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Original article

An integrated analysis of 33 *Eucalyptus* trials linking the onset of competition-induced tree growth suppression with management, physiographic and climatic factors

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Abstract – One of the greatest difficulties associated with controlling competitive vegetation during the establishment of eucalypts relates to the timing and planning of 'weeding' operations. This may be due to site related variability in vegetation species distribution and abundance, climatic conditions and methods of site preparation. Using data from 33 eucalypt vegetation management trials, multivariate statistical techniques were used to determine whether any climatic, physiographic or management related variables could be related to the time taken for competition-induced tree growth suppression to occur. Altitude, the method of site preparation (burning versus not burning) and the interaction between these two factors were significantly related to the timing of tree growth suppression. Regardless of the method of site preparation, the onset of competition-induced tree growth suppression occurred earlier at lower altitudes, where the vegetation was more diverse and vigorous. At higher altitudes, burning appears to stimulate the earlier growth of vegetation, reducing the time for competition-induced tree growth suppression to occur.

previous land use / vegetation management / inter-specific competition

Résumé – Une analyse intégrée de 33 essais avec des eucalyptus reliant le début de la baisse de croissance due à la compétition avec la gestion des peuplements, les facteurs physiographiques et climatiques. Une des grandes difficultés pour obtenir un contrôle de la végétation concurrentielle pendant l'installation de plantations d'eucalyptus est liée à la planification des opérations de désherbage. La difficulté provient de la variabilité de distribution et d'abondance des espèces qui constituent la végétation, des conditions climatiques et des méthodes de préparation du terrain. Des données de 33 essais de gestion de la végétation concurrente en plantation d'Eucalyptus ont été analysées avec des techniques statistiques multivariées pour identifier les variables climatiques, physiographiques ou de gestion susceptibles d'influencer l'apparition du ralentissement de croissance par la compétition herbacée. L'altitude, la méthode de préparation du terrain (brûlis ou non brûlis) et l'interaction entre ces deux facteurs ont eu un effet significatif sur ce ralentissement. Indépendamment de la méthode de préparation du terrain, le ralentissement de croissance se produisait plus précocement à basse altitude, là où la végétation était plus variée et plus vigoureuse. À plus haute altitude, le brûlis semble stimuler une croissance plus précoce de la végétation herbacée, en favorisant ainsi le ralentissement de la croissance des arbres.

utilisation antérieure des sols / gestion de la végétation / compétition interspécifique

1. INTRODUCTION

The presence of vegetation during the establishment of *Eucalytus* plantations may result in sub-optimal tree growth through competition for light, water and nutrients [6, 18, 33, 36]. From a management perspective, one of the greatest difficulties associated with controlling competitive vegetation during this period relates to the timing and planning of 'weeding' operations. This may be due to large site related variability in terms of weed species composition, abundance and growth, local climatic conditions as well as methods of site preparation [9, 20, 28, 30, 32]. As a result, it is difficult to prescribe operational vegetation management standards that can be effectively applied to a wide range of sites, let alone determine the critical time at which the competing vegetation should be controlled. Many studies have illustrated the benefits of site-species matching [27, 29], as well as the effect of site and vegetation type and abundance on tree growth for sites of different quality [7, 14, 22]. Little research could be found that related the development of competing vegetation to the time at which tree growth suppression occurs over a range of sites. If competition-induced tree growth suppression could be linked to the development of a competitive vegetation biomass (as determined by physiographic, climatic and site management factors) then this would allow managers to structure weeding operations at a regional level. To do this empirically would require a large data set. Where available, variables related to the physiography and climate of the site and some indication of the rate at which competition occurred between the competing vegetation and trees could be obtained.

In South Africa there is a lack of data related to the environmental variables associated with the growth of competitive vegetation in short rotation eucalypt plantations and how this relates to the onset of initial competition-induced tree growth

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suppression. From the early 1990s many short- and long-term eucalypt vegetation management trials have been planted in the summer rainfall region of South Africa. Being vegetation management trials all had a weedy (no vegetation control) and weedfree (repeated removal of all vegetation) treatment. From these trials, optimum tree performance in relation to the weedy treatment was recorded, together with climatic, physiographic and site management variables. Multiple regression was used to assess whether the joint variation of environmental variables across sites, in conjunction with site management factors (such as burning) had an influence on the time taken for competition-induced tree growth suppression to occur.

