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Phosphorus fertilisation and large legume species affect jarrah forest restoration after bauxite mining

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ABSTRACT

Re-establishing nutrient-cycling is often a key goal of mine-site restoration. This goal can be achieved by applying fertilisers (particularly P) in combination with seeding N-fixing legumes. However, the effect of this strategy on other key restoration goals such as the establishment and growth of non-leguminous species has received little attention. We investigated the effects of P-application rates either singly, or in combination with seeding seven large understorey legume species, on jarrah forest restoration after bauxite mining. Five years after P application and seeding, legume species richness, density and cover were higher in the legume-seeded treatment. However, the increased establishment of legumes did not lead to increased soil N. Increasing P-application rates from 0 to 80 kg P ha^{-1} did not affect legume species richness, but significantly reduced legume density and increased legume cover: cover was maximal (~50%) where 80 kg P ha^{-1} had been applied with large legume seeds. Increasing P-application had no effect on species richness of non-legume species, but increased the density of weeds and native ephemerals. Cover of non-legume species decreased with increasing P-application rates and was lower in plots where large legumes had been seeded compared with non-seeded plots. There was a significant legume × P interaction on weed and ephemeral density: at 80 kg P ha^{-1} the decline in density of these groups was greatest where legumes were seeded. In addition, the decline in cover for non-legume species with increasing P was greatest when legumes were seeded. Applying 20 kg P ha^{-1} significantly increased tree growth compared with tree growth in unfertilised plots, but growth was not increased further at 80 kg ha^{-1} and tree growth was not affected by seeding large legumes. Taken together, these data indicate that 80 kg ha^{-1} P-fertiliser in combination with (seeding) large legumes maximised vegetation cover at five years but could be suboptimal for re-establishing a jarrah forest community that, like unmined forest, contains a diverse community of slow-growing re-sprouter species. The species richness and cover of non-legume understorey species, especially the resprouters, was highest in plots that received either 0 or 20 kg ha^{-1} P and where large legumes had not been seeded. Therefore, our findings suggest that moderation of P-fertiliser and legumes could be the best strategy to fulfil the multiple restoration goals of establishing vegetation cover, while at the same time maximising tree growth and species richness of restored forest.

1. Introduction

Mining is an extreme form of ecosystem disturbance that results in the removal of both vegetation and the soil profile. Furthermore, when topsoil is replaced during *post* mining restoration activities, there is typically a significant degree of soil mixing and redistribution of nutrients within the re-created soil profile (Short et al., 2000). As a consequence of this disturbance, restoring productivity, nutrient-cycling and replacing nutrients lost during the mining process, are generally key goals of restoration programmes.

The goals of restoring productivity and nutrient-cycling are typically addressed in post-mining restoration by applying fertiliser and/or establishing high densities of fast-growing, often exotic,

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N-fixing species. This approach can also minimise the risk of soil erosion in newly restored sites by the rapid establishment of vegetation cover (Ward et al., 1990). In addition, it can potentially provide critical soil nitrogen to maximise the growth of other species, such as trees (Palaniappan et al., 1979; Ward and Koch, 1996). Accordingly, this strategy has become generally accepted practice in Australia (Langkamp et al., 1979; Todd et al., 2000; Grant et al., 2007; Brady and Noske, 2010) and elsewhere (Bradshaw, 1983; Parrotta and Knowles, 1999, 2001).

Growth of N-fixing legume species, and hence nitrogen fixation rates, can be maximised by applying phosphorus fertilisers. For example, legume growth in jarrah forests in Southwest Western Australia is usually limited by P-availability (Hingston et al., 1982). Adding the equivalent of 50 kg P ha^{-1} increased annual N-fixation by *Acacia pulchella* from 12 kg N ha^{-1} to 85 kg N ha^{-1} (Hingston et al., 1982). Furthermore, N-fixation by legumes results in an overall increase in soil total N (Koch, 1987; Ward and Koch, 1996), which in turn, could increase the growth of non-leguminous species via the direct benefit of increased N-availability.

However, there are a range of potential disadvantages to establishing high densities of legumes in restoration. These include increased competition, dense vegetation making areas less accessible to fauna and an increased fire risk due to high fuel loads of both leaf litter and senesced individuals (Todd et al., 2000; Grant et al., 2007). Thus, a dense legume understorey can suppress (height) growth of planted eucalypts in jarrah-forest restoration (Koch, 1987). Similarly, the establishment of dense stands of *Acacia* and/or other leguminous species following disturbance can limit the establishment of other herbaceous species due to both a dense canopy and the production of a thick leaf litter layer (Boyes et al., 2011; Le Stradic et al., 2014). In sum, there is a potential trade-off that requires further investigation.

