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The benefits of fertiliser application on tree growth are transient in restored jarrah forest

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ABSTRACT

The application of fertiliser, to both replace nutrients lost during mining and facilitate rapid vegetation re-establishment, is viewed as a key step in the restoration of post-mining landscapes. However, few studies have examined the long-term effects of a single initial fertiliser application on tree growth in restored sites. We report on a large-scale, fully replicated study that investigated the effect of an initial N and P fertiliser application (0, 80 and 120 kg ha^{-1} elemental N and P) on sites restored after bauxite mining. Growth of the two main jarrah forest tree species (jarrah - *Eucalyptus marginata* and marri - *Corymbia calophylla*) was monitored 9 and 20 years after the completion of restoration. After 20 years, soil NO_3^- and NH_4^+ were unaffected by N-application, although soil Colwell-P concentrations remained elevated following P-application. N-application had no effect on marri growth at either time interval, but increased jarrah diameter at breast height over bark (DBHOB), height and stand basal area at 9 years and DBHOB at 20 years. Applied-P increased height and DBHOB of jarrah after 9 years, but these effects did not continue. In contrast, applied-P benefitted marri growth (DBHOB and stand basal area) at both 9 and 20 years. Tree growth rates in the fertilised treatments declined more between the two-time intervals (0 – 9 years and 9 – 20 years) than the unfertilised plots, particularly for jarrah, suggesting that resource limits were reached more rapidly in the fertilised treatments. Further, for both N and P there was no additional benefit from application rates above 80 kg ha^{-1}. These results demonstrate that while fertiliser addition may benefit initial growth in restored jarrah forest, the effects reduce with restoration age and may have limited practical benefit after 20 years.

1. Introduction

Forest ecosystems support multiple land uses including biodiversity conservation, recreation and provision of commercial resources (Waring and Schlesinger, 1985; Bradshaw *et al.*, 1991). Fundamental for these, and many other forest uses is the presence of canopy trees. Canopy trees provide habitat for forest fauna, help prevent landscape erosion, shade recreational areas, and provide commercially-harvestable timber (Hall *et al.*, 1970; Bradshaw *et al.*, 1991). Mining activities also occur within forest ecosystems globally (e.g. Parrotta *et al.*, 1997; Holl, 2002; Gardner and Bell, 2007), which removes vegetation cover through land clearing prior to mining. However, as mining is generally a transient land-use, it is imperative that post-mining landscapes be restored to enable re-establishment of forest ecosystems.

Mining disrupts the soil profile, and the seedbank-containing topsoil is typically removed and stored prior to the commencement of mining (Koch *et al.*, 1996; Parrotta *et al.*, 1997; DeJong *et al.*, 2015). This is later replaced on newly restored areas to provide a seed source, organic material and nutrients that are otherwise lacking (Tacey and Glossop, 1980; Parrotta and Knowles, 1999; Spain *et al.*, 2015; Tibbett, 2015). Significant quantities of soil nutrients are also lost through vegetation removal (Hingston *et al.*, 1980; Achat *et al.*, 2015), which means that

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newly restored sites may have lower soil nutrient levels than unmined forests (e.g. Prematuri *et al.*, 2020). To address this, post-mining restoration typically includes fertiliser addition to restore pre-mining nutrient levels and facilitate vegetation establishment (Scullion and Mohammed, 1991; Short *et al.*, 2000; Grant and Koch, 2007).

Restoration in the jarrah forest aims to re-establish a self-sustaining multi-use ecosystem that provides for water management, recreation, conservation values and timber production (Gardner, 2001; Koch, 2007). To maximise the growth of tree species for timber production, fertiliser is often applied to restoration following mining (Gardner and Bell, 2007; da Silva *et al.*, 2013). Many commercial tree species, including *Eucalyptus* species, respond positively to high rates of applied-N and P fertiliser with increased height growth and wood volume (Cromer *et al.*, 2002; Albaugh *et al.*, 2015; Crous *et al.*, 2015; Bhandari *et al.*, 2021). Consequently, high fertiliser rates have often been used in re-establishing hardwood eucalypt forests and plantations, both within Australia (Smethurst *et al.*, 2004; Gardner and Bell, 2007) and elsewhere (Campion *et al.*, 2006). However, high fertiliser application rates can compromise growth and diversity of other forest species (e.g. Daws *et al.*, 2021). As the goal of restoration in the jarrah forest is also to re-establish a multi-use forest with similar diversity and structure of vegetation to the pre-mining landscape (Gardner, 2001; Koch, 2007), the choice of an appropriate fertiliser rate may represent a trade-off between canopy tree growth rates and plant species diversity. While a number of studies have investigated fertiliser impacts on tree growth in restored sites, these have predominantly considered effects in the early years of restoration (e.g. Ward and Koch, 1995; Daws *et al.*, 2013; Daws *et al.*, 2014), and generally do not investigate whether the benefits of a single initial fertiliser addition are sustained in the longer term.