2. MATERIALS AND METHODS

2.1. Description of trial sites and data

For each of the 33 eucalypt trials, data on climate, physiography, presence/absence of several vegetation types (grasses, sedges, herbaceous and woody broadleaves) and site management were collected (Tabs. I and II). For all trials the trees were planted into a compartment free of vegetation with no further weed control carried out in the weedy treatment. Thus the vegetation structure, composition and rate of growth were a function of the site conditions (as determined by climatic, physiographic and site management factors). To eliminate competition, vegetation in the weedfree treatment was controlled by a combination of hand pulling and spraying with glyphosate whenever it reached ankle height. The number of days before divergence occurred between the growth of trees in the weedy and weedfree treatment was determined by plotting tree growth curves for height, crown or groundline diameter. Divergence of the growth curves was taken to indicate the development of a competitive vegetation biomass, and thus the critical period at which some form of vegetation control was necessary. The regular measurement of the trees in these trials (every two to four weeks) allowed for plotting of the two growth curves from which the initial and subsequent divergence could be determined.

2.2. Statistical analyses

It is likely that the time of onset of competition-induced suppression in eucalypt growth could not be determined by a single site-related environmental factor. For this reason the combined effect of the measured environmental (climatic and edaphic) factors (Tab. II) on time to divergence (response variable), and their interaction with land use history and management (burning), was examined using multiple regression. However, the 33 study sites differed widely in their environmental characteristics, with measured environmental variables varying together (to a greater or lesser extent) in potentially complex ways across sites. Principal component analysis (PCA) of standardised data (on the correlation matrix) was used as a tool to understand such collinearity in the multivariate environmental data set [10]. It was used to summarise most of the joint variability of measured soil and climate variables in terms of site positions (eigenvector scores) along the first few components (axes) representing complex environmental gradients. Because the principal components are orthogonal they can be used as independent variables in multiple linear regression in a standard way [2, 10] to assess the effect of environmental variability on the response variable (time to divergence).

In the multiple regression of time to divergence on environment (PC axes) and management related explanatory variables, stepwise selection was not employed to simplify models because of the well documented limitations of stepwise regression, most important of which is that it often fails to identify the best model [34]. Instead, all-subsets regression [21] was used to fit all possible regression models based on all combinations of environmental (PC axes) and management predictor variables. The regression with the lowest AIC (Akaike Information Criterion) [24] value, that is the most parsimonious model with adequate fit, was selected for further refinement by fitting additional terms to examine the interaction between burning and environmental gradients. All analyses were carried out using the statistical package Genstat® for Windows [11].

3. RESULTS

All of the site related explanatory variables were significantly correlated (Tab. III). As the first three principal components accounted for a large proportion (91.8%) of the joint variability across sites (Tab. IV), site scores along PC axes 1-3 were used in all further analyses to represent the complex environmental gradients in the data set. The first component (76% of the variability) represented climatic and edaphic variability associated with changes in elevation. The warm, low elevation, sandy sites at the one end (high PC1 scores) and the higher-elevation sites on clays in cooler climes at the opposite end (low PC1 scores) of the gradient (Tab. IV). PC2 (8.71%) described differences in silt and organic matter content whereas PC3 (7.09%) encapsulated variability in moisture availability resulting from differences between sites in annual precipitation and atmospheric evaporative demand.

The best among all the alternative models derived through all-subsets regression for explaining variation in the time (days) to suppression of tree growth by competition included the first three principal components (environmental gradients) as well as the categorical factors, Agric (land use before plantation) and Burn (burned or not before planting). These five variables accounted for 65.4% of the variation in the response variable but PC3 and Agric had marginally non-significant coefficients in the regression (Tab. V). The model was extended to test for interactive effects of environment (PC 1-3) with those of site preparation (Burn) and previous land use (Agric), revealing a significant ($P < 0.05$) interaction between Burn and PC1 and Burn and PC2. The percentage variation accounted for by this final model, in which all terms were significant ($P < 0.05$), was 77.6% (Tab. V). Although the time until growth divergence (induced by competition) generally declined towards the low altitude (high PC1 score) end of the complex elevation gradient, there was a differential rate of response along this gradient in burned versus unburned sites. There was a marked difference attributable to burning in the number of days until growth suppression at the high, but not the low elevation sites (low PC1 score) (Fig. 1).

