeds the proportion around bull banksia roots. Recent evidence suggests that chemicals exuded by the *Acacia* roots may also act against the fungus; Dr Shea has found in the laboratory that some chemicals extracted from these roots can suppress spore formation.

The amount of litter — fallen leaves, twigs, bark, and the like — on the forest floor also seems to influence the spread of *Phytophthora*. The litter has a cooling effect. In addition, Dr Malajczuk has found that jarrah trees readily develop mycorrhizal roots — associations of root and mycorrhizal fungi that form sheaths around the roots — in the litter layer but not in the lateritic soil, and that these roots show considerable resistance to *Phytophthora* attack.

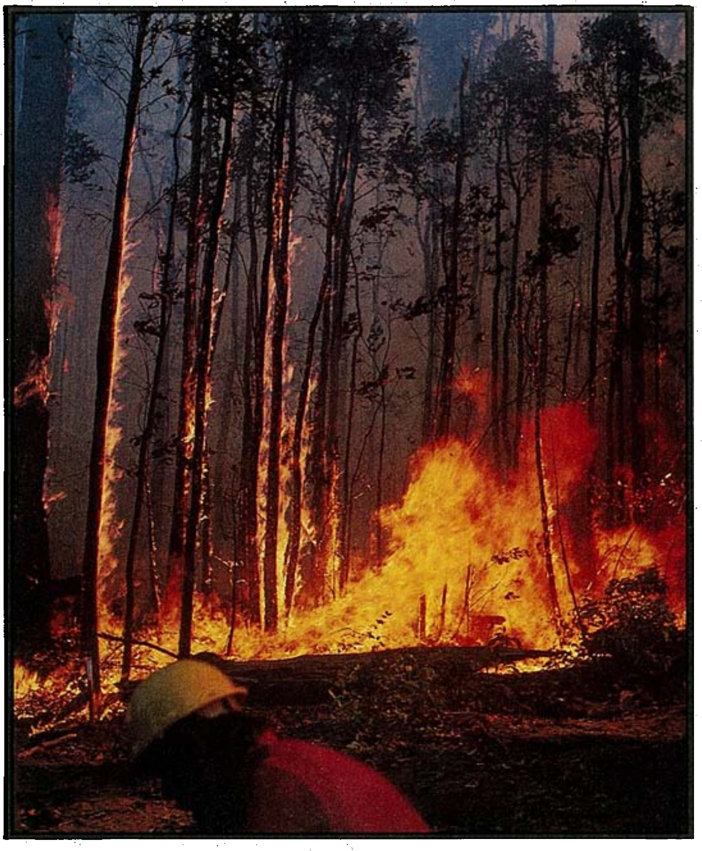
Any fire, mild or intense, removes the litter layer. If this layer is to build up further, the length of time between fires will have to be extended. If a program of hot burning were introduced, protection against *Phytophthora* might first be provided mainly by the legume understorey, and then increasingly, as the legumes died, by a growing litter layer.

But an obvious problem arises; how do you then protect the forest against wildfires? The present prescribed-burning program is designed to keep the litter at low levels, as this layer comprises the primary forest fuel. Encouragement of legumes adds to the wildfire problem; *A pulchella*, particularly, becomes highly flammable when it dries out.

So, if changes in the prescribed-burning program are introduced as a dieback-control measure, a greater wildfire risk may have to be accepted. Hopefully, it would prove possible to strike a balance that kept this risk at a low level and at the same time provided satisfactory suppression of *P. cinnamomi*.

Can it be done?

The Forests Department is conducting experiments in the forest to determine as precisely as possible how hot a fire has to be to produce strong legume regeneration, and what fuel quantities and conditions are needed to produce such a fire.



An experimental hot burn in jarrah forest.

Bossia ornata — one of the legumes that come up after hot fires.

A section of jarrah forest ravaged by dieback.

The effects of burning at high intensity on other forest plants, on animals and birds, and on timber production are also being examined.

The Department is also assessing the practical difficulties of carrying out hotter controlled burns. It is confident that these would prove manageable, but expects that the cost of the burning program would go up substantially. If a changed burning program is decided on, these experiments should make possible its rapid implementation.