Tree growth in restored forests from 0 - 5 years of age can be maximised by applying N and P fertiliser (e.g. Ward and Koch, 1995; Cromer *et al.*, 2002). While there can be varied tree growth responses, for example Siddique *et al.* (2010) reported a weaker response of tropical tree species to combined N and P fertilisation compared to N-only or P-only treatments in the Brazilian Amazon, many studies observe a reduced effect of applied-N with increasing restoration age (Siddique *et al.*, 2010; Daws *et al.*, 2014). A reducing effect of applied-N over time may result from the re-establishment of nitrogen-cycling, with N_2-fixing plant species naturally increasing levels of available-N (Koch and Ward, 2005; Banning *et al.*, 2008). For example, in jarrah forest restoration following bauxite mining in Western Australia, the dominant tree species jarrah (*Eucalyptus marginata*) exhibited no growth response to N, applied at a rate of 20 kg ha^{-1}, either two and a half or five years after N application (Daws *et al.*, 2013; Daws *et al.*, 2014), presumably because applied-N had leached from the study sites and a conservative N-cycle had developed (Banning *et al.*, 2008). In contrast, there was an ongoing growth response to applied-P (Daws *et al.*, 2013; Daws *et al.*, 2014).

Application of P-fertiliser can elevate soil-P concentrations for at least 26 years in restored eucalypt forests, including the jarrah forest (Banning *et al.*, 2008; Spain *et al.*, 2018; Tibbett *et al.*, 2019). Consequently, a single initial application of P-fertiliser has the potential to have on-going long-term benefits for tree growth. Daws *et al.* (2019) demonstrated, for jarrah growth in post mining restoration, that the benefits of applied-P for stand basal area and tree height can persist for 15 years following a single initial application. However, whether these initial benefits of applied-P (and N) are maintained in the longer term, at both the individual and stand level, has received little attention. Recent work by Bhandari *et al.* (2021) observed a long-term growth response of jarrah to fertiliser application when combined with tree thinning, and that the unthinned forest had a lower growth response to fertiliser application. This suggests that while higher rates of fertiliser may increase short-term growth of forest trees (e.g., Daws *et al.*, 2013; Daws *et al.*, 2014), it will not necessarily result in long-term benefits for timber production in fully stocked stands.

Despite the effects of fertiliser application on jarrah growth being widely studied (e.g. Daws *et al.*, 2014; Daws *et al.*, 2019), there is no published data on the response of *Corymbia calophylla* (marri) to fertiliser beyond the response of seedlings to applied-P (Barrow, 1977). Marri is also a main canopy tree within the jarrah forest and although it is generally sub-dominant to jarrah, it can become co-dominant on more fertile sites (Dell and Havel, 1989). Unlike jarrah, marri also occurs in areas where root development is limited and access to soil moisture is highly variable, such as in areas with shallow soils and riparian areas susceptible to water logging (Harris, 1956; Florence, 1996). Consequently, marri may respond differently to applied fertiliser than jarrah: however, this has not been explicitly tested.

This study aims to determine the effects of a single, initial application of N and P fertiliser (0, 80 and 120 kg ha^{-1} elemental) on soil nutrient concentrations and the growth of the two main canopy tree species (jarrah and marri) in jarrah forest restored after bauxite mining, 9 and 20 years after the experiment was established. Due to more rapid leaching of applied-N, we hypothesized that the application of N-fertiliser would have no effect on soil-N after 20 years and would not have an effect on tree growth for either monitoring year. However, as long-term persistence of applied-P has been found in previous studies, we expected that applied-P would continue to result in elevated soil P concentrations after 20 years and would continue increase tree growth at both monitoring years. Finally, despite subtle differences in habitat requirements, we hypothesized that the two main canopy trees (jarrah and marri) would respond to fertiliser in a similar way.

2. Materials and Methods

2.1. Study site

The experiment was established within the Alcoa of Australia Ltd. bauxite mining lease in the northern jarrah forest, located between 60 and 100 km south-east of Perth, Western Australia. The area has a Mediterranean climate with cool, wet winters and hot, dry summers. Annual rainfall is ~1,200 mm with average summer maximum temperatures of 29°C and average winter minimum temperatures of 6°C (Australian Bureau of Meteorology, 2018).

The forest vegetation comprises of the dominant overstorey species *Eucalyptus marginata* (jarrah) and the subdominant *Corymbia calophylla* (marri). On average, marri constitutes 20 % of the stems in both restored and unmined forest (Daws *et al.*, 2015). In addition, there is a mid-storey layer of *Banksia grandis, Allocasuarina fraseriana*, and *Xanthorrhoea preisii* and a diverse understorey layer (Dell and Havel, 1989; Gardner and Bell, 2007). The soils of the jarrah forest are gravelly with low concentrations of available nutrients (e.g., N, P and K; Hingston *et al.*, 1989; Tibbett *et al.*, 2020). Phosphorus fixation is high due to the presence of amorphous iron and aluminium oxides, and generically these soils are classified as lateritic oxisols (USDA, 1999) or ferralsols (FAO, 2012).

2.2. Experiment establishment, design and monitoring

The experiment was established in 1994 in six newly restored mine pits following the completion of mining. Restoration activities comprise deep-ripping to alleviate mine related compaction, landscaping, overburden return, topsoil return, contour ripping, seeding and fertilising (Standish *et al.*, 2015). Contour ripping and seeding of all six mine pits occurred in February and March 1994. Within seven days of contour ripping, treatment plots of 25 m × 25 m were established in each of the six mine pits using a randomised complete block design. All treatment plots were seeded with 1.44 kg ha^{-1} jarrah seed, 0.60 kg ha^{-1} marri seed, 0.72 kg ha^{-1} legume species and 0.20 kg ha^{-1} non-legume understorey species. Fertiliser was broadcast by hand on a single occasion at rates of 0, 80 and 120 kg ha^{-1} for both N and P in a fully factorial design. Thus, there were a total of nine fertiliser combinations. Phosphorus was applied as double superphosphate, and nitrogen as ammonium sulphate. No other ameliorants added to the soil, in line with restoration practices at the time.

