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Decommissioning Western Australia's First Bauxite Mine: Co-evolving vegetation restoration techniques and targets

By Carl Grant and John Koch

What is the role of environmental research in developing better standards of practice and what is the best structure to facilitate improvement? Can lessons be learned from minesite restoration to improve our understanding about how ecosystems work?

Figure 1. John Koch (left) and Carl Grant in a 16-year-old rehabilitated area at Jarrahdale. The trees are Jarrah (*Eucalyptus marginata*).

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Introduction

Alcoa World Alumina Australia currently operates two bauxite mines in the Darling Range of south-western Western Australia, 80–140 km south of Perth (Figs 1 and 2). Huntly is the largest bauxite mine in the world, producing over 20 million tons of ore every year. The bauxite from the two mines is processed into alumina at three refineries at Kwinana, Pinjarra and Wagerup. The alumina is then shipped interstate and overseas for smelting to produce aluminium. The first of Alcoa's bauxite mines in Western Australia, however, was at Jarrahdale, where mining operations commenced in 1963 and continued until rehabilitation was completed in May 2001. The 4090-ha mine produced

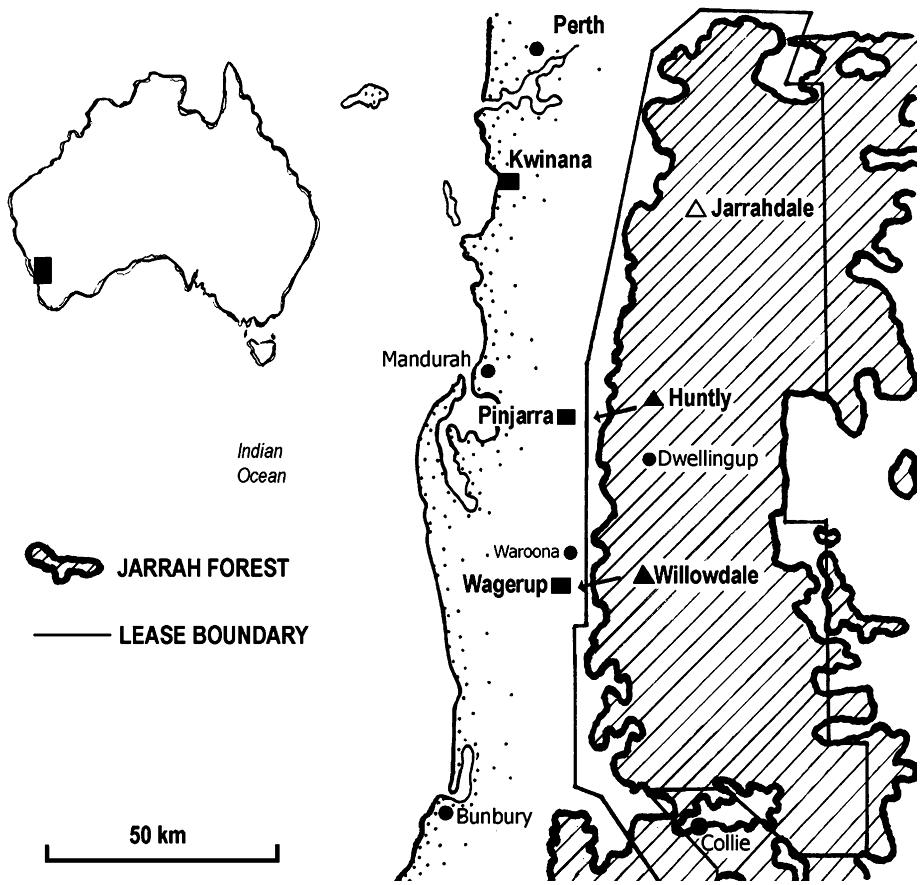

Figure 2. Alcoa's operations in Western Australia. The two operating mines are at Huntly and Willowdale. The Jarrahdale mine is now closed and rehabilitated.

some 168 million tons of bauxite from 1963 to late 1998 when the mine ceased production. Many of the key lessons in developing Alcoa's current rehabilitation methods were developed at Jarrahdale and it was the first mine in Western Australia that the company had closed and rehabilitated to pre-agreed standards (Grant 2006). Although the closure of Jarrahdale is seen as an end point, improvements in rehabilitation are ongoing at the two operating mines at Huntly and Willowdale.

The three mines are located in Jarrah (*Eucalyptus marginata*) forest (Box 1) within the South-western Botanical District, acknowledged as one of the biodiversity hotspots of the world. The high value placed on this ecosystem created additional expectations of high quality restoration. The published rehabilitation objective at Alcoa's WA bauxite mines is '. . . to establish a stable, self regenerating Jarrah forest ecosystem, planned to enhance or maintain water, timber, recreation, conservation and/or other nominated forest values'. Achieving such a broad objective to the level expected by society, however, required the evolution of increasingly stringent, specific targets and operating standards. This in turn depended on the constant evolution of improved restoration technologies, requiring significant levels of ecological research. This article focuses on the co-evolution of these techniques and targets, using lessons drawn from all three mines, with a focus on Jarrahdale, in addition to the ecological research that underpinned improvements in rehabilitation practices.

Background to Alcoa's mining operations

The Jarrah forest has high conservation value and is managed by the Western Australian State Government authorities for multiple uses including mining, forestry, biodiversity conservation and recreation. It has a diverse flora of more than 780 species (Bell & Heddle 1989) with an estimated 79% of species being endemic to the south-west region (Paczkowska & Chapman 2000) (see Box 1).

The bauxite ore is relatively shallow, averaging 4–5 m in depth, and is usually located less than 1 m below the soil surface. After timber harvest, mining involves clearing the remaining vegetation, removing the soil, blasting the cemented duricrust layer (which is part of the bauxite ore), removing and crushing the bauxite, and transporting it to the refineries. Like other open-cut mining operations, this means that the soil profile will necessarily be disturbed in the short term and changes occur in the surface geology and hydrology of the sites.

Environmental staffing and research links

The practice of mine rehabilitation and environmental management in natural ecosystems is a relatively new area of science. Particularly in Australia, much of the basic biological information required to restore native plants has been investigated only over the last three decades. For this reason, Alcoa has had its own research group since the 1970s. This in-house research capacity is unique in Western Australia and lends a high degree of integration of the outputs of research with operational practice. There are also significant benefits of information flow from practice back to research.