Whether a change is made will depend on the results of all these experiments, and on field trials, which will have to continue for at least a few more years to find out how effectively it would suppress the fungus. Dr Shea and his colleagues are confident, on the basis of the results obtained in the laboratory, that some reduction in disease intensity would result. But whether the reduction would be significant in the long term remains to be determined.

If it fails

Use of fire to manipulate the forest understorey is certainly the most promising approach to date for control of jarrah dieback, but it will have to be validated in the field before it can be applied on a broad scale. If it fails and no satisfactory alternative is devised, the use of stringent hygiene and quarantine measures to stop man-made spread of the fungus will be the only approach open. These should have a big effect in reducing the spread of dieback, but they will not stop it.

If the quality of Perth's water is to be protected under those circumstances, resistant trees may need to be planted on dieback sites in the salt-prone areas of the forest. The planting program will have to keep pace with the spread of the disease.

The Forests Department has established plots of Western Australian and eastern States eucalypts to see how they perform in dieback areas. Many species have demonstrated an ability to grow on sites infested with the fungus, and the trials indicate that reforesting the moist valley areas where jarrah is most threatened should present little difficulty.

In upland areas, replacement trees will have to both survive on soils that are unfavourable for tree growth and emulate jarrah's ability to draw water from deep in the soil if salting of Perth's water supply is to be avoided. The leading contenders are wandoo (*E. wandoo*), which is found mainly in the dry eastern part of the Darling Range, and spotted gum (*E. maculata*) from New South Wales and southern Queensland. The areas where this tree is found include hot, dry, and infertile environments similar to those in the jarrah forest. It will be many years, however, before the trials show whether any species can, in fact, successfully replace jarrah is these areas, which make up about 80% of the forest.

Use of fire to manipulate the forest understorey is the most promising approach to date for control of jarrah dieback.

Victoria

After Western Australia, Victoria is the State most severely affected by forest dieback caused by *P. cinnamomi*. Mr Podger isolated the fungus from native forest in the Brisbane Ranges, 80 km west of Melbourne, in 1969. Shortly afterwards, Dr Geoff Marks and Mr Farook Kassaby, of the Victorian Forests Commission, isolated it from forest in Gippsland — about 30 years after small patches of dieback were first reported beside the Princes Highway near Nowa Nowa.

The fungus is now known to be widely scattered. Its main impact to date has been in the forests of East Gippsland, which supply about 40% of the sawn timber used in Victoria, and in the Brisbane Ranges.

In Gippsland, from Wilsons Promontory eastwards to the New South Wales border, Victorian Forests Commission soil surveys show that the fungus is most widespread in flat, poorly drained coastal forest extending to about 25 km inland. In adjoining foothill forest areas, uninfected sites showed up more frequently in the surveys, but the fungus was found in many areas. In mountain forests, the fungus was found only in machine-made clearings, drains, and log storage areas.

Almost all recorded dieback in the Gippsland forests has occurred on the coastal strip. However, there, as in the higher areas, Forests Commission scientists have found the fungus quite widely in areas showing no sign of disease. This contrasts with the situation in Western Australia, where it has not been found in any areas not showing dieback symptoms. Also, in the Brisbane Ranges and Wilsons Promontory, a Melbourne University School of Botany team led by Dr Gretna Weste has not be able to find it outside areas that are clearly affected.