Measurements of all trees over 1 m in height in the 25 m × 25 m plots were undertaken at 9 years of age (June – July 2003). Tree height and diameter at breast height over bark (DBHOB) were measured for each individual jarrah and marri. Where multiple stems were present at breast height (1.3 m above ground), separate DBHOB measurements were taken for each stem. Three of the six mine pits were later unintentionally burnt, two in 2006 and one in 2008. The burn age for all three sites was greater than the minimum age considered appropriate to safely re-introduce fire (Grant *et al.*, 1997; Smith *et al.*, 2000; Smith *et al.*, 2004).

In 2014 a 20 m × 20 m plot was established in the centre of each 25 m × 25 m treatment plot. This created a 2.5 m wide buffer at the same fertiliser application rate around each 20 m × 20 m plot allowing for possible root growth outside of the 20 m × 20 m plot in the older restoration. Importantly, lateral root growth of jarrah both in rehabilitated mine sites at 13 years of age (Szota *et al.*, 2007) and in regrowth forest with 10 to 30-year-old trees is largely restricted to within 3 m of the base of the tree (Kimber, 1974). Height and DBHOB measurements of all jarrah and marri trees were undertaken in the 20 m × 20 m plots at 20 years of age (April 2014 – January 2015). To reduce the risk of sampling trees that established after the initial seeding event (i.e. trees less than 20-years-old), only trees over 2.5 m in height were measured. Bark depth was also recorded for each tree to allow calculation of under bark measurements (e.g. diameter at breast height under bark [DBHUB]).

In Autumn 2014, six soil samples were collected at 0 - 10 cm depths in the furrow of the rip-lines in each 20 m x 20 m plot and mixed. Soil was air-dried at 26°C and gravel removed using a 2 mm sieve (Rayment and Higginson, 1992). Samples were analysed at a commercial laboratory (CSBP Soil and Plant Laboratories, Bibra Lake, Perth, Australia) assessing KCl extract (available) nitrate nitrogen (NO_3^-), ammonium nitrogen (NH_4^+), Colwell (available) phosphorus, exchangeable calcium, sulphur and soil pH (measured in $CaCl_2$).

2.3. Statistical analysis

Univariate general linear models (GLMs) were used to analyse the effects of N and P fertiliser application on i) soil chemical properties and ii) tree growth parameters separately for jarrah and marri using the *car* package in R (Fox and Weisberg, 2019; R Core Team, 2019). In addition, as jarrah is the main commercially harvested timber and growth responses of jarrah stands can be concentrated in the fastest growing individuals in the population (Stoneman *et al.*, 1989; Stoneman and Whitford, 1995), separate analyses were conducted for the effect of N and P on DBHOB and height of the tallest 150 jarrah trees ha^{-1} (e.g. Grigg and Grant, 2009). 'Site' was included in the models as a predictor variable and measurements at different ages (9 and 20-years) were analysed independently. As tree stocking influences other variables (i.e. stand characteristics), stocking was included in the models for tree and stand growth. Data was transformed using either log or square root transformations as appropriate prior to data analysis. In all analyses an N × P interaction term was included. However, the interaction term was not significant in any of the analyses and for clarity is therefore not presented in the results. Significant differences in treatment levels were determined via a Tukey *post-hoc* test using the *agricolae* package in R (de Mendiburu, 2019).

3. Results

3.1. Soil nutrient responses

A single initial application of P-fertiliser resulted in concentrations of available Colwell-P remaining elevated, compared with the control 0 kg ha^{-1} treatment, after 20 years (Table 1; $P < 0.001$). Application of P-fertiliser also significantly reduced soil pH levels (Table 1, $P < 0.001$). However, there were no effects of applied-P on soil NH_4^+, exchangeable calcium or sulphur concentrations (Table 1; $P > 0.05$). Soil NO_3^- was not compared between fertiliser treatments as 98 % of samples had values below detection limits. In contrast, after 20 years N-fertiliser application had no effect on soil phosphorus, soil ammonium concentrations, exchangeable calcium, sulphur or pH ($P > 0.05$).

3.2. Tree stocking and survival

A total of 2,730 jarrah and 747 marri trees were recorded across the 20 m × 20 m plots at 20 years with average densities of 1,264 and 346 trees ha^{-1}, respectively. In comparison, 3,233 jarrah and 1,206 marri were recorded in the same plots at 9 years with densities, on average, of 1,497 and 559 trees ha^{-1}, respectively. Survival rates, between 9 and 20 years were, on average, 93 % and 70 % for jarrah and marri, respectively. Overall stocking rates varied between the six mine pits with a range of 920 – 3,750 trees ha^{-1} at 9 years and 817 – 2,326 trees ha^{-1} at 20 years.

