2019

Variable tree establishment in bauxite mine restoration in south-west Australia linked to rainfall distribution, seasonal temperatures and seed rain

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This article was originally published as:
White-Toney, T., Korczynskyj, D., Grigg, A., & Bulsara, M. (2019). Variable tree establishment in bauxite mine restoration in south-west Australia linked to rainfall distribution, seasonal temperatures and seed rain. *Ecological Management and Restoration, Early View (Online First)*.

Original article available here:
https://doi.org/10.1111/emr.12389

This article first published in *Ecological Management and Restoration*:

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This article has been published in final form at: -

https://onlinelibrary.wiley.com/doi/full/10.1111/emr.12389

Ecological Management
& Restoration Linking science and practice
Ecological Society of Australia

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Journal:	*Ecological Management & Restoration*
Manuscript ID	EMR-SR-2019-Mar-013.R1
Wiley - Manuscript type:	Short Report
Keywords:	eucalypt, restoration, Jarrah, Marri, Mediterranean
Abstract:	Reasons for variable establishment of Jarrah (Eucalyptus marginata D. Don ex Sm.) and Marri (Corymbia calophylla (Lindl). K. D. Hill & L. A. S. Johnson) on restored forest sites after bauxite mining in south west Australia are not well understood. To refine restoration outcomes, we compiled tree seedling density establishment data from surveys of 654 previously mined sites restored between 1998 and 2017, and applied Generalised Linear Models to discriminate the effects of 24 climatic and restoration practice variables. Final models explained 50% and 31% of the variation in Jarrah and Marri density, respectively. Broadcast seeding and fertiliser rates were positively related to seedling density. A more even rainfall distribution in the early wet season increased seedling density. However, persistent rain later in the wet season decreased density, possibly as a result of ripline soil saturation or ponding. Higher average daily maximum temperatures in the dry season decreased seedling density probably due to drought stress, but warmer daily temperature minima in both wet and dry seasons increased density. Seed rain from surrounding unmined forest was implicated as a significant, but highly variable, source of additional seed to restored sites. Restoration practices that influence soil moisture relations (tillage, depth and texture of returned soil), shallow burial of applied seed and timing of fertiliser application are likely to be important in refining restoration outcomes.

Variable tree establishment in bauxite mine restoration in south west Australia is linked to rainfall distribution, seasonal temperatures, and seed rain.

Summary

Reasons for variable establishment of Jarrah (*Eucalyptus marginata* D. Don ex Sm.) and Marri (*Corymbia calophylla* (Lindl). K. D. Hill & L. A. S. Johnson) on restored forest sites after bauxite mining in south west Australia are not well understood. To refine restoration outcomes, we compiled tree seedling density establishment data from surveys of 654 previously mined sites restored between 1998 and 2017, and applied Generalised Linear Models to discriminate the effects of 24 climatic and restoration practice variables. Final models explained 50% and 31% of the variation in Jarrah and Marri density, respectively. Broadcast seeding and fertiliser rates were positively related to seedling density. A more even rainfall distribution in the early wet season increased seedling density. However, persistent rain later in the wet season decreased density, possibly as a result of ripline soil saturation or ponding. Higher average daily maximum temperatures in the dry season decreased seedling density probably due to drought stress, but warmer daily temperature minima in both wet and dry seasons increased density. Seed rain from surrounding unmined forest was implicated as a significant, but highly variable, source of additional seed to restored sites. Restoration practices that influence soil moisture relations (tillage, depth and texture of returned soil), shallow burial of applied seed and timing of fertiliser application are likely to be important in refining restoration outcomes.

Key words: *eucalypt, restoration, Jarrah, Marri, Mediterranean*

Introduction

Variability in seedling establishment of Jarrah (*Eucalyptus marginata* D. Don ex Sm.) in the Northern Jarrah Forest of south west Australia, including after bauxite mining, has been the subject of several investigations (Stoneman & Dell 1994; McChesney *et al.* 1995; Cargill *et al.* 2019). Seed germination occurs during the winter wet season in this Mediterranean-type ecosystem (Abbott 1984). However, the interaction of seed supply and seedbed conditions leads to complex outcomes (Cargill *et al.* 2019). Alcoa of Australia (Alcoa) has been mining bauxite and undertaking rehabilitation in the Northern Jarrah Forest for more than 50 years. Since the late 1980s, restoration sites have been directly seeded with Jarrah and Marri (*Corymbia calophylla* (Lindl). K.D.Hill & L.A.S. Johnson), following methods described in detail by Koch (2007). Routine assessment of tree densities indicated variable establishment, but to date investigations into underlying reasons have been inconclusive (Norman & Koch 2009). Tree establishment densities falling outside acceptable ranges specified in mine rehabilitation standards require remedial treatment such as infill planting. Therefore, a better understanding of variable establishment could lead to improved cost efficiency. A more recent study into variability in understorey species return in the same restoration sites (Standish *et al.* 2015) identified the importance of both restoration practices and climatic drivers, suggesting that tree establishment may be affected by similar variables, along with seed supply. Here, we use a 20-year record of restoration monitoring in an effort to better understand the factors driving tree establishment variability in this environment, with the ultimate aim of improving restoration outcomes.