Furthermore, while fertiliser addition, particularly P, maximises legume growth rates, P-addition can also have negative impacts on vegetation by increasing the abundance of weeds and negatively impacting species with specialised adaptations for P-acquisition, e.g. Proteaceae (Lambers et al., 2008; Shane et al., 2004) and also a range of other families (Pang et al., 2010a,b). For example, in fynbos restoration after a simulated mining disturbance, Holmes (2001) found that adding 26 kg P ha^{-1} increased overall plant density and cover, although this effect was mainly limited to exotic weeds, and increased the mortality of Proteaceae. Similarly, in jarrah forest restored after mining, Daws et al. (2013) found that weed species and native ephemerals benefited from fertiliser P. However, the growth and density of Proteaceae was unaffected by P, although the species richness of native species of the restored sites was reduced at P-application rates greater than 20 kg ha^{-1}. However, the combined effects of P-application and a restoration strategy that includes a significant understorey legume component are unclear.

In this study we test the effects of increasing phosphorus application rates (0, 20 and 80 kg ha^{-1}), and large understorey legume species on the response of both non-leguminous understorey and overstorey species in jarrah forest restoration after bauxite mining. We manipulated abundance of large legume species ($n = 7$) by reducing quantities of their seeds in the mix that was broadcast for restoration, although we were unable to prevent recruitment of some species via the soil seed bank. Specifically we test the predictions that: (1) soil N (ammonium and nitrate) will increase with seeding large legumes, (2) increasing rates of P-application will increase the density and cover of weed species and reduce overall species richness, (3) P-addition will increase cover, especially of legume species, (4) that P-addition will have no effect on Proteaceae, (5) that seeding large legumes will increase cover of legume species, but decrease species richness, density and cover of other understorey species, and (6) that seeding large legumes will decrease overall species richness of restored jarrah forest.

2. Materials and methods

2.1. Study site

Alcoa of Australia Ltd., (hereafter Alcoa) mines and restores ~550 ha of forest each year (Koch, 2007). The experiment described here was established in 2001 within the Alcoa mining lease which is located within the Darling Range of Southwest Western Australia (32°35′06″ S, 116°06′44″ E). The region experiences a Mediterranean climate with hot, dry summers and cool, wet winters. Annual rainfall is 1200 mm with an average summer monthly maximum temperature of 28 °C and average winter minimum of 5 °C.

The overstorey vegetation in the mining lease is dominated by jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*). In addition, there is a small-tree component, with *Allocasuarina fraseriana*, *Banksia grandis*, *Persoonia longifolia* and *Xylomelum occidentale* being most common. The understorey consists of shrubs and herbs predominantly in the families Myrtaceae, Proteaceae, Fabaceae, Restionaceae, Orchidaceae, Apiaceae, Liliaceae (*sensu lato*), Ericaceae, Asteraceae and Cyperaceae.

Mine pits range from 1 to 20 ha in size and are surrounded by intact forest. Alcoa's restoration aim is to establish a self-sustaining jarrah forest ecosystem that fulfils pre-mining forest land uses including nature conservation, recreation, timber production and water catchments. Restoration involves reshaping the mine pit, ripping to alleviate compaction and spreading fresh topsoil (Standish et al., 2015). Restored areas receive fresh topsoil sourced from adjacent areas that have been cleared of vegetation in advance of being mined. This practice ensures availability of soil stored seeds such as legumes (Grant et al., 2007), and microorganisms, for restoration, including the rhizobia that form nitrogen-fixing symbioses with the native legumes (Jasper, 2007). Seeds of local plants are spread over the restored mine pits and planting of nursery grown plants occurs for species where direct seeding is not a viable establishment method. A fertiliser mix is applied by helicopter in late winter or early spring after the completion of restoration activities. In 2001 this mix contained the equivalent of 80 kg elemental P ha^{-1} and 80 kg elemental N ha^{-1}. The mine pits used for this current experiment were excluded from this routine fertiliser application programme.

2.2. Experimental design

In March 2001 within each of six newly restored mine pits, a block containing six 40 m × 50 m plots was established. We used a factorial design with two factors: with and without seeding of 7 large legume species (Table 1); and P-fertiliser application, including none, 20 kg elemental P ha^{-1} and 80 kg elemental P ha^{-1}. Treatments were allocated randomly to the 40 m × 50 m plots within each block.

Each experimental plot received a generic seed mix containing seeds of 108 jarrah forest species including the two tree species jarrah and marri, understorey shrubs and herbs collected from within ~20 km of each site. Seeds of understorey species were applied at a rate of 310 g ha^{-1} and 950 g $ha^{-1}$for the tree species. Seeds were broadcast by hand onto plots in March 2001. For the additional legume treatment, the equivalent of 217 g ha^{-1} of seed of 7 comparatively large understorey legume species was added to the generic seed mix (Table 1). After seeding, P was applied once as diammonium phosphate, and nitrogen (urea) was added once to each plot at an application rate of 80 kg elemental N ha^{-1}.