A pedo-geomorphic approach for predicting drought deaths in Eucalyptus globulus (Labill.) plantations

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Abstract

The reforestation of farmland with trees is a rapidly emerging activity in Australia, to produce wood products, to restore hydrological balances, for carbon dioxide sinks or as a source of bio-energy. Irrespective of purpose, the benefits of reforestation depend on its survival and adequate growth. While management affects tree survival and growth, both are also strongly related to soil conditions. To define the soil survey requirements for these new plantations we studied the relationships between the survival of Tasmanian blue-gums (*Eucalyptus globulus* Labill.) and a range of soil and climatic attributes. Widespread tree deaths occurred in years with both average and below average rainfall. Dead trees did not occur everywhere and appeared to be related to soil and geomorphic attributes. These relationships are discussed in this paper.

Soils were examined in three plantations established in 1989. Tree survival two years after planting was independent of all soil and site factors and averaged 79% of those trees initially planted. By seven years of age, tree survival was substantially less on soils (a) <2 m deep compared to >2 m deep (22 vs 70%) and (b) where ferricrete gravels were absent compared to where present (19 vs 68%). Importantly, live standing tree volumes increased between 4 and 7 years of age on sites with deep soils, whereas volume decreased slightly on the shallow soils.

The soil factors important to tree survival are related to soil water storage capacity, with the ferricrete gravels being an indicator of deep weathering profiles, rather than affecting water storage capacity *per se*. The major limitation to tree survival in this region comes from the overall soil volume. This is due to the limited ability of these soils to store all the annual rainfall and a consequent lack of a supply during the annual summer drought.

There are practical difficulties in routinely surveying soil depths in excess of 2 m over broad areas. The occurrence of ferricrete gravels provides a useful surrogate of the presence of deeper soils. In this region the distribution of soil depth and soil fertility has a geomorphic basis, being related to previous patterns of deep weathering and regolith stripping. Soils have developed on various horizons of deeply weathered profiles, formed from granites and gneisses. These materials have been stripped to a variable extent by erosion, leading to a range of soil depths. The original weathered profiles, which correspond to the soils with ferricrete gravels, comprise the deepest soil/regolith materials (~30 m deep), whereas along drainage lines the regolith has been completely stripped, the soils are shallow and plantations are most susceptible to drought. Regional indications of drought risk can thus be developed from regional soil mapping.

Keywords: *Eucalyptus globulus*, plantations, reforestation, greenhouse, soil survey

Introduction

One of Australia's fastest growing primary industries is the reforestation of farmland. This reforestation is driven by several factors, including investment for the production of pulp and timber, predominantly in higher rainfall areas, and increasingly for environmental benefits. Much plantation activity has occurred in southwestern Australia, with 211,128 ha of Tasmanian blue-gum (*Eucalyptus globulus* Labill.) planted between 1985 and 2000 (Wood *et al.*, 2001).

Future reforestation may comprise additional species and involve investment from new sources such as from those seeking carbon sinks, fuel for bioenergy, or enhanced habitats for wildlife. For example, it is estimated that by 2050 up to 17 Mha of land will be affected by dryland salinity (National Land and Water Resources Audit 2001) and several million hectares of reforestation with a range of species may be required to restore the hydrological balance across southern Australia. Plantations may also be established as sinks to off-set emissions of carbon dioxide from elsewhere in response to the Kyoto Protocol.

Irrespective of purpose, the benefits of reforestation depend on its survival and adequate growth. While management affects tree survival and growth, both are also strongly related to soil conditions. Soil surveys at an appropriate scale for management (1:10,000) are invariably not available, thus these will be required prior to reforestation. A key requirement is to identify the key soil properties that should be assessed in these surveys and refine methodologies to allow surveys to be undertaken at a reasonable cost and speed.