Methods

We compiled records of Jarrah and Marri seedling densities from surveys of restoration sites at Alcoa's Huntly (32°42'S 116°03'E) and Willowdale (35°09'S 116°05'E; Figure 1) mines that had been restored over the period 1998 to 2017 inclusive (n = 654). Surveys were carried out usually in late March, approximately one year after the completion of restoration and seeding activities, using a 2 m-wide transect of sufficient length to randomly cover 3-5% of each site. We then obtained or calculated, for each restoration site, a range of climatic and restoration practice variables (Table 1) that were considered likely to be important to seedling establishment (McChesney *et al.* 1995; Standish *et al.* 2015).

Daily rainfall records were obtained from one of six rain gauges nearest to each restoration site (mean distance 7.8 km; Figure 1). Daily air temperature data for all sites were sourced from the nearest Climate Station at Dwellingup (32°72'S 116°07'E; Bureau of Meteorology http://www.bom.gov.au; Figure 1). The wet season was defined as the period in each year when rainfall (R) was greater than twice the mean temperature (2T), following Standish *et al.* (2015), based on running 30-day rainfall totals and 30-day average maximum temperatures (i.e. R/T>2). 'False starts' to a wet season (Standish *et al.* 2015) were also identified. In our study, the dry season was defined as the period from the end of the wet season to the last day of March, coincident with the approximate timing of tree monitoring. Wet season rainfall evenness during the first 30, 60, 90 and 120 days and for the full season was calculated using a modified measure of species evenness (Simpson's Diversity index; Bronikowski & Webb 1996). Evenness values vary from 0 (all rain recorded for the period falls on one day) to 1 (rain recorded for the period falls in equal amounts each day). Seed of Jarrah and Marri was typically broadcast onto the freshly prepared soil surface in the dry season prior to the first winter wet season. Bulking of seedlots and seed viability checks as standard practice minimised the potential for variability in seed quality across restoration sites and years. Reductions in seeding rate over the study period (described in Table 1) were a management response to changes in mine rehabilitation standards for acceptable tree establishment densities. A standard fertiliser blend of di-ammonium phosphate plus potassium and micronutrients was typically applied in the first spring after completion of restoration activities. From 2016 onwards, application was delayed until the second spring after establishment, resulting in zero fertiliser at the time of monitoring. Topsoil management for each restored site was scored from 'best' (7) to 'worst' (1), following Standish *et al.* (2015). Seed rain was not measured as part of this study, however three surrogate variables were included: the proportion of each restoration site's perimeter that was composed of intact mature forest, the perimeter to area ratio of the restoration site, and total annual rainfall two years prior to monitoring, which is correlated with seed supply (Johnstone & Kirkby 1999).

We used Generalised Linear Models (GLMs) with normal distributions and identity link functions within the statistical package Stata Ver. 15 (StataCorp 2017) to identify the explanatory variables, and their interactions, important for predicting Jarrah and Marri seedling densities at establishment. The analysis omits collinear variables prior to model fit, and because no collinear variables were identified, all potential variables were included in the model selection process. The final model for each species was obtained by backward step elimination of variables from the saturated model until only significant variables remained ($p<0.05$). The goodness of fit of each model was assessed using Pseudo R^2, and effect size was calculated to rank the relative importance of each explanatory variable. Model output includes the expected change in tree seedling density for a unit change in a given explanatory variable (β value), holding all other model variables at their mean value (Vittinghoff *et al.* 2012). Each β value must be interpreted within the context of the observed range for the explanatory variable.

Results and Discussion

A total of 13 climate and restoration practice variables were included in the final model for Jarrah, and 11 for Marri (Table 1), explaining 50.1% and 30.6% of the variation in seedling density, respectively. No one factor had an effect size (ES) greater than 8% (Supplementary material Table

S1), which may help to explain why previous short-term attempts to isolate single important explanatory variables were met with limited success (Norman & Koch 2009). As expected, seed application rate was highly significant in both models, and ranked first and second by effect size for Jarrah and Marri, respectively (Supplementary material Table S1). Observed trends in annual average density for Jarrah, from 2368 seedlings/ha in 1998 to 247 seedlings/ha in 2017, and for Marri from 852 seedlings/ha in 1999 to 229 seedlings/ha in 2013, are consistent with reductions in seeding rates for each of the two species over the study period (Table 1).