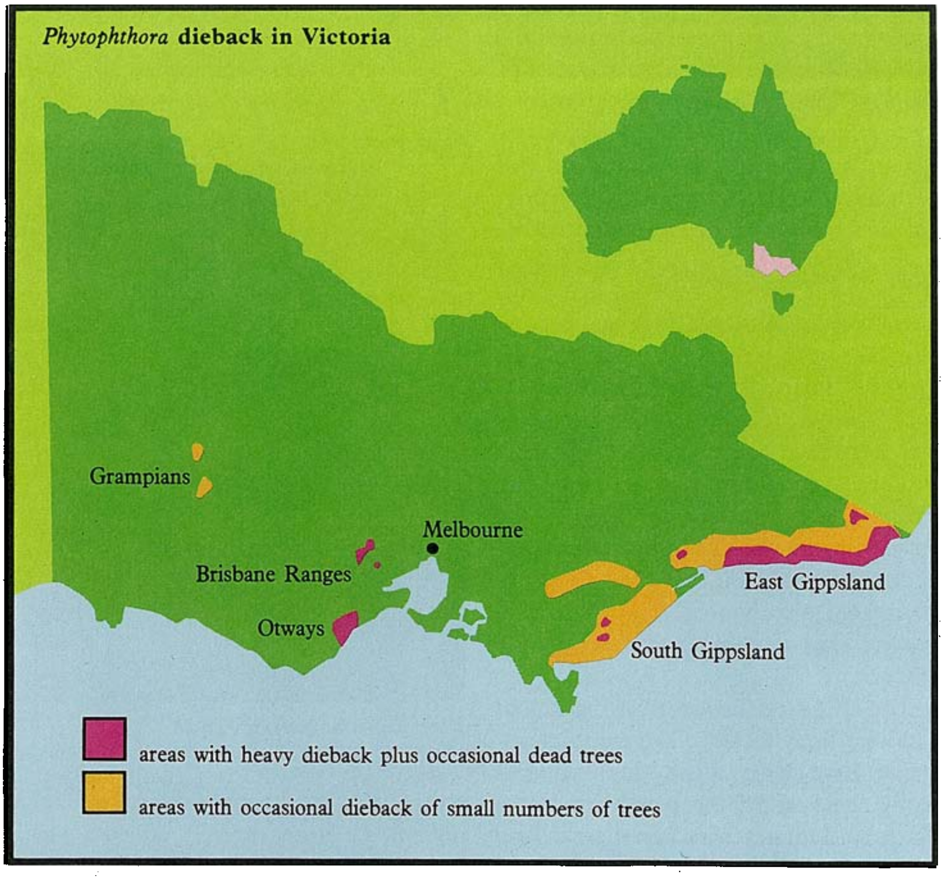
Area affected

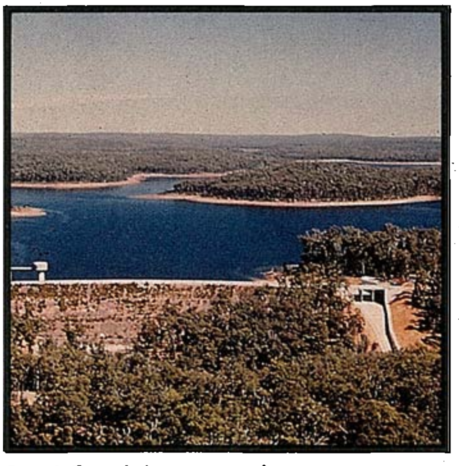
The Forests Commission estimates, from aerial and field surveys, that dieback has 'severely affected' about 5000 ha of forest in East Gippsland—east of Lakes Entrance. This description means that most trees within significant areas have died. The biggest individual patches of severe dieback cover about 50 ha. Areas of severe dieback also exist in South Gippsland — between Wilsons Promontory and Lakes Entrance. Both East and South Gippsland contain much larger areas described as 'moderately affected', where destruction of the forest has been less complete. Effects of fire, other diseases, and the forest's logging history make it difficult in some areas to work out just what impact the fungus has had.

The main timber species affected are silvertop ash (*Eucalyptus sieberi*) in East Gippsland and messmate stringybark (*E. obliqua*) and yellow stringybark (*E. muellerana*) in South Gippsland. All the tree species now dominant in these forests are susceptible to the fungus, and so is some of the understorey vegetation. In the most severely affected areas the damage is as complete as in the jarrah forest, but the range of effects is much greater in Gippsland — from virtually none to almost complete destruction.

In general, the Gippsland environment seems to be considerably less favourable for forest destruction by the fungus than the jarrah forest environment. As rainfall is more evenly distributed through the year in Gippsland, trees whose roots have been attacked by the fungus are less likely to have to cope with severe drought stress. But natural spread of infection appears to be very much faster than in Western Australia, occurring at all times of the year.

In 1952–53, 1956, 1966, and 1970–71, heavier-than-average summer rainfall produced conditions favouring the spread of dieback. Existing dieback areas grew, and scattered tree deaths were recorded in other areas. Conditions in 1970–71 were particularly severe because a very dry autumn followed the very wet summer, and dieback areas expanded by 10–15%. The Forests Commission has examined the weather records and concludes that conditions as favourable as those of 1970–71 are likely to occur infrequently. But reasonably favourable conditions will occur more often.