Applied-P significantly increased the initial stocking rate of marri with the density remaining elevated after 20 years (Figure 1; $P < 0.001$). For jarrah, P-application rate had no effect on stocking rate in either year (Figure 1; $P > 0.05$). The application of N had no effect on the stocking rate of jarrah or marri in either year ($P > 0.05$). Finally, total survival rates between the study years were independent of both N ($P > 0.05$) and P application ($P > 0.05$).

Across all fertiliser treatments, 20 years after restoration jarrah had a mean diameter at breast height over bark (DBHOB) of 15.7 cm, a diameter at breast height under bark (DBHUB) of 12.6 cm and a mean tree height of 9.73 m. Marri growth was lower with a mean DBHOB of 11.6 cm, a mean DBHUB of 8.20 cm and a mean tree height of 7.75 m. All measurements had increased since measured at 9 years of age when the mean jarrah and marri DBHOB was 8.97 and 5.41 cm, respectively and mean tree heights were 5.38 and 3.94 m respectively.

Table 1
The effect of a single initial application of different rates of N and P fertiliser at the onset of restoration on soil NH_4^+, NO_3^-, Colwell (available) P, Ca, S, and pH ($CaCl_2$) in 20-year-old jarrah forest restored after bauxite mining. Treatments were applied in a fully factorial design but as the interaction term was not significant the means for N and P application are presented separately. Values for the unmined forest are also presented for comparison with restored areas.

Fertiliser treatment	Application rate(kg ha^{-1})	Colwell P(mg kg^{-1})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})	Ca(meq 100g^{-1})	S(mg kg^{-1})	Soil pH ($CaCl_2$)
	0	4.94 ± 1.72^a	5.50 ± 1.15^a	< 1	0.50 ± 0.06^a	6.86 ± 0.46^a	4.71 ± 0.08^a
Nitrogen	80	4.28 ± 1.19^a	4.67 ± 0.56^a	< 1	0.60 ± 0.07^a	6.33 ± 0.37^a	4.77 ± 0.09^a
	120	4.72 ± 1.58^a	5.11 ± 1.00^a	< 1	0.54 ± 0.06^a	6.87 ± 0.35^a	4.77 ± 0.08^a
Phosphorus	0	1.28 ± 0.23^A	5.22 ± 0.23^A	< 1	0.56 ± 0.06^A	6.68 ± 0.37^A	4.93 ± 0.08^A
	80	4.94 ± 0.82^B	5.11 ± 0.82^A	< 1	0.55 ± 0.06^A	6.88 ± 0.42^A	4.68 ± 0.06^B
	120	7.72 ± 1.58^C	4.94 ± 1.58^A	< 1	0.54 ± 0.09^A	6.50 ± 0.40^A	4.63 ± 0.05^B
Unmined forest	N/A	2[†], 3.7[‡]	3[†], 4.3[‡]	< 1[†], < 1[‡]	0.44[*]	4.3[†]	5.20[†], 5.1[‡]

Within each column superscripts indicate a significant difference (GLM, $P < 0.05$) between values, associated with either N or P application rate.
[†] Data from Standish *et al.* (2008).
[‡] Data from Tibbett et al. (2020).
[*] Data from O'Connell and Mendham (2004)