The research team has carried out short- and long-term mine environmental improvement research and direct consulting to the mine operations staff at the Jarrahdale, Huntly and Willowdale mines. Over time, the team has expanded to more than 10 researchers and acts as a central environmental research and advisory group to three other groups of environmental staff involved in Alcoa's mines. The other three groups comprise (i) on-site

Box 1. The biodiversity of the Jarrah forest

The Jarrah forest (Fig. 3) is part of the South-western Botanical District, recognized by Myers *et al*. (2000) as one of the biodiversity hotspots of the world and ranking alongside tropical rainforest for animal and plant diversity. Unlike the areas to the east and west of the forest, the Jarrah (*Eucalyptus marginata*)-dominated area is relatively intact because of its historical unsuitability for agriculture. The entire Jarrah forest is home to more than 780 native plant species. In the 80-m^2 sampling plots used in Alcoa's monitoring programs the mean number of native plant species range from 53 to 78.

Figure 3. Typical upland Jarrah forest vegetation.

The Jarrah forest is also home to at least 235 vertebrate species (excluding fish). Invertebrate diversity is unknown but studies of particular taxa indicate that total invertebrate diversity will be in the order of tens of thousands. Both Hemiptera (sucking bugs) and spiders have yielded more than 300 species each in relatively small sampling areas in the northern Jarrah forest (Brennan *et al*. 2003; Moir *et al*. 2005). Two-thirds of the species in these groups were undescribed taxa, which points to a large gap in our biodiversity knowledge. Fungi populations are also diverse, with molecular techniques identifying over 100 species in single study sites (Glen *et al*. 2006).

Vegetation

Structurally, the vegetation is defined as open forest dominated by Jarrah and Marri (*Corymbia calophylla*), with Sheoak, *Banksia* and *Persoonia* forming a small tree component. The shrub layer typically contains many Papilionaceae. Proteaceae, Myrtaceae and Mimosaceae. The ground layer consists of small shrubs and herbs predominantly from the families Anthericaceae, Dasypogonaceae, Leguminosae, Orchidaceae, Apiaceae, Epacridaceae, Asteraceae, Restionaceae and Cyperaceae. Because of the severe summer drought in this Mediterranean-type climate, there is a strong representation of geophytic species particularly in the Orchidaceae and Liliales.

environmental staff who oversee daily environmental and mine-rehabilitation issues and operations and who provide environmental training to production personnel; (ii) a central mine environmental operations group who carry out planning and liaise with government and statutory authorities; and (iii) the nursery operation staff who are responsible for seed collection and plant propagation for mine restoration. This adds up to more than 30 environmental staff within Alcoa's mining group.

The research department has also strengthened Alcoa's ability to create effective research partmentships with all five WA universities, the Botanic Gardens and Parks Authority (Kings Park), and CSIRO. Over 150 PhD, master's and honours projects have been carried out over the last 20 years, often partially funded by Australian Research Council grants.

Development of three-tiered hierarchy of objectives

Alcoa has a three-tiered hierarchy of objectives which cascade from broad completion criteria, through 'working

Box 2. Example of one of the 31 completion criteria for post-1988 rehabilitation

3. Early (from establishment to 5 years)

3.1 Sustainable growth and development

Criteria and intent	Guidelines for acceptance	Standard	Corrective action
3.1.1 Establishment of overstorey			
Are there appropriate numbers of both Jarrah and Marri to meet the multiple land uses?	Rehabilitated areas must have a stocking rate which will meet designated land uses. Alcoa must submit 9-month monitoring data to Department of Environment and Conservation (DEC) annually. DEC must review and advise Alcoa of acceptance or request corrective actions. Establishment of overstorey will be deemed acceptable unless DEC writes to Alcoa within 3 months of self-certification to advise otherwise.	The average number of stems per hectare based on 9-month establishment monitoring will meet the following standards: • Minimum: 600 Eucalypt stems per hectare; • Minimum: 150 Marri stems per hectare; • Maximum: 2500 Eucalypt stems per hectare (with the exception of haul roads and pits less than 2 ha); • Target: 1300 Eucalypt stems per hectare Vegetation establishment monitoring is undertaken as defined in the Alcoa/DEC working arrangements.	Rehabilitated areas that do not meet the minimum standard will be inspected by DEC and planted or seeded if required. Rehabilitated areas that do not meet the maximum standard will be inspected by DEC and thinned to reduce tree density back to the identified acceptable range if required.

arrangements' to specific internal targets. Completion criteria are the most generic level of formal performance indicators expected to be achieved by Alcoa before a mine can be decommissioned to state government standards. They were developed during the life of the Jarrahdale mine in collaboration with the state agencies ultimately, responsible for the site. Effectively, these represent milestones in the biophysical processes of rehabilitation that provide confidence that a rehabilitated mine site will eventually reach the desired objective. Rehabilitation could be considered successful when the site can be managed for its designated land use without any greater management inputs than other land in the area being used for a similar purpose.

Completion criteria cover a range of environmental issues including water catchment protection, minimizing the spread of *Phytophthora* dieback disease, re-instating timber productivity, return of flora and fauna diversity, and minimizing impacts on neighbours and local communities (such as access to forest). Specifically relating to vegetation reinstatement, there are five broad principles for completion criteria; namely, that the areas meet land-use objectives, are integrated into the landscape, exhibit sustained growth and development, contain resilient Jarrah forest species, and can be integrated with existing forest management strategies. These criteria are assessed under five time categories (from planning to >15-year-old rehabilitation), with intent, guidelines for acceptance, accepted standard and corrective actions identified for each criterion. (See an example in Box 2.)

As completion criteria are generic statements, more specific objectives cascading to measurable targets are needed to facilitate and maintain improvements in rehabilitation performance. The first Alcoa-CALM working arrangements were written in 1979. 'Working

Arrangements', are more detailed and stringent and are developed by Alcoa in consultation with the Department of Environment and Conservation (DEC, formerly Conservation and Land Management, CALM), the Water Corporation and the Department of Water – the State agencies ultimately responsible for managing the site. Sitting under those working arrangements are the internal 'targets' that are often more stringent than the working arrangements. At the most applied level, machine operators are trained using written internal procedures and training packages.

An example of one of the 31 completion criteria is the establishment of overstorey. The completion criterion is that rehabilitation areas must have 600–2500 stems per hectare. In this case, the working arrangement standard and the internal target is the same. Other examples of criteria standards and targets are shown in Table 1.