South Dandalup reservoir

Spread by machinery

The Commission has traced most of the Gippsland outbreaks to the use of *Phytophthora*-infested gravel in road-making, infested soil moved by heavy equipment, or movement of the fungus in drainage water. Since the fungus was implicated as the cause of the dieback, the Commission has introduced measures in the forests aimed at preventing soil being moved from infested to healthy areas, and it checks gravel pits for *Phytophthora* before using the gravel.

Research by Dr Weste shows that soil type is as important in Gippsland as in the jarrah forests in determining what impact *Phytophthora* will have. Its influence is particularly obvious in areas of coastal forest where patches of infertile, poorly drained, podzolic soil adjoin patches of more-fertile, better-drained soil. Although it is present in both soils, dieback is much more severe in the podzolic areas.

The Forests Commission estimates, on the basis of soil and drainage variations, that severe dieback could occur in perhaps 30 000–40 000 ha out of the total Gippsland coastal forest area of 800 000 ha. But the fungus appears capable of causing less-severe effects over considerably larger areas.

The hazard in the adjoining foothill forests is believed to be small, because the soils are comparatively fertile and well drained. The mountain forests, despite the susceptibility of mountain ash (*E. regnans*) to the fungus, should be still safer because the soils are cool, fertile, and rich in litter and hence in microbes.

Role of timber-getting

As in Western Australia, logging has contributed to the dieback problem with the spread of infested soil by heavy machinery. Selective removal of the best trees may also have contributed by removing portions of the forest canopy, raising soil moisture and temperature. Also in the early timber-getting days, the trees most in demand tended to be those — such as Gippsland grey box (*E. bosistoana*) — that are least susceptible to attack by the fungus.

The effects on the spread of dieback of a change from selective logging to clear-felling have been much discussed recently, because of the possibility that a woodchip industry based on clear-felling may be established.

The risk of dieback in the forest around an area being cleared may rise because of the possibility of fungus being spread on machinery and because the soil around the cleared area would probably become warmer and wetter. On the other hand, vigorous regenerating forest on the cleared area may keep the soil drier and cooler than it had been under the removed mixed-age forest, and as a result reduce the dieback risk. The size of either effect would probably vary greatly with soil types and other features of particular forest sites.

In the Eden woodchip area, just across the State border on the southern New South Wales coast, observations indicate that clear-felling has not so far caused the low incidence of dieback to increase. *P. cinnamomi* is present in the area, and scientists from the New South Wales Forestry Commission and the CSIRO Division of Plant Industry are attempting to assess, among other things, any effects of the fungus on regeneration there. This work may provide clues to possible effects of clear-felling in some Gippsland forest areas.

Approaches to control

Planting and seeding trials in Gippsland by the Victorian Forests Commission give ground for some optimism that, in contrast to the situation in the jarrah forest, the original species can be re-established

Dieback in South Gippsland.

on dieback sites there, although possibly not on the most severely affected sites. However, most of the trials began after 1971, and only time will tell whether re-establishment will succeed in the long run.

The Commission is trying out various combinations of endemic species, and different tree-establishment techniques, in these trials. It is also testing the possibility of lessening the impact of the fungus by using earth-moving operations to improve drainage in the soil.

In other experiments, Commission scientists are seeing whether genetic variability within species can be used to assist re-establishment of the original species on severely affected sites. Seeds from trees that have remained healthy-looking in dieback areas have been propagated in glasshouses, and the young plants tested for susceptibility to *Phytophthora* attack. The results indicate that genetic differences do make some plants more tolerant of the fungus than others. Trials to test this tolerance in the field have begun.

Recent work by Dr Marks and Mr Ian Smith of the Commission shows that, as in Western Australia, there is a possibility that hotter prescribed burns may help

As in Western Australia, logging has contributed to the dieback problem.

control the fungus by encouraging regeneration of acacias in the forest understorey. This work is at an earlier stage than the parallel research in Western Australia.