Although the effect of site preparation by burning was contingent upon climate and soils, the effect of previous land use (Agric) was consistent across environment. The impact of previous land use (Agric) on the response variable DAP indicated that where land had previously been used for agricultural

Table I. Description of the 33 trial sites included in the multivariate analyses to link physiographic, climatic and site management factors to weed-induced *Eucalyptus* suppression in South Africa.

Trial No.	Location Plantation (Region)	Species planted	Date planted	Latitude and longitude	Map (mm)	Mat (°C)	Soil type	Altitude (m a.s.l.)	DAP
1	Mtunzini (Zululand)	*E. grandis* × *E. camaldulensis*	16/10/1990	28° 59' S 31° 42' E	1201	21.1	Sand	47	64
2	Mtunzini (Zululand)	*E. grandis* × *E. camaldulensis*	22/10/1990	28° 59' S 31° 42' E	1201	21.1	Sand	47	58
3	ICFR Nursery (Midlands)	*E. grandis*	31/01/1992	29° 37' S 30° 24' E	720	18.6	Clay loam	677	74
4	Duzi Estates (Zululand)	*E. grandis*	18/08/1992	28° 42' S 31° 58' E	995	21.4	Loamy sand	76	28
5	Nseleni (Zululand)	*E. grandis*	18/08/1992	28° 41' S 32° 04' E	1232	21.6	Sand	55	66
6	Nseleni (Zululand)	*E. grandis*	18/08/1992	28° 41' S 32° 04' E	1232	21.6	Sand	55	59
7	Central Area (Zululand)	*E. grandis* × *E. urophylla*	20/08/1992	28° 34' S 32° 13' E	1182	21.6	Sand	63	153
8	Shafton (Midlands)	*E. grandis*	11/12/1992	29° 23' S 30° 15' E	914	16.7	Silty clay loam	1120	88
9	Nseleni (Zululand)	*E. grandis* × *E. camaldulensis*	21/10/1993	28° 45' S 31° 59' E	1129	21.5	Sand	34	60
10	Futululu (Zululand)	*E. grandis*	13/09/1994	28° 24' S 32° 15' E	896	21.8	Sandy clay loam	63	56
11	Trust (Zululand)	*E. grandis* × *E. urophylla*	16/09/1994	28° 33' S 32° 09' E	1115	21.7	Sand	55	75
12	Trust (Zululand)	*E. grandis* × *E. urophylla*	16/09/1994	28° 33' S 32° 09' E	1115	21.7	Sand	55	75
13	Futululu (Zululand)	*E. grandis*	29/09/1994	28° 24' S 32° 15' E	896	21.8	Sandy clay loam	63	40
14	Futululu (Zululand)	*E. grandis*	29/09/1994	28° 24' S 32° 15' E	896	21.8	Sandy clay loam	63	40
15	Oaklands (Zululand)	*E. grandis* × *E. camaldulensis*	06/07/1995	28° 35' S 32° 05' E	1057	21.6	Sand	87	68
16	Oaklands (Zululand)	*E. grandis* × *E. camaldulensis*	06/07/1995	28° 35' S 32° 05' E	1057	21.6	Sand	87	40
17	Grafton (Midlands)	*E. nitens*	01/10/1995	20° 09' S 29° 44' E	823	15.4	Silty clay loam	1448	110
18	Piet Retief (Mpumalanga)	*E. grandis* × *E. nitens*	04/11/1996	26° 56' S 30° 49' E	867	16.5	Sandy clay loam	1385	133
19	Trust (Zululand)	*E. grandis* × *E. urophylla*	06/08/1997	28° 32' S 32° 10' E	1033	21.8	Sand	39	30
20	Mtn. Home (Midlands)	*E. dunnii*	04/09/1997	29° 34' S 30° 17' E	1062	16.3	Silty clay loam	1181	163
21	Mtn. Home (Midlands)	*E. dunnii*	17/09/1997	29° 32' S 30° 17' E	760	16.5	Silty clay loam	1134	163
22	Tweefonntein (Midlands)	*E. macarthurii*	07/01/1999	29° 15' S 30° 13' E	842	13.1	Clay	1600	365[a]
23	Draycott (Midlands)	*E. nitens*	29/01/1999	29° 04' S 29° 36' E	824	15.9	Clay	1685	365[a]
24	Nyalazi (Zululand)	*E. grandis* × *E. camaldulensis*	06/06/2001	28° 16' S 32° 16' E	815	21.8	Sand	55	82
25	Kwambonambi (Zululand)	*E. grandis* × *E. urophylla*	20/08/2001	28° 42' S 32° 07' E	1246	21.5	Sand	47	115
26	KT (Zululand)	*E. grandis* × *E. urophylla*	03/09/2001	28° 36' S 32° 07' E	1106	21.6	Sand	71	21
27	KT (Zululand)	*E. grandis*	02/10/2001	28° 36' S 32° 07' E	1106	21.6	Sand	71	93
28	Winterton (Midlands)	*E. smithii*	24/10/2001	29° 01' S 29° 29' E	848	17.1	Clay	1173	365[a]
29	Eston (Midlands)	*E. grandis*	15/11/2002	28° 53' S 30° 26' E	792	17.2	Sandy loam	929	28
30	Oaklands (Zululand)	*E. grandis* × *E. camaldulensis*	06/05/2003	28° 35' S 32° 05' E	1057	21.6	Sand	87	92
31	Oaklands (Zululand)	*E. grandis* × *E. camaldulensis*	06/05/2003	28° 35' S 32° 05' E	1057	21.6	Sand	87	92
32	KT (Zululand)	*E. grandis* × *E. urophylla*	01/08/2003	28° 34' S 32° 08' E	1136	21.6	Sand	71	62
33	Enon (Midlands)	*E. smithii*	24/11/2003	29° 49' S 30° 14' E	1070	16.3	Clay	1180	149