This hierarchy allows Alcoa to focus on the achievement of internal procedures and targets, which will then ensure the achievement of the working arrangements, and ultimately, the completion criteria. This arrangement also ensures that the rehabilitation standard is higher than legislative requirements that may develop in the foreseeable future. We can therefore anticipate and influence higher standards across the broader industry rather than wait for changes to be imposed. Specific examples of recent internal improvement targets are:

1 to rip 80% or more of all pit floor areas to 1.5 m or deeper;

2 to achieve (by 2000) an equivalent species richness of indigenous plant species found in representative Jarrah forest sites in 15-month-old rehabilitation, with at least 20% of these from the recalcitrant species priority list; and

3 to reduce the spread of *Phytophthora* dieback caused by Alcoa's mining to less than 0.003 hectares per hectare of area mined.

This hierarchy of standards provides a framework for gradually improving implementation techniques, informed by research and monitoring.

Senior management must support all objectives and targets, both financially and by openly promoting them to the workforce. The company's senior management is aware of the importance of environmental issues and provide strong leadership in this area. The mine rehabilitation objective is well known to all levels of management in Alcoa's mining group.

There is a two-way relationship between evolving standards and evolving techniques. That is, high targets could not be devised unless feasible techniques could be developed. Similarly, improved techniques could not be driven without high targets.

Rehabilitation implementation – evolving treatments

There is a two-way relationship between evolving standards and evolving techniques – and both are informed by interactions between research and practice. That is, high targets could not be devised unless feasible techniques could be developed. Similarly, improved techniques could not be driven without high targets. An example is the development of a tissue culture laboratory that produces over 100 000 plants each year for the purpose of meeting the target of 100% species richness, including the 20% of species that are 'recalcitrant'. High targets and advanced techniques are therefore synergistic and creatively interact, enabled by strong links between research and practice.

Rehabilitation before 1988

Restoration standards and techniques have improved over time (Table 2). For example, when rehabilitation of mined areas at Jarrahdale commenced in 1966, the expectation for minesite restoration were typical of the era. Early prescriptions involved planting exotic pine trees with little site preparation. Later (up to 1988), non-native eucalypt species were used in most areas, because of the unknown impact that dieback caused by *Phytophthora cinnamomi* was going to have on the susceptible forest dominant Jarrah (Box 3).

Research conducted through the 1980s, however, indicated that Jarrah would survive well in rehabilitated areas even if the soil contained the dieback fungus (Colquhoun & Hardy 2000). As a result, only native overstorey species, including Jarrah, have been used in rehabilitation since 1988. This important change in the composition of the overstorey has led to the splitting of rehabilitation into the pre- and post-1988 eras, with different completion criteria used for each era. Similarly, technologies for topsoil return and direct seeding were in their infancy in the 1960s and it was not until 1975 that it was recognized that the potential to reinstate the forest would be enhanced by using the seed and nutrient resources of the existing forest (Box 4). Restoration prescriptions also began to include deep ripping and improved landscaping of pits, return of topsoil and ultimately seeding of an understorey. A process of adaptive management led to improvements over time that influenced the quality of restoration at Jarrahdale and elsewhere in Australia.

Rehabilitation after 1988

All rehabilitation completed since 1988 has been undertaken as per a continually updated Alcoa/DEC prescription, based on feedback from research and

Table 1. Examples of agreed completion criteria standards and the related working arrangement and internal targets. These all fall under the mine rehabilitation objective

Measure	Ripping	Plant species richness	Coarse woody debris replaced as fauna habitat
Completion criteria standard	No uncontrolled water runoff or unacceptable soil erosion.	Minimum of 60% of forest controls based on 15-month monitoring.	Rehabilitation will include one constructed habitat per 2 ha.
DEC/Alcoa working arrangements	Areas must be ripped to at least 1.2 m with the winged tine.	No standard	Constructed fauna habitats should be returned at a minimum of one per 2 ha.
Alcoa internal target or standard	Eighty per cent or more of all pit floor areas will be deep ripped to 1.5 m or deeper	The average number of indigenous plant species in 15-month-old rehabilitation is 100% of the number found in representative Jarrah forest sites, with at least 20% of these from the recalcitrant species priority list (for areas rehabilitated in 2000).	Constructed fauna habitats will be returned at a minimum of one per hectare.

Table 2. History of rehabilitation at Alcoa's Darling Range Bauxite mines. The Department of Conservation and Land Management (CALM) became the Department of Environment and Conservation (DEC) in 2006

1963	Mining operations begin at Jarrahdale.
1966	First rehabilitation. Plantations of pines, cypress and eastern Australian eucalypts returned with minimal landscaping, topsoil returned but no ripping of compacted pit floors.
1971–1972	Development of ripping of mined areas to break up soil compaction, and fertilizer applied after planting. Del Park Mine established to supply the newly commissioned Pinjarra refinery.
1975	First experiments on direct return of topsoil and double stripping at Jarrahdale. High plant diversity achieved with these techniques.
1976	First use of understorey seed in restored areas. Mostly Acacias and other indigenous legume species.
1978	Double stripping and direct return of topsoil became operational practice. Jarrah and other WA eucalypts introduced into tree mixes. Wagerup ERMP approved which included a new mine at Willowdale.
1979	First formal restoration prescription agreed with CALM.
1984	Introduction of winged tine for deep ripping. Willowdale mine begins production to supply ore to the Wagerup refinery.
1985	Restoration understorey seed mixes made more diverse by including non-legume shrub and herb species.
1986	First use of helicopter for broadcast fertilizer application.
1988	Eucalypts direct seeded in restoration.
1989	Jarrah and Marri the dominant eucalypt species directly seeded into restored areas.
1990	Alcoa's mine restoration recognized by the United Nations Environment Program and included on the Global 500 Roll of Honour.
1991	Trees and understorey include only indigenous, local species with defined provenance zones for seed collection. Target of 80% plant species richness set for mine restoration.
1992	Marrinup Nursery Tissue Culture Laboratory started production of recalcitrant plants for mine restoration and dieback-resistant Jarrah.
1994	Field trials commenced on vegetatively propagated understorey plant species.
1995	Use of Predicted Species Index model for restoration planning.
1996	Seed of all smoke responsive species is treated. Experiments showed that smoke treatment of topsoil was not necessary. Target of 100% plant species richness is set for mine restoration.
1997	Soil screening trials start and the benefits demonstrated. This removed gravel and concentrated the amount of seed in topsoil to be used in restoration of mined areas.
1998	Jarrahdale mine closure and final restoration program begins. Planting recalcitrant species begins at operational scale. Post-1988 rehabilitation completion criteria are signed-off.
1999	Soil screening implemented at Jarrahdale, air seeder machine developed. Dieback-resistant Jarrah seed orchards established.
2000	Adjustments to eucalypt and legume seeding rates. Orion crusher region facilities established at Willowdale Mine incorporated some water harvesting initiatives into site design.
2001	Soil fractionation trials start; this involved passing screened topsoil through an air stream to further concentrate seed. Screened soil from Huntly used at Jarrahdale which gave high botanical richness at Jarrahdale. Jarrahdale restoration completed. One hundred per cent forest plant species richness target reached.
2002	Thinning and burning trials established. Pre-1988 completion criteria agreed with CALM. Alcoa wins third Golden Gecko award from the WA State Government for environmental excellence in mining.
2003	Maximum eucalypt target densities set. Alcoa receives model project award from Society for Ecological Restoration International for leadership in restoration.
2004	New McCoy mine operations facility commissioned at Huntly Mine. Design of facility focused on water conservation, minimal disturbance footprint, hydrocarbon management and decommisioning.
2005	Multi-tine contour ripping and deep preripping of pit floor implemented. Alcoa Marrinup nursery wins Australian Garden Industry State award for environmental excellence. Alcoa sets up trial with Simcoa to take excess wood residue from cleared areas. Alcoa receives the first certificate of acceptance from CALM for 975 ha of restoration at Jarrahdale.

