Identification, persistence and management of environmental weeds in bauxite mine rehabilitation in Western Australia

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Summary  Alcoa has been rehabilitating bauxite mines in the northern jarrah (Eucalyptus marginata D.Don ex Sm.) forest of Western Australia since 1966. Management of declared weeds occurs as part of routine operations, while research has targeted weed persistence in rehabilitated sites and the identification of potential environmental weeds. Alcoa routinely monitors rehabilitated sites after nine months of growth for a range of purposes including identification of infestations of the declared perennial red inkweed (Phytolacca octandra L.). Only 9% of 2000–2004 rehabilitated sites had densities >50 plants ha⁻¹. These plants were sprayed with herbicide before the onset of the second winter rains. The density of ephemeral weeds was relatively high in rehabilitated sites less than five years of age, however density and cover were reduced to unmined forest levels by 14 years of age. Unseeded sites had significantly higher weed density and cover than sites seeded with a jarrah forest species mix, while the application of fertiliser also increased weed density.

Prior to 1989, rehabilitated sites were planted with a range of native and eastern Australian eucalypt (Eucalyptus) species, and seeded with an understorey mix that included species not indigenous to the mining area. Eastern Australian eucalypts only recruited following soil disturbance, while three non-indigenous understorey species (Acacia celastrifolia Benth., Mirbelia dilatata R.Br. ex Dryland. and Viminaria juncea (Schrad.) Hoffmanns.) had high density (>0.1 plants m⁻²) and cover in rehabilitated sites. Fire further increased the proliferation of eastern Australian eucalypts and resulted in an extra four understorey species exhibiting weed-like recruitment. Spraying at a young age, or immediately after burning, successfully removes these species. The implications of these results to the long-term management and sustainability of Alcoa’s rehabilitated areas are discussed.

Keywords  Bauxite mining, non-indigenous species, herbicide, weed management.

INTRODUCTION
Alcoa World Alumina Australia (Alcoa) commenced mining in the Darling Range of Western Australia in 1966 and has two operating mines (Huntly and Willowdale), with a third site decommissioned in 2001 (Jarrahdale). Following clearing and mining operations, the landform is re-shaped and deep-ripped to 1.5 m, overburden and topsoil are returned and the final surface is contour ripped, seeded and planted. Sites are then aerially fertilised with 250 kg ha⁻¹ diammonium phosphate (DAP). Approximately 550 ha of rehabilitation are completed each year. Annual monitoring of newly rehabilitated sites occurs in March, nine months following rehabilitation operations, to determine if tree, understorey and declared weed densities meet completion criteria standards (DoIR 2002). Remedial work of under-performing sites is undertaken before the onset of the second winter rains. Unlike declared perennial weeds, ephemeral weeds are not removed from rehabilitated sites. These species are short-lived and produce little biomass, therefore are not generally interfering with the successional development of the rehabilitated areas. Application of DAP fertiliser increased weed species richness, cover and density at nine months of age compared with sites only receiving superphosphate fertiliser (Koch and Ward 1994). Persistence of ephemeral weeds in rehabilitated sites over time requires quantification.

Since 1989, the seed mix has included the two dominant tree species (jarrah and Corymbia calophylla (Lindl.) K.D.Hill & L.A.S.Johnson) occurring in the jarrah forest and a diverse range of approximately 100 indigenous understorey species. Earlier rehabilitation included eastern Australian eucalypt species due to the unknown impact of jarrah dieback disease (caused by Phytophthora cinnamomi Rands.) at the time (Colquhoun and Hardy 2000). Non-indigenous understorey species were included due to different objectives for rehabilitation of that era. The introduced species are outside their natural environment and have the potential to become environmental weeds, possibly invading adjacent forest or post-1988 rehabilitation (Norman and Grant 2005). Environmental weeds are plants that invade, persist and proliferate in natural ecosystems and cause changes in indigenous biodiversity and ecosystem function (Williams and West 2000). Disturbance such as fire may increase recruitment of environmental weeds (Grant 1997). Alcoa’s completion criteria state that rehabilitated sites must
be resilient to fire, therefore it is important to determine the consequences of burning on environmental weed recruitment in rehabilitated areas. In this paper, we will report on routine weed removal operations, the persistence of ephemeral weeds over time and the management of non-indigenous environmental weeds in rehabilitated sites.