[a] As divergence was not detected due to sub-competitive weed growth, the value of 365 days was used to separate these sites from the rest.

Table II. Abbreviation and description for the explanatory (physiographic, climatic and site preparation variables) and response (time to divergence) variables used in the multivariate analysis.

Variable No.	Abbreviation of variable	Description of variable
		Response variable
1	DAP	Days after planting to when divergence first detected.
		Site related explanatory variables
1	Alt	Altitude of the site (m a.s.l.)
2	Mat	Mean annual temperature (°C)
3	Map	Mean annual precipitation (mm yr^{-1})
4	Pevap	Actual evapotranspiration divided by potential evapotranspiration, for the site.
5	Sunrad	Total annual solar radiation (MJ m^{-2} day^{-1})
6	Clay	% clay in top 15 cm of soil
7	Sand	% sand in top 15 cm of soil
8	Silt	% silt in top 15 cm of soil
9	Oc	% organic carbon in top 15 cm of soil
		Management related explanatory variables
10	Seedling	
11	Cutting	Scored as 1, 0 dependent on whether the trees planted were seedlings, cuttings or a hybrid combination
12	Hybrid	
13	Grass	Presence / absence of grasses (1, 0)
14	Sedge	Presence / absence of sedges (1, 0)
15	Hbl	Presence / absence of herbaceous broadleaves (1, 0)
16	Woody	Presence / absence of woody vegetation (1, 0)
17	Burn	Land preparation: 0 = not burned before planting; 1 = burned before planting
18	Pit_rip	Preparation of a planting position:1 = pit; 2 = rip
19	Hist	Classification of landtype: 1 = coastal bush; 2 = grassland; 3 = bushveld
20	Agric	Classification of land use before plantation establishment: 0 = natural vegetation; 1 = agricultural land
21	Ro_no	Number of rotations on the site (more than 2 rotations has been scored as 3)

Table III. Correlation matrix for all site related physiographic and climatic variables collected for 33 *Eucalyptus* trials in South Africa.