Box 3. *Phytophthora* dieback

Phytophthora dieback is caused by a microscopic soil pathogen (*Phytophthora cinnamomi*) that was introduced to the state in the late 19th or early 20th century probably from infected fruit trees. *Phytophthora* attacks the roots of plants and kills about 40% of the native Jarrah forest plant species including Jarrah and grasstrees (*Xanthorrhoea* spp., see Fig. 4). In 1978, a technical committee appointed by the Western Australian State Government predicted that bauxite mining in the Jarrah forest would spread the dieback pathogen to between 1 and 4 ha of uninfested forest for every hectare that was cleared for mining (Technical Advisory Group 1978).

Figure 4. Jarrah forest infected by the Jarrah dieback disease, *Phytophthora cinnamomi*.

For Alcoa's mining operations, a dieback management manual was written that specified strict protocols to be used in all phases of the operations from premining vegetation surveys and bauxite exploration through to the final stages of rehabilitation (Colquhoun & Hardy 2000). The principles of disease control were: mapping where the pathogen is present; restricting vehicle movement from infested to uninfested areas; cleaning vehicles before entering uninfested areas; preventing infested and uninfested soils mixing during handling and stockpiling; preventing water draining from infested to uninfested areas; training all field staff and planners; monitoring the spread of the disease attributable to mining; and investigating the causes.

The Technical Advisory Group's 1978 estimate of the area of *Phytophthora* dieback that bauxite mining would spread was not based on any measurements. Over the years, Alcoa applied a range of disease management procedures to its operations and experience showed that rates of spread were much lower than the predicted figure. An intensive, quantitative and transparent measuring system was developed to determine an accurate figure for this spread. The first measurement of spread rate gave a figure of 0.003 ha per hectare cleared for mining. A target was then set to ensure spread rates remained below this figure. Subsequent monitoring programs using this measuring technique have determined that the rate of spread due to mining is 0.0006–0.007 ha of spread per hectare cleared for mining. These monitoring results show that Alcoa's intensive dieback management system is working and that rates of spread due to mining are very low. In most cases the monitoring also allows the causes of any spread to be identified and then these can be rectified which leads to continual improvement.

improved operational activities. Specific areas of research where improvements have been made include: improved fertilizer regimes (Koch *et al*. 1988); improved topsoil handling techniques (Koch *et al*. 1996); improved fire management (Grant *et al*. 1998); improved *Phytophthora* management (Colquhoun & Hardy 2000); increased richness of understorey plants due to improved dormancy-breaking and propagation techniques (Mullins & Koch 2001); reduced seeding rates to avoid dominance by *Acacia* spp. (Koch & Ward 2005); improved recolonization by invertebrates and other fauna (Moir *et al*. 2005); and improved deep ripping treatments (Mengler *et al*. 2006). As a result, a set

Box 4. Using pre-existing forest resilience to achieve restoration

Jarrah forest restoration techniques are informed by ecological knowledge about the resilience responses of individual species to natural disturbances.

Jarrah forest species, like fire-adapted species throughout Australia, tend to fall into one of three groups in terms of their capacity to recover after large disturbances that damage the above-ground vegetation. Species in the first group have a capacity to resprout from rootstocks and canopy stored seed (Jarrah for example); the second group are 'obligate seeders' as they do not store seed in the canopy or resprout but can recover by germination from soil-stored seed (many species of *Acacia*); while a third group, 'obligate resprouters', recover mainly by resprouting and produce little or no viable seeds (many rushes and sedges). Species from this last group are also called 'recalcitrant' by Alcoa.

These differences between the species groups meant that three approaches to restoration were needed: (i) stripping and direct return of topsoil (which would capture many of the geosporous species); (ii) pre-clearing collection of seeds of serotinous and some geosporous species and subsequent direct sowing of these seeds onto the returned topsoil; and (iii) vegetative propagation and greenstock planting of the 'recalcitrant' species.

Topsoil stripping, storage and replacement commenced at Jarrahdale in 1975 (Tacey & Glossop 1980). Unmined topsoil was found to have a natural seedbank of several hundred seeds per square metre (Ward *et al*. 1997). The number and density of native species regenerating from returned topsoil, however, was dependent on topsoil handling and storage practices. Viability of soil-stored propagules, for example, decreased with increasing time since stripping; particularly if moist conditions occurred during storage. For that reason, direct-return processes (i.e. avoiding or minimizing storage) became the preferred approach throughout the industry during the 1980s.

Disturbance of topsoil is thought to have a similar effect of breaking seed dormancy for several species in a manner similar to that achieved by burning or smoking. This is due to rapid oxidation of plant material. For that reason, the topsoil is not treated with smoke extract.

Several tons of local provenance seed is collected and broadcast each year in the rehabilitated areas. Leguminous species, which normally germinate following fires in the unmined forest, are heat treated and known smoke responsive species are treated with smoke. Many species, including the eucalypts, germinate readily and require no seed treatments.

The 'recalcitrant' obligate resprouters are well adapted to the natural perturbations of fire, drought and grazing. However, they are poorly equipped to recover from the new impact of mining. To restore these species, vegetative propagation methods are used, cuttings if possible, but tissue culture as a last resort.

of procedures has been developed that achieves a high recovery of plant species that occur in the uncleared Jarrah forest.