Widespread deaths of trees in plantations occur periodically in south-western Australia in response to below average rainfall (McGrath *et al.*, 1991). This region has a Mediterranean climate with most rain received in the cooler months (April-November) and an annual summer drought. Deaths in *Eucalyptus globulus* plantations, established predominantly for pulp-wood in a 10 year rotation, were particularly noticeable between 1993 and 1995, during the early expansion phase of this industry. Accurate assessments of the areas affected by drought deaths are not available, however in some plantations deaths exceeded half the planted area.

Tree deaths were not uniformly distributed within or between plantations, thus it was considered that the pattern of deaths was related to soil properties. A study of the relationship between soil properties and drought deaths was undertaken to identify major soil properties associated with tree mortality, and their critical values. Once identified it was considered that these properties could be incorporated into soil survey procedures and such sites avoided to prevent a recurrence of the problem. Similar issues of identifying key limiting factors to tree growth and survival apply to all reforestation of farmland. This paper will describe this work and by so doing outline some challenges in developing site selection standards for reforestation of farmland generally.

Methods

Land-use and climate

South-western Australia has a Mediterranean environment, with a predominance of winter rainfall and an annual summer drought. The annual rainfall ranges from

1,400 mm in the south-western corner to around 250 mm at the limit of agriculture. Similarly, annual pan evaporation varies from 1,200 mm on the south-coast at Albany to 2,600 mm, at Geraldton, near the northern extent of agriculture. The area developed for agriculture comprises 18 Mha of the total land area of 24 Mha.

Measurement plots

Fifty six permanent inventory plots were examined in three plantations, all established in 1989. These plantations were approximately 100 km south of Perth. These 400 m^2 plots were randomly established in the plantations in 1991. Plots covered the range of health, productivity, landscape position and soils found within the plantings. Plots were measured to assess tree height and basal area (BA). Top height (TH) was based on the heights of the 75 tallest trees ha^{-1}, and tree basal area (m^2 ha^{-1}) and survival (%) were calculated from the trees alive at the time of measurement. Tree standing volume was estimated from the cone formula BA x TH/3.

Climate

For the three plantations daily rainfall (R) and evaporation (E) data were obtained from the SILO climate data base (Jeffrey *et al.,* 2001). This program interpolates data from recording stations, such that estimates can be made for any location in Australia. Data estimates encompassed the period from January 1957 to August 2001. An approximate water balance was estimated from $R - 0.7E$.

Soils

Soils were examined to depths of up to 3 m, via backhoe pits. Soil profile and landscape attributes were described using the procedures of McDonald *et al.* (1990). Soil depth was described as depth to saprolite and expressed as three depth intervals (<1, 1-2 and >2 m). Some of the deep soils are substantially deeper than 2 m, with subsequent drilling revealing >10 m depth of regolith. Surface samples (0-10 cm) were analysed for a range of physical and chemical properties. Duplicate bulk density cores were taken at 20 cm intervals. Ferricrete gravel was considered in terms of presence or absence anywhere within the soil profile.

Results

Climate

Table 1 summarizes the mean climate for the period for which records are available (1970-2000). Mean climatic conditions are similar for each plantation and do not significantly differ for the period of growth of the plantations (1989-96). The total annual (April-March) and summer (November to March) rainfalls for Plantation A are plotted in Figure 1a. Figure 1a clearly shows that the annual rainfall to March 1994 and March 1995 were both below average, with the summer rainfall in Nov 1994-March 1995 being particularly low with only 19 mm. This low rainfall coincided with a higher than average annual evaporation (Figure 1b) with a resultant negative water balance for the year of –561 mm and for the summer of –852 mm. Figure 1 also shows the recurrent nature of drought in this environment.

Table 1 Mean climatic (1970-2000), tree growth at 7 years of age and soil depth (m) data for each of the three plantations. *P* is probability that the mean values are significantly different, using a one-way ANOVA.