Additional seed supplied from the forest surrounding restored sites is strongly implicated in this study and, due to high spatial heterogeneity of canopy-borne seed in the forest (Cargill *et al.* 2019), is likely to be an important contributor to seedling density variability among restoration sites within a single year. Furthermore, temporal variation in Jarrah seed production has previously been reported (Abbott & Loneragan 1986) which may contribute to variability across years. Restoration sites with an increasing proportion of forest perimeter (Jarrah ES, 0.041; Marri ES, 0.023), and to a lesser extent those with a higher ratio of perimeter to area (Jarrah ES, 0.014), were estimated to have increased seedling establishment: more than 400 additional seedlings/ha for a fully forested perimeter for Jarrah and nearly 140 seedlings/ha for Marri (Table 1) when compared to sites with no forest edge. Restoration site geometry (here measured as perimeter to area ratio) becomes increasingly important with increasing seed dispersal distance since this enhances overall site coverage by seed rain. The inclusion of this variable in the model for Jarrah but not Marri may be because Marri seed is much larger than Jarrah (average seed mass 0.113 g for Marri vs. 0.020 g for Jarrah; Abbott 1984) and hence has a smaller dispersal distance. Abbot & Loneragan (1986) report dispersal distances for Jarrah seed of up to 1.5 times tree height; dispersal distances for Marri seed are unknown. The importance of seed rain is underscored by the inclusion in the final models of both species of annual rainfall two years prior to restoration activities (Jarrah ES, 0.007; Marri ES, 0.006). Years with high wet season rainfall are associated with abundant flowering in the following spring (Johnstone & Kirkby 1999), potentially resulting in increased capsule production and seed supply in the summer dry season approximately 12 months later. Quantification of the potential contribution of seedfall from the forest on the perimeter of restoration sites is the focus of a separate study.

The positive relationship between fertiliser rate and both Jarrah (ES, 0.030) and Marri (ES, 0.046) density (Table 1) was unexpected, as this had not been detected in previous fertiliser field trials (e.g. Lockley & Koch 1996). Presumably, increased nutrient availability from fertiliser application promotes root growth of the young seedlings, thus improving survival over the ensuing dry season. While higher fertiliser application rates may increase tree seedling density, lower application rates promote greater understorey species richness and similarity of restored sites to unmined forest (Daws *et al.* 2015), presenting competing objectives. Since current practice is to apply fertiliser in the second year after establishment, earlier application of fertiliser warrants further investigation as a possible solution.

Jarrah and Marri densities were both positively and negatively related to the evenness of rainfall distribution during the wet season depending on the period of measurement, while the total amount of wet season rainfall received was not important (Table 1). Rainfall received more evenly through the early part of the wet season (typically May-July for Jarrah, May-August for Marri) had a positive relationship with density (effect size of rainfall evenness over the first 30 days was 0.055 for Jarrah and 0.027 for Marri). However, continued wet conditions later into the wet season had a negative relationship (effect size of rainfall evenness over the full wet season was 0.041 for Jarrah and 0.042 for Marri). Early and more even rainfall is likely to provide a consistently moist soil environment at the surface, promoting successful seedling emergence and survival of the small seedling, which is at heightened risk of desiccation. Persistent rainfall may result in saturated soil or even ponding within the contour riplines, leading to anoxic soil conditions and seedling death. Jarrah seedlings maintain open leaf stomata even after waterlogging, leaving this species particularly susceptible to anoxic soil conditions (Davison & Tay 1985). Brief but heavy rainfall events in the dry season may also have a similar effect (Table 1).

Given the importance of rainfall evenness, soil management practices that influence moisture holding capacity (tillage depth, and depth and texture of returned soil layers over the mine pit floor) could be important in determining tree seedling density among and within restoration sites. Stoneman *et al.* (1994) also implicated seedbed conditions in bauxite mine pits, as they related to water deficits, in successful Jarrah seedling survival. Topsoil quality as determined by storage, processing and return, and by the presence of a soil pathogen, were not included in either model (Table 1). This contrasts with understorey species which have been shown to be strongly influenced by soil management practices (Standish *et al.* 2015). This difference most likely reflects differing sources of seed, being dominated by the soil seedbank in the case of understorey but not for Jarrah or Marri (Koch *et al.* 1996). The results of this study are consistent with the conclusions of Cargill *et al.* (2019) in that the overwhelming driver of Jarrah seedling establishment is seed supply.