MATERIALS AND METHODS
Counts and locations of red inkweed are recorded in every rehabilitated site during the nine month monitoring program. The species is sprayed with a glyphosate solution (360 g L⁻¹) if densities exceed 50 plants ha⁻¹. The persistence of ephemeral weeds was assessed in an experiment established in 1988 rehabilitated sites and monitored at 1, 2, 5, 8 and 14 years. Three seed (legume and small understory mix, small understory mix only and no seed) and two fertiliser (250 kg ha⁻¹ DAP and none) treatments were applied at each of nine sites (Koch and Ward 1994). Twenty 2 m × 2 m permanent quadrats (a total of 80 m²) were established in each treatment, and the density and cover of ephemeral weed species recorded.

Invasion by eastern Australian eucalypts was monitored across six boundary types: pre-1988 rehabilitation to pre-1988 haul road, post-1988 rehabilitation, post-1988 haul road and unburnt forest, and burnt pre-1988 rehabilitation to burnt and unburnt forest. Three 40 m transects were positioned across the boundary and sampling plots (2 m × 2 m) placed at 1, 5 and 20 m either side to count eastern Australian eucalypts. Nine woody understory species with a ‘high risk’ of becoming environmental weeds were also examined: A. celastrifolia, A. saligna (Labill.) H.L.Wendl., Calothamnus quadrifidus R.Br., Dryandra polycophala Benth., Leptospermum laeavigatum (Gaertn.) F.Muell., Melaleuca incana R.Br., Mirbelia dilatata, Paraserianthes lophantha (Willd.) I.C.Nielsen and Viminaria juncea. Species were classified as high-risk according to a known post-fire increase in density (Grant 1997, Smith 2001) and/or field observations at Alcoa’s mines. Twenty 2 m × 2 m quadrats (a total of 80 m²) were established in 20 m × 20 m plots in pre- and post-1988 rehabilitated sites and the density and cover of the target species recorded. Recruitment into adjacent post-1988 rehabilitation, haul roads or native forest areas was monitored as described above.

Control methods for A. celastrifolia, C. quadrifidus and M. dilatata were trialled in 1 ha plots in rehabilitated sites of various age. All species were sprayed with herbicide two to three-years post-burn, A. celastrifolia and M. dilatata were felled when 7–10 years old, and A. celastrifolia and C. quadrifidus were notchted at 20 years of age. Plants were sprayed with a glyphosate solution (described previously), felled with a chainsaw, or stem notchted with a tomahawk axe followed by pump-pack application of glyphosate.

RESULTS
Red inkweed was recorded in 34% of pits at an average density of 10 plants ha⁻¹ in sites rehabilitated from 2000 to 2004. Only 9% of nine-month-old rehabilitated sites required weed control (>50 plants ha⁻¹). The ephemeral weed species establishing in rehabilitated sites were mainly from the Asteraceae and Poaceae families. Ephemerl weeds dominated plant density in rehabilitated sites until five years of age, after which density began to decline (Figure 1).

Unseeded sites had significantly higher weed density and cover than seeded sites at 5, 8 and 14 years of age. There was higher weed density and cover in sites that received DAP fertiliser (23 plants m⁻² and 5% cover) compared with unfertilised sites (15 plants m⁻² and 2% cover). Apart from one-year-old sites, rehabilitated sites had higher ephemeral weed density and cover compared with forest sites (0.6 plants m⁻² and 0.3% cover). However, by 14 years of age the cover of weeds in seeded rehabilitated sites was significantly reduced to forest levels and a similar trend was noted for density (Figure 1).