Plantation	Rainfall	Evaporation	Top Ht	Volume	Survival	Soil depth
	(mm)		(m)	(m^3 ha^{-1})	(%)	(m)
A	1010	1599	15.7	22	17	1.2
B	996	1555	17.1	28	16	1.3
C	980	1560	20.8	108	64	2.1
P			0.001	0.0001	0.0001	0.003

Table 2 Mean soil properties of a random sub-set of soils <2 m and >2 m deep. *n*: number of samples; N: total Nitrogen (%), OC: total organic carbon; Clay: <2 µm; silt 2-20 µm; FS Fine sand 20-200 µm (%); CS Coarse sand 200-2000 µm (%); EC: electrical conductivity (dSm^{-1}); BD Bulk density from 0.9 m deep (mg m^{-3}). Other soil analyses on 0-10 cm sample. *P* is probability that the mean values are significantly different, using a one-way ANOVA.

Soil depth (m)	n	N	OC	Particle Size				EC (mS m^{-1})	Exch. Cations				BD (Mg m^{-3})
				Clay	Silt	FS	CS		Ca	Mg	Na	K	
		(%)							(cmol p^+ kg^{-1})				
<2	26	0.20	2.5	14	11	34	41	7.1	3.55	1.32	0.19	0.13	1.65
>2	12	0.14	2.2	10	8	30	52	6.6	1.71	0.43	0.12	0.13	1.56
P		*n.s*	*n.s.*	*0.01*	*n.s.*	*n.s.*	*0.001*	*n.s.*	*n.s*	*n.s.*	*n.s.*	*n.s*	*0.01*

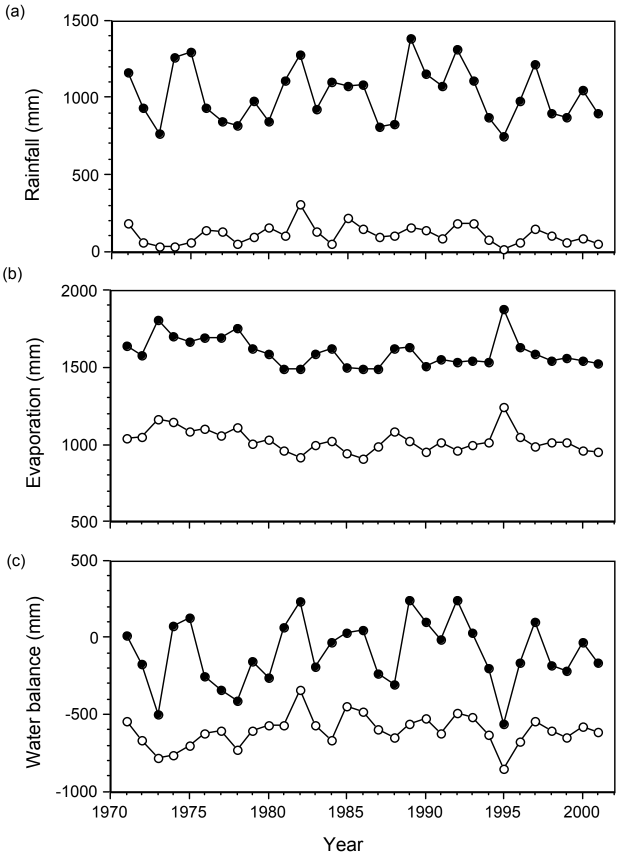

Figure 1 Variation in annual (April-March) (●), and Nov.-March ("summer") (○) climate for Plantation A. (a) rainfall (R), (b) evaporation (E) and (c) water balance estimated from R-0.7E.

Incidence of drought deaths in relation to soil properties

Soils occurred in two main groups: those derived from deep weathering profiles and those from exposed bedrock and shallow slope deposits. The former soils (Dystric Regosols) invariably have sandy surface horizons dominated by ferricrete gravel to a depth of 1.0-1.5 m overlying yellow-brown (mottled zone), then white, medium-heavy clays (pallid zone) continuing for several metres. In contrast, soils derived from bedrock (Chromic Luvisols) comprised loamy surface horizons 10-30 cm deep, overlying reddy brown medium-heavy clays and granitic saprolite. Sites were on valley sides and crests, with slopes to 15%. Major properties of the surface (0-10 cm) horizons of the soils are summarized in Table 2.