Temperature conditions were most important during the dry season. Higher average daily maximum temperatures were associated with reduced densities of both species (Table 1; Jarrah ES, 0.026 and Marri ES, 0.058), probably linked to drought stress. A positive relationship between density and higher dry season minimum temperatures (Jarrah ES, 0.011 and Marri ES, 0.039), and possibly also brief hot spells for Jarrah (ES, 0.013), may be related to enhanced capsule ripening and seed fall leading to increased contribution of seed from peripheral forest under these conditions, although this requires further investigation. A positive relationship with the only significant wet season temperature variable, the lowest daily minimum (Jarrah ES, 0.009 and Marri ES, 0.024), possibly relates to the damaging effects of frost (Matusick *et al*. 2014). Alternatively, lower wet season overnight temperatures are often associated with dry periods with clear night skies, suggesting an indirect effect of soil moisture availability.

The only variable in this study that was significant for Marri but not Jarrah was the delay between seeding and the onset of the wet season (Table 1). A longer delay between seed broadcasting and commencement of the wet season was associated with lower Marri establishment (ES, 0.045). Marri seed is much larger than Jarrah, as indicated above, and it may be that these seeds are more likely to remain on the soil surface and be subject to greater predation and/or temperature and moisture extremes than Jarrah seed. Seed delivery approaches that result in shallow (5-15mm) burial may therefore lead to improved Marri establishment success.

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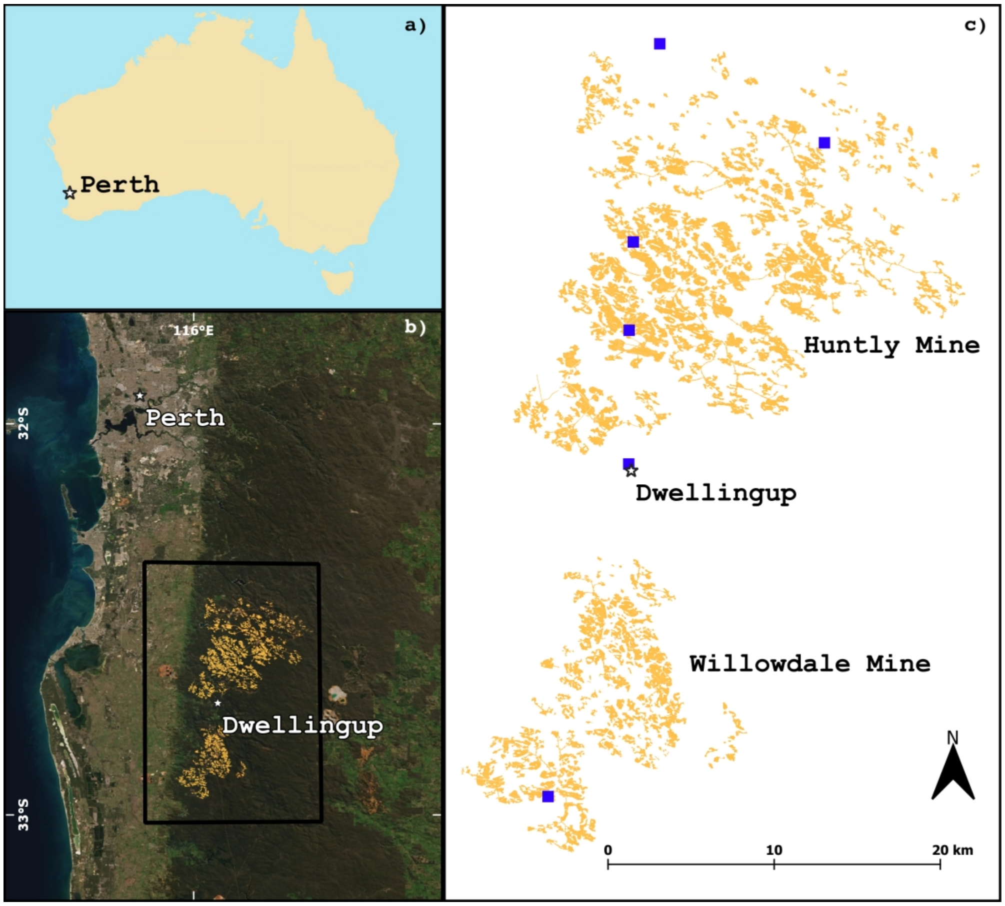
Table 1. Explanatory variables included in the saturated models for Jarrah and Marri establishment density (seedlings/ha). Final models included only significant variables (p<0.05); variables denoted "NS" and all interaction terms (not listed) did not significantly improve the model. The β coefficients (standard error in parentheses) for the final models indicate the magnitude and direction (+ or –) of the effect of an increase in one unit of each explanatory variable on seedling density. The observed range of each variable is provided to assist in assessing the potential magnitude of effect on seedling density. WS wet season, DS dry season – see text for definitions.