The current restoration process starts with shaping the mine pit (Fig. 5a), preripping the pit floor to 1.5-m deep using a bulldozer with a winged tine, returning the soil (Fig. 5b) and contour-ripping (with logs and rocks returned to provide habitat for native fauna) (Fig. 5c). Seeds of local plants are spread, and nursery-grown plants are planted for species where broadcast seeding is not a viable method of establishment. A fertilizer mix is then applied in late winter or early spring (Aug–Sept) using a helicopter.

Some specific issues triggering technical developments

Deep ripping

Deep ripping is fundamental to the establishment and persistence of vegetation. The Jarrah forest is unique as it is the only forest that grows in a Mediterranean-type climate. The deep friable soils of the Darling Range provide a year-long water supply for forest growth even though there is an annual 5- to 6-month drought. To ensure the newly restored forest has the same access to a year-long water supply, it is essential that the restored mines have the same deep friable soil profile that can store the winter rainfall for use by the vegetation throughout the whole year. The average May–August rainfall in the area is 950 mm. Deep ripping prevents soil erosion which can occur if there is overland flow of these heavy winter rains. In addition, mining machinery can compact soil to a depth of 0.5–0.8 m and ripping is required to relieve this compaction to allow rainfall infiltration and plant root growth.

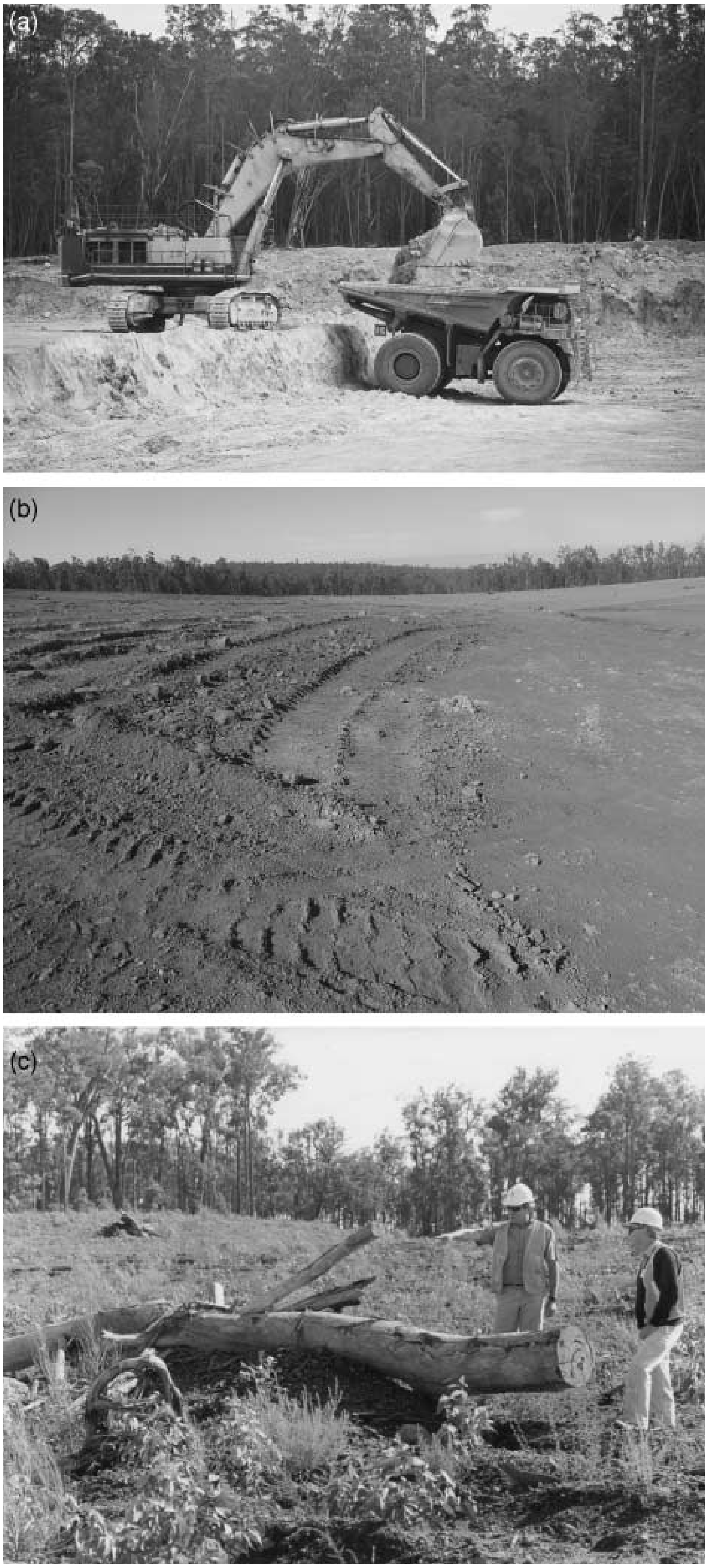

Figure 5. Some steps in the mining sequence. (a) Mining. (b) Respread topsoil ready for ripping (left and background). (c) One-year-old rehabilitated area with logs to provide fauna habitat.

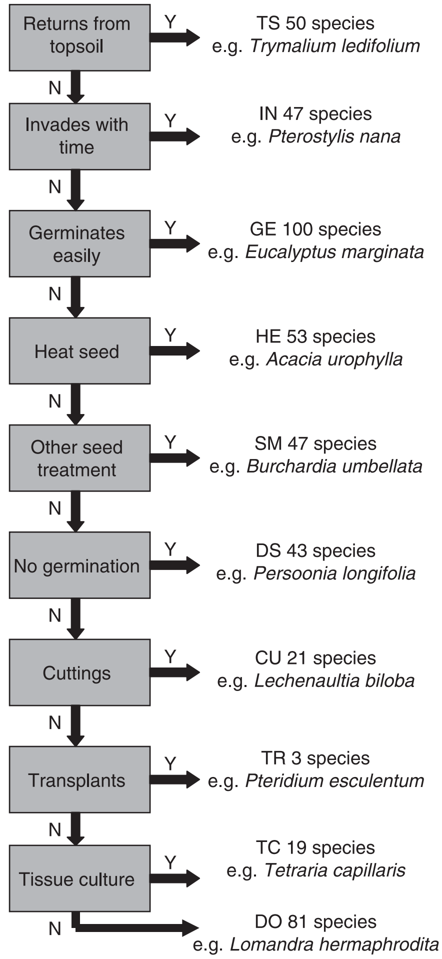

Figure 6. Classification of 465 upland Jarrah forest species using Alcoa's plant propagation protocol. These categories can change with research and development of propagation techniques. The last category (DO) is for species where a propagation method is currently unknown.