Tree survival two years after planting was independent of all soil and site factors and averaged 79% of those trees initially planted. Seven years after planting (1996), tree survival was significantly less on soils <2 m deep compared to >2 m deep (22 vs 70%), with no apparent difference between the 0-1 and 1-2 m depth increments (Figure 2a). Whereas the standing live tree volume on the soils <2 m deep declined from 43 to 37 m^3 ha^{-1}, between four and seven years of age, there was a marked increase in growth on the soils >2 m deep from 56 to 119 m^3 ha^{-1}.

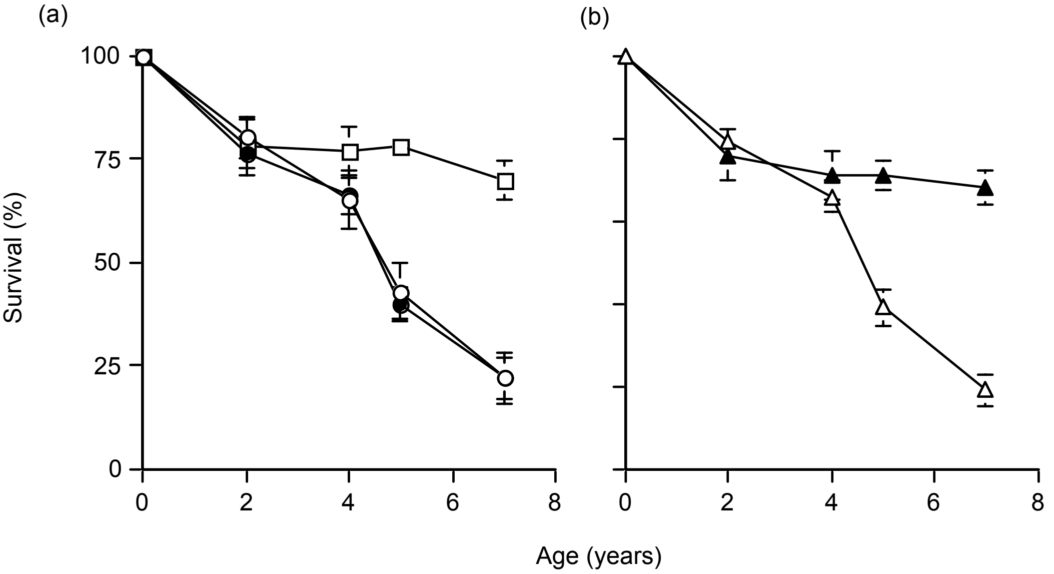

Figure 2 Variation in tree survival with (a) soil depth 0-1 m (○), 1-2 m (●) and >2-m (□) and (b) absence (△) or presence (▲) of ferricrete gravel within the soils.

Soils containing ferricrete gravels are generally deeply weathered; hence in this region this soil attribute may provide a useful field indicator (surrogate) of soils with an adequate volume of root penetrable material. Ferricrete gravels gave a similar discrimination of tree survival as soil depth. Again there was no difference two years after planting, however after seven years sites where ferricrete gravel was absent had markedly poorer survival than where it occurred (19 vs 68%) (Figure 2b). There was again a small decrease in tree volumes between four and seven years of age (44 to 30 m^3 ha^{-1}) where ferricrete was absent, whereas volumes increased markedly where it was present (50 to 121 m^3 ha^{-1}). The mean soil depth, based on observations to 3 m, of sites without ferricrete was markedly less than where it was present (1.2 m vs 2.4 m).