Variates									
1. Pevap	1.00								
2. Sunrad	**–0.57**	1.00							
3. Alt	**–0.63**	**0.80**	1.00						
4. Mat	**0.86**	**–0.85**	**–0.85**	1.00					
5. Map	**0.45**	**–0.74**	**–0.63**	**0.64**	1.00				
6. Clay	**–0.70**	**0.72**	**0.83**	**–0.83**	**–0.67**	1.00			
7. Silt	**–0.56**	**0.69**	**0.79**	**–0.67**	**–0.59**	**0.73**	1.00		
8. Sand	**0.67**	**–0.76**	**–0.86**	**0.80**	**0.68**	**–0.93**	**–0.93**	1.00	
9. Oc	**–0.57**	**0.59**	**0.77**	**–0.64**	**–0.47**	**0.74**	**0.95**	**–0.91**	1.00
Variates	1	2	3	4	5	6	7	8	9

Figures in bold refer to significance at $P < 0.05$.

purposes there was a significant decrease (166 days to 66 days) in the average time taken for competition-induced tree growth suppression to occur.

4. DISCUSSION

The results of the PCA and multiple linear regression analyses indicated that there were variables in the data set that could be used to estimate the time at which competition-induced tree growth suppression was likely to occur during eucalypt re-establishment. These included the environmental variables associated with changes in altitude (PC1 – 3) the method of site preparation (Burn) and their interaction. PC1 summarised the main variability among sites in soil physical properties and climate with altitude and accounted for 46.2% of the variation in the response variable DAP. This result reflects the

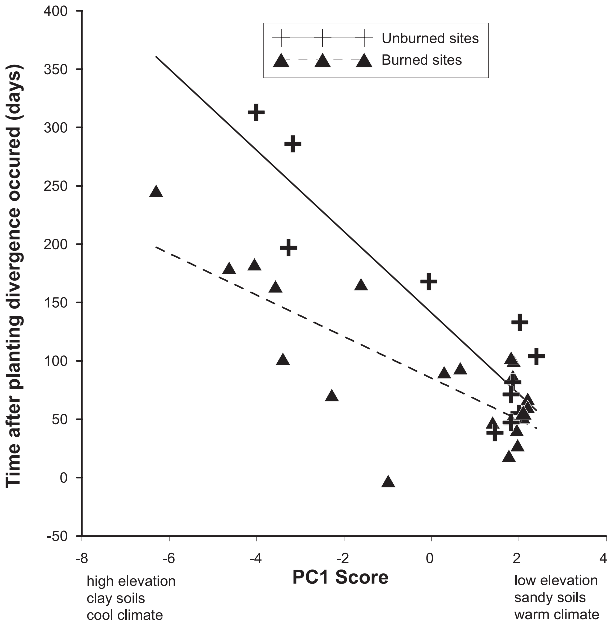

Figure 1. Plot of the interaction ($P < 0.05$) between PC1 and Burn for the dependent variable DAP (days after planting when divergence of the growth curves for the weedy and weedfree treatments occurred).

Table IV. Latent vectors and summary statistics for principle components analysis carried out on standardised site related environmental data.

	Principle component		
Variable	1	2	3
Alt	–0.3516	0.0073	–0.0225
MAP	0.2847	0.3471	0.6213
MAT	0.3486	0.3516	–0.2620
Pevap	0.2926	0.2855	–0.6688
Sunrad	–0.3282	–0.3179	–0.2776
Clay	–0.3506	–0.0385	0.0479
Sand	0.3695	–0.2263	0.0371
Silt	–0.3387	0.4541	–0.1092
Oc	–0.3260	0.5607	0.0699
Variance (%) in X[a] explained by the PC axis	76.01	8.71	7.09

[a] X refers to the data matrix being analysed.

association between competition-induced tree growth suppression and altitude, and is supported by previous studies on vegetation growth and management in pine plantations [9, 14, 32]. In two separate studies carried out in pine growing regions in South Africa, van Heerden and Masson [32] and Jarvel and Pallett [9] found altitude to be one of the most important predictors of vegetation species distribution and abundance (measured as percentage cover), with abundance generally decreasing with increasing altitude. Van Heerden and Mason [32] showed that at the Usutu pulpwood plantation in Swaziland, sites at lower altitudes (< 1 100 m) were typically characterised by a high abundance of grasses, woody vegetation and herbaceous broadleaves whilst mid to high altitude sites (> 1 400 m) were characterised by less vigorous and competitive vegetation such as inkberry (*Phytolacca octandra*) and pine regeneration. This, together with cooler mean annual temperatures at higher elevations, delays the onset of the development of a competitive vegetation biomass. It follows that tree growth suppression from inter-specific competition is likely to occur sooner at lower altitude sites [14].