Restoring recalcitrant plant species

Some Jarrah forest plant species did not re-establish in mined areas from applied seeds or from the natural soil seed bank (see Figs 6 and 7). These were species that respond to natural stresses (drought, fire, frost and grazing) by vegetative regrowth. They are called 'obligate resprouters' and either produce little or no viable seeds, or the seeds are difficult to collect or do not germinate with known dormancy-breaking treatments. These species, which Alcoa calls 'recalcitrant species', are a common component of the unmined

Figure 7. *Loxocarya cinerea* (in the family Restionaceae) resprouting after a fire in the Jarrah forest. This species is an important component of the flora but produces little or no viable seed and can currently can only be propagated by tissue culture. Between 18 000 and 30 000 are grown by micropropagation for planting in restored mine areas each year.

forest. They were under-represented in restored mines so a new target was developed that recognized their importance to the Jarrah forest ecosystem.

These recalcitrant species are now propagated at Alcoa's Marrinup nursery and planted into the restored mines. Various methods were used to produce the greenstock: germination of scarce seeds, cuttings, division of large plants and micropropagation (tissue culture). In 1996, a tissue culture laboratory was built to carry out the micropropagation. Many of the native rushes and sedges, and other grass-like species, can only be produced by micropropagation. Up to 230 000 of these recalcitrant species are propagated and planted in rehabilitated areas each year.

Monitoring effects of treatments

Most monitoring is integrated between the three mines because the soils, vegetation and environment are very similar. However, because it was the first mine, Jarrahdale's lessons were the most influential in developing current practices. Since the early 1990s, rehabilitation at each treated subsite at Jarrahdale (and all other mines) has been monitored at 9 and 15 months of age to determine performance against a number of parameters. June each year is nominally considered age zero, because it is the month when plants germinate and establish in this Mediterranean climate. Since 1998, a staged sign-off process has been used at the mines that involves a company officer signing off at each stage of the rehabilitation that the work has been carried out to the agreed standard. Any deviations to these standards and the reasons why are noted, sites are inspected by DEC and re-work is undertaken if required. As a result of these processes, there was confidence that all of the post-1988 rehabilitation met agreed completion criteria.

Ecological monitoring data from rehabilitated sites is compared to that from unmined Jarrah forest. Standard monitoring carried out in-house through Alcoa's own research department focuses on forest composition (particularly indicated by understorey plant species composition), forest structure (indicated by tree density and understorey cover) and forest function (indicated by tree density, girth, invertebrate presence and litter decomposition). These three parameters are selected because the Jarrah forest animals and micro-organisms are highly dependent on the plants, particularly when vegetation structure develops and as organic matter builds up in the soil. Once that occurs, functions such as decomposition, nutrient cycling and complex habitat webs follow (Collins *et al*. 2005). Provided there are no other limiting factors such as soil compaction, restoring the plant species richness and vegetation structure of the forest after mining should therefore ensure that the composition (biodiversity), the structure and finally the function of the forest will be returned.

In addition, a long-term flora and fauna monitoring program was developed to provide comprehensive data on successional development. The resilience of rehabilitated sites to fire at different ages, seasons and intensities was also monitored.

Several monitoring techniques have been used in Alcoa's restored areas. The standard methodology for vegetation monitoring carried out by Alcoa each year since 1990 involved 20 m × 20 m plots for trees, and twenty 2 m × 2 m quadrats within each of these plots for understorey. A modified levy-pole technique is used to compare structure between unmined forest and rehabilitated sites. Every third year, a subsample of the monitoring plots become part of the long-term successional monitoring program that re-examines all plots at 1, 6, 15, 30 and 50 years of age. The fauna monitoring program was designed in 1991 to monitor mammals, birds, reptiles, frogs and ants. Assessments occur during summer and winter every 3 years at 20 plots located in rehabilitated sites and in nearby forest, remote from mining, at Jarrahdale, Huntly and Karnet (Nichols & Nichols 2003).

Progressive rehabilitation results – adaptive restoration

Reinstating forest composition

Early research at Jarrahdale showed that replaced topsoil was the most important source of native species recorded in restored areas, followed by broadcast seeds and planted seedlings (Ward *et al*. 1997). Monitoring showed little change in the floristic composition for many years (see Norman *et al*. 2006) indicating the importance of the initial floristic composition in determining plant succession. The exception is the orchids that require the development of leaf litter and essential mycorrhizal fungi before they establish in restored mined areas. They have fine wind-borne seed and most species re-establish after 5–10 years (Grant & Koch 2003).

In areas rehabilitated in 1990, the average native species richness at 1-year-old was 65% of the values recorded in unmined forest sites. A 5-year target of 80% species richness was set for 1996 rehabilitation – a target reached by improving the quality of sown seeds, more comprehensive seed collecting, optimizing seed pre-treatments, restricting handling of topsoil to the dry summer–autumn period, double-stripping topsoil and then direct returning the topsoil.

By optimizing the establishment of plant species from applied seeds, the natural soil seed bank and by planting recalcitrant species, the 100% species richness target was reached in areas rehabilitated in 2001. Values for 2002 and 2003 were significantly lower (88 and 89%) than the target because of flow-on effects from the 2001 drought- and wet-season ripping. Species establishment in 2004 rehabilitation areas was close to target (96%) but was 90% in 2005 areas.

Improving forest structure

Forest structure develops over time, and rehabilitation treatments have been continually modified to more closely achieve the aim of duplicating the Jarrah forest structure. Current practice results in vigorous vegetation growth in the early years (Fig. 8a), with structural complexity increasing progressively over 10–15 years (Fig. 8b,c). In pre-1988 sites, however, Acacias that were sown to enhance nitrogen fixation in the early stages of recovery made a disproportionate contribution to vegetation cover, potentially causing loss of species richness in the recovery phase. They were also creating a predominant shrub layer, absent from the unmined forest, which created an artificially high fuel load (Grant 2003). High tree establishment densities meant that silvicultural thinning may be required for future management of these areas. Subsequent adjustments were made to the seed mix to avoid excessive competition by Acacias and refinements are still being made to the tree seed mix to achieve tree stem densities similar to unmined forests.