Explanatory variable	**Variable description; observed range**	**β coefficient**	
		Jarrah	Marri
Restoration practice			
Jarrah seeding rate	Jarrah seeding rate (g/ha); 1360 (1998-99), 700 (2000-02), 550 (2003-12), 490 (2013-15), 285 (2016-17)	+ 1.2 (0.2)	NS
Marri seeding rate	Marri seeding rate (g/ha); 500-540 (1998-99), 250 (2000-10), 200 (2011-12), 180 (2013-15), 237 (2016-17)	NS	+ 0.9 (0.2)
Forest perimeter	Proportion of the perimeter of a mine pit that is forested; 0-0.99	+ 428.1 (82.3)	+ 139.3 (35.9)
Perimeter to area ratio	Perimeter of a restoration site divided by the area of restoration site; 91.5-928.7 m/ha	+ 0.6 (0.2)	NS
Fertiliser rate	Rate of fertiliser applied before monitoring date (kg/ha); 500 (1998-2003), 280 (2004-15), 140 (2009), 0 (2016-17)	+ 1.3 (0.3)	+ 0.4 (0.1)
Topsoil handling score	Relative measure of topsoil storage, movement and spreading; 1-7 ('worst' to 'best'; Standish *et al.*, 2015)	NS	NS
Soil pathogen presence	Detection of *Phytophthora cinnamomi* in the topsoil; present or absent	NS	NS
Wet start	Number of days between seeding and the start of the wet season; – 47-186 days	NS	– 1.0 (0.2)
Climate			
Annual rainfall 2 years prior	Total rainfall (January to December) two years before the year of monitoring; 454.7-1442.9 mm	+0.3(0.01)	+ 0.1 (0.05)
Rain evenness full WS	Rainfall evenness over wet season; 0.13-0.28	– 5839.2 (1118.0)	– 2755.7 (520.0)
Rain evenness at 30 days	As above for first 30 days of wet season; 0.10-0.34	+ 2887.5 (472.9)	+ 807.0 (190.6)
Rain evenness at 60 days	As above for first 60 days of wet season; 0.10-0.39	NS	NS
Rain evenness at 90 days	As above for first 90 days of wet season; 0.01-0.33	+ 1235.0 (477.5)	NS
Rain evenness at 120 days	As above for first 120 days of the wet season; 0.14-0.35	NS	+ 1561.8 (346.0)
WS rainfall	Total rainfall from the start of the wet season to the start of the dry season; 339.4-1400.3 mm	NS	NS

False start	Wet (Rain > 2Temp) followed by dry (R < 2T) conditions before the onset of the sustained wet season; yes or no	NS	NS
WS average max. temp.	Average daily maximum temperature recorded during the wet season; 16.5-20.5 °C	NS	NS
WS highest temperature	Highest daily maximum temperature recorded during the wet season; 24.3-38.0 °C	NS	NS
WS lowest temperature	Lowest daily minimum temperature recorded during the wet season; –2.0-1.0 °C	+ 80.9 (33.6)	+ 56.7 (14.2)
DS average max. temp.	Average daily maximum temperature recorded during the dry season; 27.1-31.2 °C	– 158.7 (38.5)	– 98.8 (15.7)
DS highest temperature	Highest daily maximum temperature recorded during the dry season; 35.0-42.0 °C	+ 54.2 (19.0)	NS
DS lowest temperature	Lowest daily minimum temperature recorded during the dry season; 1.5-8.0 °C	+ 50.6 (19.2)	+ 38.7 (7.6)
Days over 40°C	Number of days in the dry season with a maximum temperature of over 40.1°C; 0-4 days	NS	NS
DS rainfall	Total rainfall from the start of the dry season to the time of monitoring (31 March); 4.8-265.0 mm	– 1.3 (0.6)	NS

Figure 1. The study area is located in south west Australia (a) and comprised of restoration sites (orange areas, b & c) associated with Alcoa's Huntly and Willowdale mines located within the Northern Jarrah Forest (dark green areas, b). The position of the Dwellingup climate station used to obtain daily air temperature, and rain gauge locations (c; blue squares) are shown.



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