Eastern Australian eucalypts (Corymbia maculata (Hook.) K.D.Hill & L.A.S.Johnson, Eucalyptus globulus Labill. and Eucalyptus resinifera Sm.) recruited into post-1988 rehabilitated haul roads but not other post-1988 rehabilitated sites or forest. High densities of E. resinifera were recorded in post-1988 haul roads (1.3 stems m⁻³). Recruits were also recorded in pre-1988 rehabilitated areas following burning. Three of the nine investigated understory species were identified as potential environmental weeds, with high density (>0.1 plants m⁻²) and cover in rehabilitated sites (i.e. A. celastrifolia, M. dilatata and V. juncea). Burning further increased the recruitment of A. celastrifolia (Figures 2 and 3) and M. dilatata. A further four species exhibited high recruitment following fire namely A. saligna, C. quadrifidus, L. laeavigatum and M. incana. No recruitment was recorded in adjacent post-1988 rehabilitation, haul roads or forest.

Spraying A. celastrifolia, C. quadrifidus and M. dilatata two to three years post-burn was a fast and effective control treatment. Felling was not successful for seven-year-old M. dilatata, as the stems were too thin (<2 cm diameter) to cut, while A. celastrifolia survived if not all branches were felled. Notching successfully killed 20-year-old A. celastrifolia plants, while C. quadrifidus plants were stressed (approximately 50% dead foliage) but survived.
**Figure 1.** Density (plants m\(^{-2}\)) and cover (%) of ephemeral weeds over time in rehabilitated sites. Legume and small understorey mix (♦), small understorey mix (●) and no seed (■).

**Figure 2.** *Acacia celastrifolia* density (plants m\(^{-2}\)) and cover (%) in forest and unburnt, autumn burnt and spring burnt pre-1988 rehabilitated sites over time.

**Figure 3.** Three-year post-burn recruitment of *A. celastrifolia*, an understorey environmental weed.
DISCUSSION

There were minor occurrences of the declared perennial red inkweed in rehabilitated sites, which were successfully removed with herbicide at nine months of age. Ephemeral weeds did not persist in seeded rehabilitated sites, with density and cover returning to forest levels after 14 years. This is a relatively short period of time for ephemeral weed densities to return to unmined forest levels given that bauxite mining involves complete removal of the existing vegetation. Ephemeral weeds were suppressed in seeded compared with unseeded rehabilitated sites, possibly due to shading by larger overstorey and understorey species (Norman et al. 2006). The current rehabilitation prescription utilises the legumes plus small understorey species seed mix (with a reduced abundance of large legumes), which produces a vegetation structure and floristic composition most similar to the forest.

The eastern Australian eucalypts and non-indigenous understorey species in pre-1988 rehabilitation did not recruit into adjacent native forest and post-1988 rehabilitated sites. These areas have well-established vegetation and were therefore not particularly vulnerable to invasion. The eastern Australian eucalypts only recruited into newly rehabilitated haul roads and pre-1988 rehabilitation following burning, indicating disturbance is required. In contrast, the woody understorey weeds *A. celastrifolia*, *M. dilatata* and *V. juncea* proliferated in previously seeded rehabilitated sites without disturbance. Fire further increased recruitment and resulted in another four species exhibiting weed-like recruitment. One of the priorities of post-1988 rehabilitation is to restore the botanical richness of the pre-mining jarrah forest. Invasion by eastern Australian eucalypts and non-indigenous understorey species into rehabilitation areas outside those in which they were intentionally placed may jeopardise the long-term sustainability of the rehabilitation. Burning in spring rather than autumn minimises the proliferation of eastern Australian eucalypts (Grant et al. 1997). Any recruiting eucalypts should be sprayed at 2–3 years of age when the jarrah have established as coppices and it is less likely that the removed weedy eucalypts will be replaced by further recruitment (Morley and Grant 2002). For woody understorey weeds, the fastest and most effective method of control is to spray young recruiting seedlings post-burn, while certain established species can be removed by herbicide stem injection.

REFERENCES


Department of Industry and Resources (DoIR) (2002). Alcoa World Alumina Australia darling range bauxite mine rehabilitation completion criteria. DoIR, Perth.