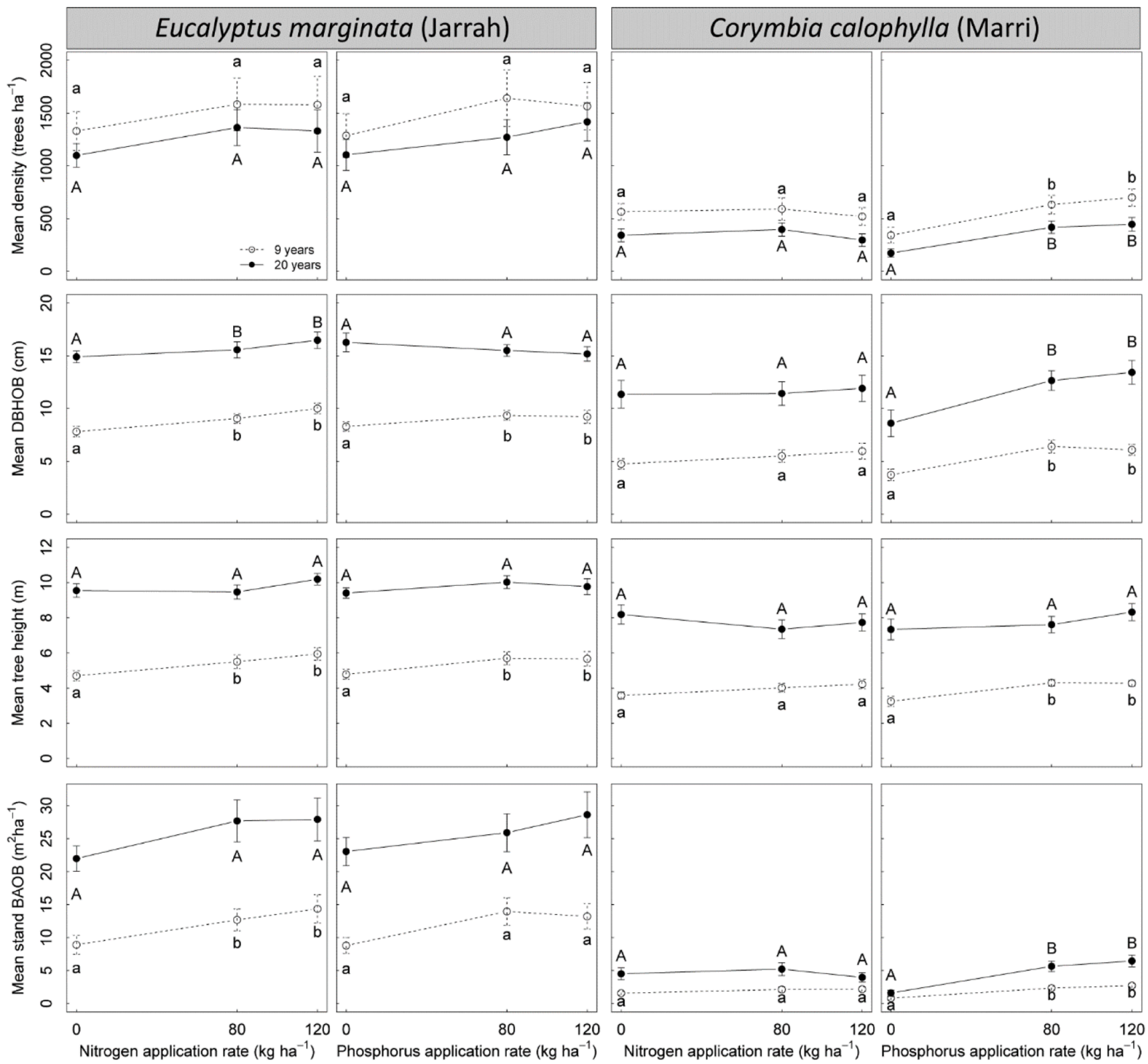

Fig. 1. The effect of a single initial fertiliser application on individual tree and stand-level attributes measured after 9 and 20 years in forest restored after bauxite mining. Data are presented separately for jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*). Error bars are ± 1 SE of the mean. Treatments were applied in a fully factorial design but as the interaction term was not significant the means for N and P application are presented separately. Letters indicate significant differences ($P < 0.05$) in tree density at the different fertiliser treatment levels as determined by Tukey's post-hoc tests. Upper and lower case letters cannot be directly compared.

3.3. Jarrah responses to fertiliser application

Application of N fertiliser significantly increased both DBHOB and tree height after 9 years (Figure 1; $P < 0.001$). A similar effect on height (Figure 1; $P < 0.01$) and DBHOB (Figure 1; $P < 0.05$) was also observed for P. After 20 years, P-application no longer affected tree growth ($P > 0.05$) but applied-N continued to influence DBHOB ($P < 0.05$), although the effects on DBHOB were less significant than at 9 years. The tallest 150 jarrah ha^{-1} were ca. 3 m taller than the population average and had a DBHOB ca. 4 cm larger Similar to the population as a whole, there were no significant effects of P on either DBH (18.5, 19.6 and 20.3 cm for 0, 80 and 120 kg ha^{-1}, respectively), or height after 20 years (12.1, 13.2 and 13.8 cm for 0, 80 and 120 kg ha^{-1}, respectively). Unlike the whole population, where there was a significant effect of N on DBHOB after 20 years (Figure 1), there was no effect of N on DBHOB of the tallest 150 trees ha^{-1} (19.3, 19.7 and 19.4 cm for 0, 80 and 120 kg ha^{-1}, respectively), nor was there any effect on height (13.1, 12.8 and 13.1 cm for 0, 80 and 120 kg ha^{-1}, respectively).

For jarrah, applying N significantly increased the mean annual increment (MAI) for individual tree diameter and height growth ($P < 0.001$) for the interval 0 – 9 years. Applied-N also significantly increased the MAI for jarrah stand basal area between 0 – 9 years ($P < 0.05$) although this effect was no longer observed between 9 – 20 years (Figure 2). The MAIs for 0 – 9 years increased with P-application although this was only significant for height ($P < 0.01$). However, these effects were no longer observed between 9 – 20 years ($P > 0.05$). Overall, the mean annual increment (MAI) for DBHOB and height growth rates of jarrah declined by more than 33 % over the study period for individual trees, from 1.00 cm year^{-1} to 0.61 cm year^{-1} for DBHOB and from 0.60 m year^{-1} to 0.40 m year^{-1} for height. The annual increment in stand basal area over bark (BAOB) for jarrah also decreased between the two study periods from 1.33 m^2 ha^{-1} year^{-1} between 0 – 9 years to 1.26 m^2 ha^{-1} year^{-1} between 9 – 20 years.

3.4. Marri responses to fertiliser application

Application of P significantly increased both DBHOB and height for marri trees after 9 years (Figure 1; $P < 0.001$ and $P < 0.05$, respectively) while no effect of N application was observed ($P > 0.05$). Similar patterns were observed at 20 years, with applied-N having no effect (Figure 1; $P > 0.05$) and P-application significantly increasing DBHOB (Figure 1; $P < 0.001$): the effect of P on tree height was no longer