In pot trials, a wattle common in East Gippsland, *A. suaveolens*, has shown that it can protect silvertop ash from infection in the way that *A. pulchella* protects jarrah. The scientists are testing a number of *Acacia* species from eastern Victoria to see if others have this protective effect. They plan to examine whether establishing protective acacias with susceptible eucalypts on dieback sites would reduce the risk of further dieback.

Elsewhere in Victoria

The area in Victoria where the impact of *P. cinnamomi* most resembles jarrah dieback in the completeness of destruction of trees and understorey is the Brisbane Ranges. Conditions in these low hills are very favourable for dieback. The soil is generally poorly drained, and low in organic matter and hence in microbes antagonistic to the fungus. Autumn drought is common, and the eucalypts are susceptible slow-growing stringybarks.

Dieback has spread rapidly in the Brisbane Ranges since four small patches totalling less than half a hectare were noticed beside a gravel road in 1969. Dr Weste and Melbourne University colleagues are monitoring the spread, and have measured average extension rates of 171 m per year along ridges and 400 m per year along the path of drainage water. The origin of the disease has been identified as an infested gravel pit used in road-making.

In the Grampians, rocky ranges in western Victoria noted for their spectacular scenery and wildflowers, mapping by the Forests Commission again suggests an association between dieback and the use of infested gravel in road-making. The destruction in affected areas is not nearly as complete as in the Brisbane Ranges, but the plants that die include some of the most attractive wildflowers. Although individual areas affected are small, the disease is widely distributed and the dieback areas can be expected to grow. Forests Commission and University of Melbourne scientists have a joint study program to assess the problem.

The fungus may have been introduced to Wilsons Promontory National Park by vehicles brought in from South Gippsland in 1962 to help fight a bushfire. Dieback there is restricted to small areas in the north of the park. Although infertile, the

An ancient immigrant, or a newcomer?

Like the rabbit and many diseases, *Phytophthora cinnamomi* seems to have been spread around the world by European voyagers of the 17th, 18th, and 19th Centuries. The evidence indicates that it evolved somewhere in the islands north of Australia, and was carried to Africa, Europe, and North and South America along ocean trade routes from the Indonesian spice islands.

When did it arrive in Australia? This question has aroused considerable discussion among scientists working with the fungus. It is generally agreed that *P. cinnamomi* was introduced into Western Australia early this century, probably on plants imported from south-eastern Australia. But its origins in the other States are much less clear.

Some scientists have suggested that it might have been in eastern Australia a very long time. According to a hypothesis put forward by Dr Shepherd, the fungus originated in the New Guinea—Celebes area and crossed into Australia some 1–10 million years ago with rainforest flora. At that time a land bridge joined New Guinea and Queensland. He suggests that it spread down the east coast and, again with rainforest flora, entered Tasmania at a time when the island was linked with the mainland by land.

One factor supporting the hypothesis that the fungus has been around for a very long time is the distribution of its sexual types. Two types — described as A_1 and A_2 — exist, but the A_1 type is rarely found in parts of the world where the fungus is known to have been introduced. However, it is found quite commonly in Queensland and northern New South Wales.

Other supporting factors are the wide distribution of the fungus and the considerable genetic variation found between samples taken from different areas. Also there is evidence that the fungus may have influenced species distribution in some areas of native forest. For example, near Coffs Harbour, N.S.W., the susceptible blackbutt (*Eucalyptus pilularis*) is restricted to ridges where the environment is unfavourable for *P. cinnamomi*. Species on the lower slopes and in gullies, where the fungus is found, are more resistant.

Other scientists believe that *P. cinnamomi* has been introduced into eastern Australia since European settlement.

They point to the fact that highly susceptible species grow in many areas where the fungus can flourish, suggesting that it has not had a role there in determining where different species are found. The recent outbreaks of dieback show its capacity to make big changes in the composition of forest in parts of Victoria.

These scientists argue that, if the fungus had been around for a long time, we would not now be seeing patches of dieback spreading outwards from scattered areas of infection that can be traced to human activities.

From the evidence, which has only been touched on here, one might conclude that the fungus has been in New South Wales and Queensland since ancient times, and entered the southern States after European settlement. The problem with that theory is that there seems to be no good reason why it should have stopped its ancient southward progress at the New South Wales—Victoria border.

The question remains unresolved.