The method of site preparation alone (Burn) accounted for 7.8% of the variation in the response variable. That low-intensity burning has the potential to stimulate the growth of vegetation, particularly some woody species, has been recorded [1, 16, 23, 31]. Conversely, retaining the post-harvest residues as an organic mulch on the site has been shown to reduce the rate of growth of competitive vegetation [4, 8, 12, 16]. Schumann et al. [26] demonstrated that post-harvest residues act as a physical and chemical barrier, reducing the rate of seed germination thereby delaying the onset of inter-specific competition. The interaction between the site related variables (PC1 and 2) and method of site preparation (Burn) accounted for 11.8% variation in the response variable. At higher altitudes, burning reduced the time taken for competition induced tree growth suppression to occur, a response to the effect of site preparation on the rate of seed germination (Fig. 1). At lower altitudes, regardless of whether the site was burned or not, the growth of the vegetation was vigorous and competition-induced tree growth suppression occurred in about three months (Tab. I and Fig. 1).

That previous land use affects plant species distribution is well documented [3, 19, 35]. In this study, the occurrence of previous agricultural practices significantly reduced the time taken for tree growth suppression to occur relative to

Table V. Summary ANOVA table for the multiple regression analyses carried out with the variables PC1, 2, 3, Agric and Burn, including the interaction terms PC1 × Burn and PC2 × Burn, to best explain the variation in the dependent variable DAP (days after planting when divergence between the weedy and weedfree growth curves occurred).

	Without interaction terms			With interaction terms		
Source of variation	df	ms	*F* prob.	df	ms	*F* prob.
+ PC 1	1	125 099	< 0.001	1	125 142	< 0.001
+ PC 2	1	24 831	0.007	1	24 804	0.001
+ PC 3	1	8 591	0.098	1	8 545	0.044
+ Agric	1	12 275	0.051	1	12 259	0.018
+ Burn	1	21 131	0.012	1	21 124	0.003
+ PC1.Burn				1	11 898	0.019
+ PC2.Burn				1	19 998	0.003
Residual	27	79 195		25	47 351	
Total	32	27 1122		32	271 122	
	R^2 = 65.4%			R^2 = 77.6%		

sites where natural vegetation existed prior to plantation establishment. In the summer rainfall region of South Africa, plant species common to land previously used for agriculture include sedges (*Cyperus* spp.), grasses (*Panicum maximum*) and herbaceous annuals (*Bidens pilosa, Conyza* spp.) that are very competitive during the first few months following planting [13, 15, 17].

In South Africa, commercial eucalypt species are grown across a wide range of sites in KwaZulu-Natal and Mpumulanga [5]. The low altitude (< 250 m a.s.l.) sub-tropical coastal regions in KwaZulu-Natal, planted extensively to eucalypts, have a year-round growing season [25]. To avoid tree growth suppression on sites in this region, early (within the first 3 months of planting) and frequent weeding operations are required regardless of the method of site preparation. This would also apply on lower altitude sites (< 1 100 m a.s.l.) in the KwaZulu-Natal midlands and Mpumulanga Escarpment. Subject to site preparation practices, on sites at mid to higher altitudes (> 1 400 m a.s.l.) fewer weeding operations are required. To avoid tree growth suppression where burning is practised in the mid to high altitude range of sites, the frequency of weeding operations will need to be increased.

The purpose of this study was to highlight factors that are related to the onset of competition-induced tree growth suppression and not to develop a parameterized model for prediction. Because of the complexity of environmental interactions these results cannot be used to predict with any certainty, when the biomass of vegetation at any particular site will reach a critical management level. Nevertheless this study shows that the time to suppression declines with declining altitude, on burnt compared to unburnt sites and on sites where agriculture was practiced prior to plantation establishment (as opposed to native vegetation).

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