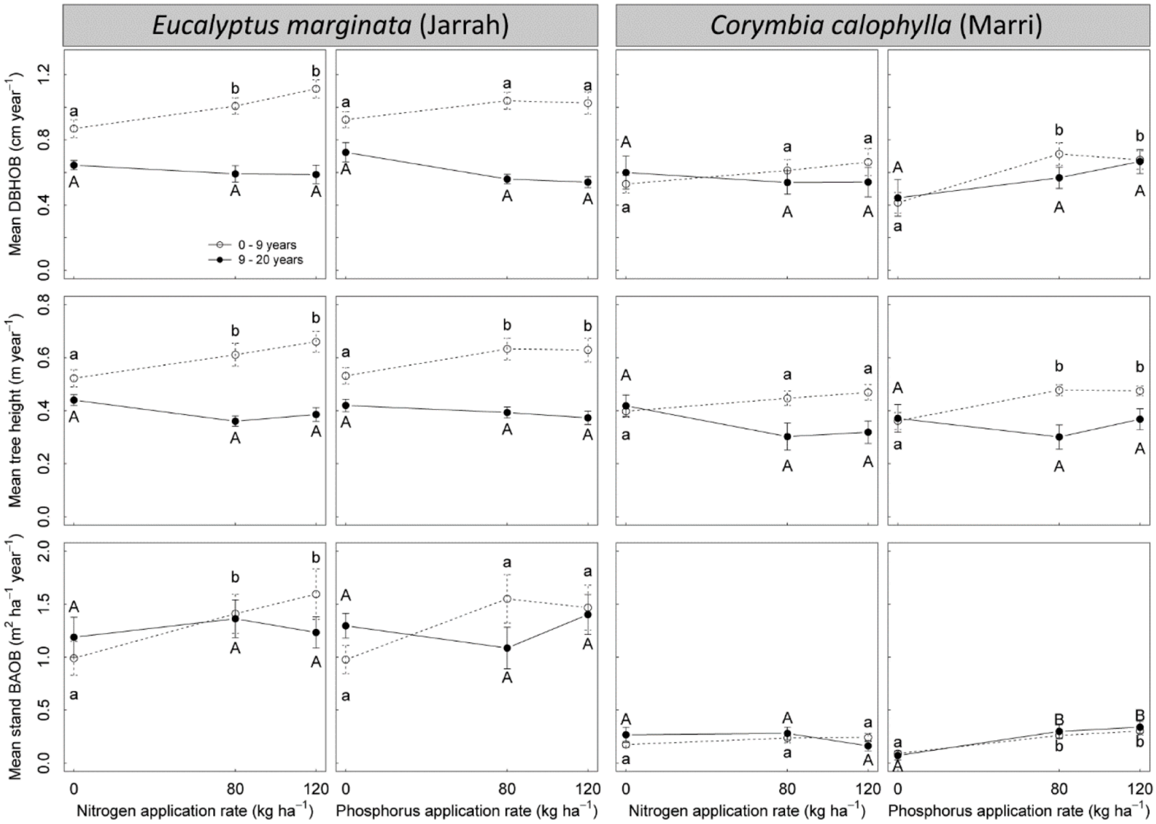

Fig. 2. The effect of a single initial fertiliser application on growth increments for individual tree and stand-level attributes over the periods 0–9 and 9–20 years in forest restored after bauxite mining. Data are presented separately for jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*). Error bars are ± 1 SE of the mean. Treatments were applied in a fully factorial design but as the interaction term was not significant the means for N and P application are presented separately. Letters indicate significant differences ($P < 0.05$) between the different fertiliser treatment levels as determined by Tukey's post-hoc tests. Upper and lower case letters cannot be directly compared.

significant ($P > 0.05$).

For marri, applying P but not N, significantly increased the MAI for individual tree growth (i.e. diameter and height) as well as stand basal area between 0 – 9 years (Figure 2; $P < 0.05$). In the 9 – 20 year interval the only ongoing significant effect on MAIs was for stand basal area (Figure 2; $P < 0.01$). Between the two study period intervals, MAIs for marri DBHOB and height also declined, from 0.60 cm year^{-1} to 0.56 cm year^{-1} for DBHOB and from 0.44 m year^{-1} to 0.35 m year^{-1} for height, but to a lesser extent than for jarrah. Unlike jarrah, the annual increment in stand BAOB for marri increased slightly, from 0.22 m^2 ha^{-1} year^{-1} to 0.24 m^2 ha^{-1} year^{-1}.

3.5. Effects of N and P on stand level characteristics

Overall, the mean stand BAOB after 20 years was 25.9 m^2 ha^{-1} for jarrah and 4.57 m^2 ha^{-1} for marri, compared to 12.0 m^2 ha^{-1} and 1.96 m^2 ha^{-1} after 9 years, respectively. Neither N nor P application affected the BAOB of the 20-year-old jarrah stand ($P > 0.05$), although applied-P did have an effect on marri stand BAOB ($P < 0.05$; Figure 1).

4. Discussion

Twenty years after a single initial fertiliser application, we found that N fertiliser had no effect on soil-N or marri tree growth, as expected, and there were only minimal benefits to jarrah DBHOB. As hypothesized, P fertiliser continued to influence soil chemical properties, and increase tree growth, particularly for marri with effects on DBHOB, density and stand BAOB. For jarrah these elevated soil P concentrations coincided with increased tree height up to 9 years of age, but not beyond. This suggests that the two main canopy trees respond to applied nutrients in different ways, despite our prediction for similar responses in these co-occurring eucalypts.