The role of *Phytophthora cinnamomi* in dieback diseases of Australian eucalypt forests. F.D. Podger. In 'Biology and Control of Soil-borne Plant Pathogens', ed. G.W. Bruehl. (The American Phytopathological Society: St. Paul, 1975.)

Phytophthora cinnamomi — an ancient immigrant to Australia. C.J. Shepherd. *Search*, 1975, **6**, 484–90.

soil is deep and well drained, and this limits the activity of the fungus.

The Melbourne University botanists have begun a long-term project to monitor the impact of dieback on tree species, wildflowers, and other plants in the Brisbane Ranges, the Grampians, and Wilsons Promontory, and in affected forest near Narbethong, north-east of Melbourne.

Around Australia

In other States, forest damage due to *P. cinnamomi* appears to be relatively minor. Dr Palzer of the Tasmanian Forestry Commission has shown the fungus to be the cause of some dieback in eastern Tasmania, but it is not responsible for more serious dieback problems elsewhere on the island. In New South Wales, it is present in some dieback areas, but seems to be rarely the principal cause of the problem.

Two years ago, P. cinnamomi *was found for the first time in patches of dieback in tropical rainforest in Australia.*

For example, it is widespread in Ourimbah State Forest, north of Sydney, and dieback is severe in some parts of the forest. However, there is no clear association between the fungus and the disease; Dr Luciano Gerrettson-Cornell of the New South Wales Forestry Commission has found it near healthy and unhealthy trees, and associated with dieback in susceptible tree species and also in species that tests have indicated are not susceptible.

He concludes that the fungus may contribute to the deterioration of trees first weakened by insects, particularly leaf-attacking psyllids, and by a shortage of water, but that it is not the primary cause of the problem.

Two years ago, *P. cinnamomi* was found for the first time in patches of dieback in tropical rainforest in Australia. The discovery came as a surprise, because earlier evidence suggested that rainforest was safe from attack. Near Coffs Harbour, N.S.W., the fungus had been found in rainforest, but without any sign of it causing disease. In southern Queensland and northern New South Wales, a number of attempts to find it in rainforest adjacent to heavily infected pineapple and avocado farms had failed.

Stringybark species are generally particularly susceptible, for some unknown reason.

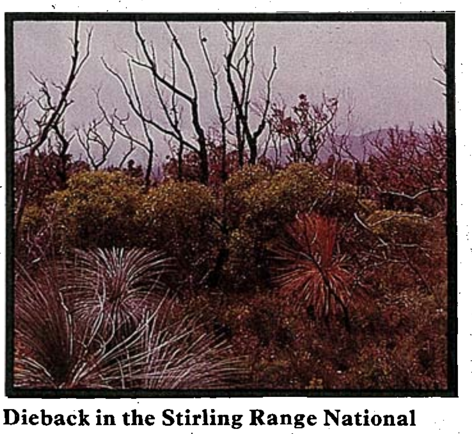
The dieback patches are in virgin and logged rainforest near Mackay and Ingham, in central and northern Queensland. It remains to be definitely proved that the fungus has caused them, but all the evidence points in that direction.

Observations by Mr Bruce Brown of the Queensland Forestry Department suggest that some of the dieback is due to fungus spread or activated by logging and road construction. But some patches are clearly not associated with these activities; Mr Brown suggests that wild pigs may have done the job in these patches that heavy machinery did in the others. Ridge-top dieback patches in the affected virgin rainforest in the Mackay area are on shallow, poorly drained sites, most of which contain pig wallows.

The apparent ability of *Phytophthora* to damage rainforest in these areas but not in some areas further south may be due to differing species composition or environment. The rainforests of eastern Australia vary greatly with latitude, elevation, and soil type. Possibly soil type alone caused the difference. Mr Brown and colleagues in the Forestry Department have begun experiments to find out more about the susceptibility of different rainforest types to the fungus and the importance of soil type, drainage, and so on. At present, it is impossible to predict whether substantial portions of Australia's rainforests may be at risk.

A recently infected area of jarrah forest. The banksias have died, but the trees still look healthy.

An attractive wildflower of the jarrah forest, *Hibbertia hypericoides*.



Dieback in the Stirling Range National Park.

More about the topic

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