Improving function – food web and faunal habitat

Growth of the vegetation on the rehabilitation sites has led to the accumulation of leaf litter, providing habitat for decomposers and subsequent food web development. Return of some wood waste from the forest clearing process to rehabilitated areas, followed

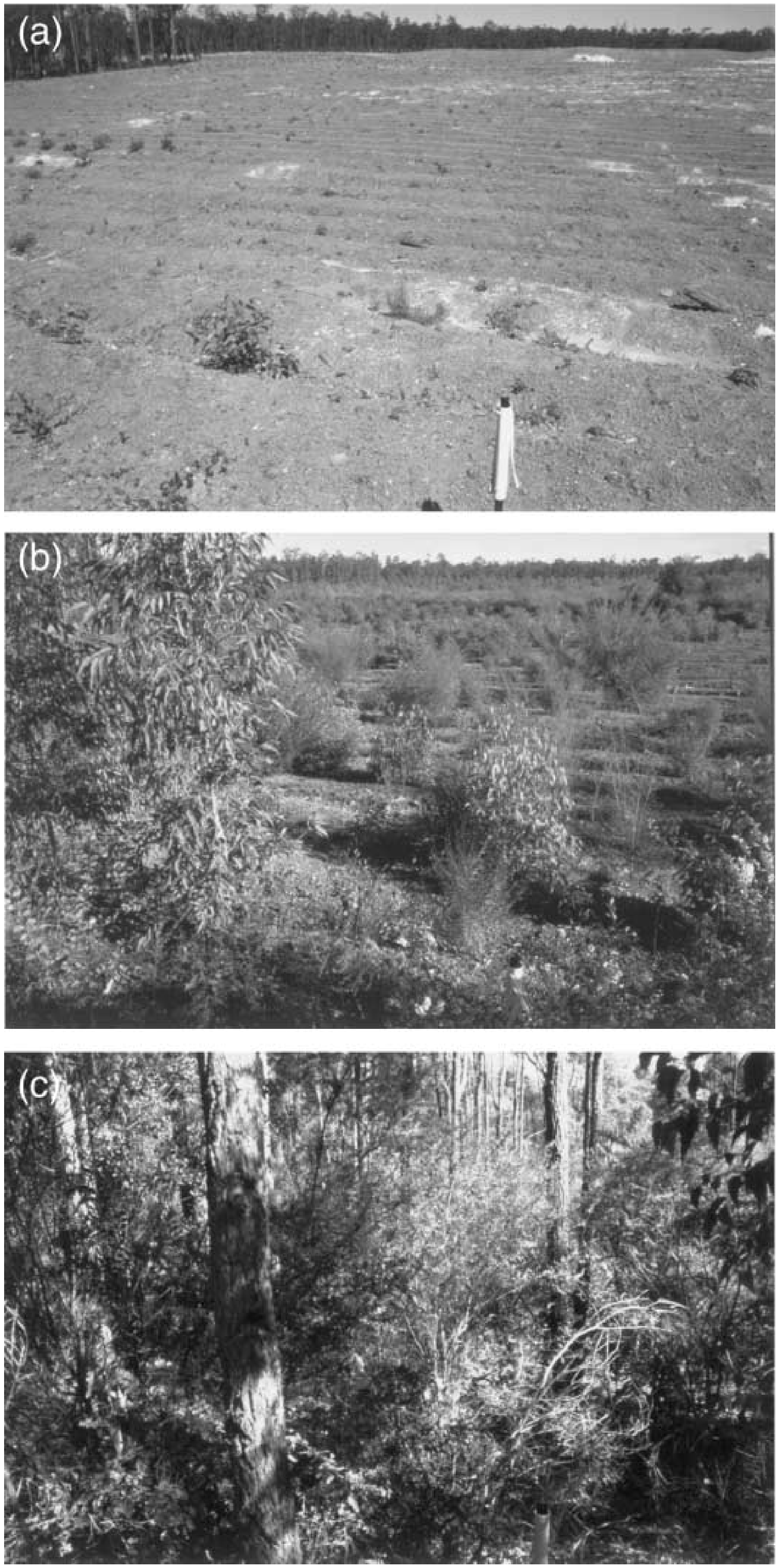

Figure 8. (a–c) Time sequence photos of one restored site at 1 year of age, 2 years and 13 years.

by the development of the new forest, provided habitat for colonizing reptiles, birds, small mammals and invertebrates. Structural changes to the vegetation over time, particularly reduction of the shrub layer and increase in tree height has resulted in concomitant changes to the suite of fauna using the forest as habitat.

The fauna monitoring program (Nichols & Nichols 2003) reported substantial but fluctuating numbers of indigenous mammal, bird, reptile, frog and ant species in the rehabilitation areas over the 1990s and early 2000s. Many of the medium-sized mammal species that occur in the Jarrah forest suffered significant declines in the years leading up to the mid-1990s. Some, such as the Chuditch, *Dasyurus geoffroii*, originally occurred over large areas of Australia but have declined to small remnant populations in the south-west. For others, such as the Common Brushtail Possum (*Trichosurus vulpecula*) and Mardo (*Antechinus flavipes*), the decline has not been as extensive.

Research demonstrated that the major reason for the significant decline in abundance of many species in the Jarrah forest was fox predation (Bailey 1996). Research into the fox-predation problem led to the development of a dried-meat bait containing sodium fluoroacetate (1080), a naturally occurring chemical found in Jarrah forest plant species. Indigenous fauna species have developed a high tolerance to this toxin, but introduced species such as the fox are highly susceptible. Broad-scale trials demonstrated that if large areas of the forest were aerially baited, within 2–3 years, numbers of mammal species such as the Chuditch increased (Morris *et al*. 1998). On the basis of these results, the decision was made to implement fox baiting over 700 000 ha of the northern Jarrah forest in order to halt the decline in numbers of those mammal species known to be susceptible to fox predation. Alcoa funded this program (called Operation Foxglove), which has been ongoing since 1994.

Following baiting, Alcoa began a program of reporting all key fauna sightings by field staff. This showed that numbers of fox sightings recorded at Huntly mine decreased from 15 in 1994 to zero in 1999 and 2000. There has also been a large increase in the abundance of medium-sized mammals in both the umnined forest and in rehabilitated areas as a result of this fox baiting.

Bird species recorded in rehabilitated sites at 8 years old in both winter and summer were comparable to those present in healthy forest although the numbers in one Jarrahdale rehabilitation site declined in summer possibly because of the senescence of Acacias. Classification analyses showed that the composition of the rehabilitation avifaunal communities had become more similar to that of unmined forest over time, and was most similar to stream zone sites. In winter, high numbers of feeding honeyeaters resulted in a decrease in quantitative similarity values compared to the upland forest.