We observed significant responses of jarrah to N fertiliser for all measured growth variables at 9 years but only for DBHOB at 20 years. While these effects persisted for longer than in other jarrah forest research (e.g. Daws *et al.*, 2013; Daws *et al.*, 2014), this may be due to the higher application rates (80 and 120 kg ha^{-1}) compared with previous studies. For instance, Daws *et al.* (2013) found a single application of 20 kg ha^{-1} of N had no impact on jarrah growth after 2.5 years. Short-term benefits of N-application have also been observed in *Eucalyptus globulus* plantations in south-eastern Australia with application rates of 200 kg ha^{-1} significantly increasing tree volume for up to 4 years after application compared to unfertilised plots (Judd *et al.*, 1996).

Despite the DBHOB being higher in the N-treatments, there was no effect of N fertiliser on the annual diameter growth increment in the 9 – 20 year interval, suggesting that greater DBHOB at 20 years was a legacy of faster growth in the 0 – 9 year interval. Limited ongoing long term benefits of applied-N on growth in our current study and other research (e.g. Siddique *et al.*, 2010) likely results from leaching of applied-N from the study sites and the re-establishment of N-cycling processes where the majority of soil N comes from N_2-fixation by legumes (Koch and Ward, 2005; Grant *et al.*, 2007; Banning *et al.*, 2008). Regeneration of nitrogen-fixing legumes (e.g. *Acacia* spp) species from the topsoil is common in jarrah forest restoration (e.g., Daws *et al.*, 2015; Daws *et al.*, 2019), including within these study sites (Standish *et al.*, 2008). This raises the question of how long differences in N will persist and whether the trees in the zero N treatment will ultimately 'catch up' with those that were initially fertilised.

In contrast to applied-N, we found that after 20 years the application of P fertiliser resulted in elevated soil-P concentrations and marri growth responses. Specifically, soil-P levels in plots of both application rates (80 and 120 kg ha^{-1}) were more than double concentrations in unmined forest (McArthur, 1991; Lambers *et al.*, 2008). The higher application rates within this study reflect rates commonly used at the time of trial establishment (e.g. Ward, 2000), which were greater than the quantity of nutrients estimated to be lost due to vegetation removal prior to mining (see Hingston *et al.*, 1980). The persistence of applied-P following a single fertiliser application could be due to the high rates of initial application and/or the highly P fixing soils of the jarrah forest, with elevated P having been observed up to 26 years following restoration of other *Eucalyptus* forest communities on oxisols and ferralsols (Spain *et al.*, 2018).

P fertiliser also continued to significantly influence marri DBHOB and stand basal area after 20 years. However, as the P-application rate had no effect on the annual increment in DBHOB for the 9 – 20 year interval, the ongoing effect on DBHOB (and by implication basal area) at 20 years is likely to be a legacy of more rapid stem diameter growth in the 0 – 9 year interval. Although the P fertiliser (double superphosphate) was applied to replace levels of P lost during vegetation removal, it also supplies large quantities of calcium to the soil (52 and 78 kg ha^{-1} for the 80 and 120 kg ha^{-1} P treatments, respectively). Therefore, increased growth of marri in fertilised treatments could be due to application of P, or possibility due to a calcium deficiency in the unfertilised treatments, although it is worth noting that after 20 years there were no differences in soil Ca between treatments. Furthermore, although P fertiliser increased marri basal area after 20 years, marri only makes up a comparatively small component of the stand basal area and is not used for timber production in the northern jarrah forest.

While jarrah growth responded positively to P fertiliser over the first monitoring interval (0 – 9 years), there were no ongoing effects on growth beyond 9 years and the P-related differences in tree growth disappeared after 20 years. Short-term, up to five-years, positive effects of applied-P on jarrah height and diameter growth have been reported previously (e.g. Daws *et al.*, 2013; Daws *et al.*, 2015), while Daws *et al.* (2019) reported a significant effect on both tree height and basal area for 15-year-old jarrah stands. Further, Grigg and Grant (2009) thinned restored jarrah stands aged 10-13 years and observed that growth responses to applied fertiliser only occurred in thinned, but not un-thinned stands. They attributed this response to these jarrah stands being primarily water limited rather nutrient limited. Interestingly, the stands in Daws *et al.* (2019) had a lower stocking rate (average stocking of 1,170 stems ha^{-1}) than both our current study (average stocking of 1,610 ha^{-1}) and Grigg and Grant (2009) (average stocking of 1,520 stems ha^{-1}). Therefore, one explanation for a continued response to P at 15 years in Daws *et al.* (2019) is that these developing stands were less constrained by water availability, due to the lower stocking, and thereby still able to respond to elevated soil P. This observation is also not unique to jarrah with 4-year-old *Eucalyptus grandis* in South Africa constrained more by water availability than soil nutrient supply (Campion *et al.*, 2006). For more mature (35-45 year old) thinned regrowth jarrah stands, Abbott and Loneragan (1986) reported that applied-N (but not P) benefitted diameter growth and concluded that N is more likely to limit long-term jarrah productivity than P. Another possible explanation could be that tree growth rates are reached more rapidly in fertilised treatments compared to unfertilised plots, although distinguishing these effects from those of resource limitation will require further work.

Jarrah growth responses can be concentrated within the largest trees in a stand: the largest trees access the majority of the available site resources and grow most rapidly (Stoneman *et al.*, 1989; Stoneman and Whitford, 1995; Grigg and Grant, 2009). However, we found that the response of the largest trees in the population to applied fertiliser was similar to the whole population. The absence of a different response for the larger trees may be due to the single age stand structure; these trees may not be sufficiently large, compared to the rest of the population, to monopolise soil nutrients. Taken together, these results suggest that while applying P fertiliser may initially increase jarrah growth, there may be limited long-term benefits to forest restoration and timber production.

Overall, the effects of fertiliser application on tree growth were not analogous for jarrah and marri. For example, for marri, there were no responses to applied-N for either monitoring interval, and the effect of applied-P on stem diameter (but not the annual increment in diameter growth) was still significant in the 9 – 20 year interval. In contrast, jarrah initially responded strongly to N (for DBHOB, height and BAOB) and to P for height growth, with the initial (0 – 9 year) benefit of N for diameter growth resulting in greater DBHOB even after 20 years. While fertiliser responses of the dominant, commercially important species jarrah have been reported in restored (e.g. Stoneman *et al.*, 1995; Daws *et al.*, 2014; Daws *et al.*, 2015; Daws *et al.*, 2019) and unmined forest (Stoneman *et al.*, 1995; Stoneman *et al.*, 1997), to our knowledge this is the first study to investigate the response of marri trees to fertiliser. Whilst the basis of the differences between species is unknown, the fact that the usually sub-dominant marri can become co-dominant with jarrah on more fertile sites (Dell and Havel, 1989) may reflect either a greater ability to respond to available soil-P (this study), and / or growth being less constrained by limited water availability (e.g. Szota *et al.*, 2011).

Despite the reduction in total stocking rates over the 20-year course of the experiment being independent of N or P application rate, higher stocking rates were observed in the P fertiliser treatments for both species, but this was only statistically significant for marri. White-Toney *et al.* (2019) previously reported that jarrah and marri density 9 months after seeding was positively related to fertiliser application rate, and one explanation could be that fertiliser may increase stocking rate by increasing initial seedling size (Stoneman *et al.*, 1995), thereby increasing survival over the first summer drought (e.g. Daws *et al.*, 2005). While jarrah has been reported to not exhibit self-thinning (Stoneman *et al.*, 1989), our current data suggest that restored jarrah stands, many of which are over-stocked compared with unmined forest (Grant, 2006), will reduce in stocking density over time potentially militating against the need for silvicultural treatment (c.f. Grigg and Grant, 2009). Whether this reduction in stocking rate is density dependent (self-thinning) or related to other factors such as occurrence of fire (i.e. density independent) is unclear and requires further investigation.

The elevated soil-P concentrations after 20 years may mean that in restored stands, which received 80 kg of N and P ha^{-1} as standard practice (Standish *et al.*, 2015), the soil is effectively 'pre-fertilised' in the event of thinning and may not require additional P-inputs. While it is currently unknown if the post thinning growth responses of jarrah and marri in this scenario are analogous, our current data suggests that marri may be more responsive to elevated post-thinning soil P. Consistent with elevated residual soil P concentrations, Grigg and Grant (2009) reported vigorous establishment of a dense legume understorey consisting of highly P-responsive species following thinning and burning of restored jarrah stands. Consequently, there is a need to develop silvicultural practices and burning regimes that enable these restored stands to be reintegrated within standard forest management and to understand potentially differential responses of jarrah and marri.

We found no additional benefit in increasing N or P application rates beyond 80 kg ha^{-1}. Indeed, at least for P the optimum application rate could be even lower. For example, in 5-year-old restored stands there was no difference in jarrah height growth or basal area between P application rates of 20, 40 and 80 kg ha^{-1} (Daws *et al.*, 2014; Daws *et al.*, 2015), although growth was reduced at 0 and 10 kg ha^{-1}. Indeed, our current data suggests that, for jarrah, there is little long-term (20 year) benefit from applying any P-fertiliser although further studies should assess whether the initial benefit of N persist beyond 20 years. Our results for 20-year-old restored jarrah stands also suggest that, even when no fertiliser is applied, growth is similar to unmined forest stands. For example, regenerating jarrah coppice, which represents the fastest possible height growth rate in unmined forest, was ~9.8 m tall after 20 years with a DBHUB of ~10 cm (Abbott and Loneragan, 1982) compared with ~9.7 m and 12.7 cm, for height and DBHUB, respectively in our current study. In addition, Stoneman *et al.* (1988) reported annual BAOB increments, in 26-year-old heavily cut-over regrowth jarrah stands, of 0.95 $m^2\ ha^{-1}\ y^{-1}$. For 20-year-old jarrah we observed annual increments in BAOB of ca. 1.3 $m^2\ ha^{-1}\ y^{-1}$ suggesting that these restored stands are performing favourably when compared with unmined forest.

5. Conclusion

In restored jarrah forest, the practical effect of N and P application on jarrah and marri tree growth, at the rates examined, reduced considerably over time. Tree growth rates in the fertilised treatments generally declined more between the two-time intervals (0 – 9 years and 9 – 20 years) than the unfertilised plots, particularly for jarrah, suggesting that trees may have reached nutrient and / or growth limits more rapidly in the fertilised treatments. Overall, this data indicates that while fertiliser may provide an initial benefit to tree establishment and growth, the effects reduce with restoration age and may have limited practical benefit after 20 years.

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