Of the 17 reptile species recorded in the 2001 Long-term Fauna Monitoring Program, only one has not been recorded in rehabilitated bauxite mined areas. This is the Ornate Rock Dragon (*Ctenophorus ornatus*), which is only recorded on granite outcrops, and would not be expected to colonize rehabilitation. However, the total number of reptile species recorded in all rehabilitated sites continued to be lower than the total recorded in all healthy forest sites, with no sign of the two converging. It is likely that the lower reptile numbers is due to decreased solar insulation in the young vigorously growing rehabilitated areas.

The other taxon that is routinely monitored in rehabilitated areas in this program is ants. At Jarrahdale after 8 years, ant richness, diversity and abundance at rehabilitated sites were within the range of values recorded in healthy forest control sites. Frogs are monitored in stream zones both near and distant from rehabilitated mine areas. Frog abundances have decreased in recent times because of declining rainfall. The frog Chytrid fungus disease has not been implicated in causing declines in the relatively dry northern Jarrah forest.

Testing the resilience of restored areas

During the development of completion criteria, the most contentious issues related to the resilience of rehabilitation to further disturbance (such as burning and logging) and the ability to integrate the management of rehabilitated areas with the surrounding unmined forest. DEC undertakes prescribed burning in the majority of Jarrah forest on an 8- to 15-year rotation. In recognition of the need to determine if rehabilitated areas can be managed in association with the surrounding unmined forest, a major research program was commenced in the early 1990s to investigate the integration of the management of rehabilitated areas with the surrounding unmined forest (reviewed in Grant *et al*. in press).

A review based on 10 years of research, mostly at Jarrahdale (Grant *et al*. 1998) outlined a process for the development of prescriptions for rehabilitation burns. More than 3000 ha of pre- and post-1988 rehabilitation had been burnt to the end of 2006. Because of natural fire tolerance or adaptations of the Australian flora, rehabilitated areas showed strong resilience to both wildfires and prescribed burns. The majority of the early burning of rehabilitated areas was for research purposes, but in the last 5 years, significant areas have been burnt as part of routine DEC operations.

The major outcomes from the research and monitoring in relation to completion criteria were identification of the most appropriate fire regime for rehabilitated areas, fire risk assessments and planning, stocking of rehabilitation with fire resilient overstorey species, and integration of silvicultural and burning practices. It is a formal requirement that the completion criteria for Alcoa's rehabilitated areas are reviewed every 5 years. As part of this process, a fire working group with representatives from DEC and Alcoa was established in 2005 to resolve any outstanding issues relating to the fire management of rehabilitated areas. The report from this group was finalized in late 2006 and the review of completion criteria completed in early 2007.The reviewed completion criteria are available on the Department of Industry and Resources (WA) website (DoIR 2007).

Decommisioning of Jarrahdale Mine

Assessing and re-treating pre-1988 sites

Approximately 2000 ha of rehabilitation at Jarrahdale was completed before 1988, prior to the adoption of significantly improved restoration prescriptions. For example, in a number of older areas, pit faces were not landscaped into the surrounding landform, and sumps and contour banks were installed to manage drainage. To determine whether the pre-1988 rehabilitation would meet the completion criteria, all areas at the Jarrahdale Mine were inspected and assessed.

The assessment determined whether the vegetation at the site was exhibiting sustained growth and development. If a site did not meet the criteria, it was reviewed with DEC to determine the need for corrective action and the extent of rework required. Re-work prescriptions aimed to re-establish Jarrah forest species and suppress the re-establishment of non-native species. Areas that did not meet the standards due to the presence of significant infrastructure, such as pit faces, were automatically reviewed with DEC regardless of growth on the site. Following these inspections, a total of 133 ha was identified as requiring re-work. These areas were rehabilitated according to the post-1988 rehabilitation completion criteria and monitored accordingly.

Although all re-worked areas eventually met the appropriate criteria, the quality of the rehabilitation in these areas was sometimes lower than areas being rehabilitated for the first time using the current, improved prescriptions.

Key components of Alcoa's strategy have been a commitment to study the baseline native ecosystem and the restored ecosystem, and to seek convergence in similarity of biodiversity and function.

Certificate of acceptance

Alcoa's completion criteria contained broad guidelines about how an area of rehabilitation would be relinquished and a certificate of acceptance issued, but no detail about how this would be administrated. An area containing 975 ha of rehabilitation at the Jarrahdale Mine was identified as the first area to be submitted for a certificate of acceptance; and subsequently the first certificate of acceptance for a significant area of mining rehabilitation in Australia was issued in November 2005. This represented about a quarter of the area mined and rehabilitated at Jarrahdale. A second area that includes 380 hectares of rehabilitated land is currently in the sign-off process.

Conclusion

Substantial areas of Jarrahdale have met the required completion criteria. This should allow these areas to be managed in an integrated manner with the surrounding unmined Jarrah forest. Although the rehabilitated areas are not identical to the premined condition, all the sites at Jarrahdale have reached approximate compositional goals to unmined sites and to have demonstrated processes of self-perpetuation.

Key components of Alcoa's strategy have been a commitment to study the baseline native ecosystem and the restored ecosystem, and to seek convergence in similarity of biodiversity and function. Specific applied knowledge gained from this research are the use of direct-returned topsoil; the sowing of seed of a wide range of native species; the proximity of colonization sources for other species; propagation and planting of difficult to propagate species; and the refinement of ratios of species to duplicate the forest structure and function.

Researchers will never have all the answers to the full suite of challenges raised by mine rehabilitation and environmental management. Alcoa's ongoing research and improvements to rehabilitation treatments suggest, however, that 10 years from now, mine restoration achievements are going to be better than the high standard being achieved today. These refinements will also raise the level of environmental and rehabilitation performance that is expected by the community and will continue to drive ongoing improvement for the whole industry at a global level.

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Summary **The closure and decommissioning of Alcoa's first mine in Western Australia at Jarrahdale was a landmark for the company. This article describes the strategies and research contributing to successful mine rehabilitation in the Jarrah forest. Lessons learnt at Jarrahdale are being applied to other Western Australian mines. Over 30 years of research have resulted in a strong working knowledge of ecosystem function in this environment. The direct linkage of research to operational practices provides two-way benefits for practitioners and researchers. The Jarrahdale mine is the first mine in Western Australia to have received a certificate of completion from the state government.**

Key words: *rehabilitation, completion criteria, closure, resilience.*