Across the study sites, bulk density of the sub-soil clays ranged from 1.3 to 2.1 Mg m^{-3} and had no apparent effect on growth (wood volume increment) or survival. A number of other soil and site factors were assessed, however none were related to tree growth or survival. These included the field texture, pH and electrical conductivity of the surface and clayey sub-soil horizons, and the slope and aspect of the sites. Lack of relationships may be partly due to the relatively narrow range of soils and sites considered within this study.

A drought stress index was developed using a four-layer daily soil-water balance program that incorporated both pasture (before canopy closure) and tree transpiration. This was based on GRASP (Day *et al.,* 1997) with modifications to allow for dynamic tree growth, survival and deep drainage (J.O. Carter unpubl.) Modelling used daily climate data for Plantation A for the period 1990-2000. The model was calibrated to give the observed tree basal area at 7 years after planting. The stress index counted the number of days in which soil water fell below a threshold value (Figure 3) and was compared to soil storage in the range of 125-375 mm. There appeared to be no stress in the trees with 375 mm of soil water storage capacity, with the stress index increasing systematically in a non-linear fashion with decreasing soil water storage capacity.

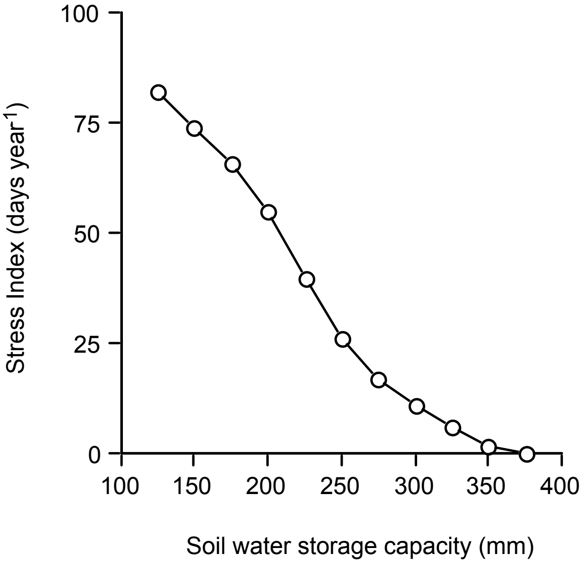

Figure 3 Variation in nominal drought stress index (days year^{-1} beyond wilting point) compared to soil water storage capacity, modelled using 1990-2000 daily climate data from Plantation A using a derivation of GRASP.

Discussion

Deaths in relation to soil properties

The major limitation to tree survival in this environment comes from the overall soil volume, with deaths occurring on shallow soils every year from age three, irrespective of rainfall deficit. These results support those of previous studies into drought deaths in *P. pinaster* and *P. radiata* (McGrath *et al.,* 1991), however the drought deaths in *E. globulus* occur at a much younger age than the other species. Not only do the trees on the shallower soils have greater mortality than those on deeper soils, but also net growth had effectively ceased between the ages of four and seven. In environments such as this, with an annual summer drought, the interaction between water supply and soil water storage capacity is paramount. Sites selected for plantations require soil conditions that allow survival through extreme rather than average conditions.

The occurrence of ferricrete gravels is an indicator of the presence of deep weathering profiles, rather than affecting water storage capacity *per se*. The deep weathering profiles in this region may be 30-50 m deep overlying bedrock (McArthur 1991), and subsequent drilling to 10 m at various plantations indicated water depletion to at least this depth under trees whereas adjacent soils under agriculture contained plant available water below the top metre (Crombie and Harper unpubl.)

The question thus arises as to the influence of the deep soil profiles on tree survival and whether this is through (a) the contribution of soil water stored under the previous agricultural land-use or (b) the capacity of these profiles to store winter rainfall for use in the subsequent summer. If the former is important drought deaths will be expected to occur in plantations on all soils following depletion of the stored soil water, however this has not happened, despite a regional drought in 2000/1. If the contribution is related to the capacity to store annual rainfall, then there will be a maximum soil volume required, with this decreasing with decreasing rainfall. The contribution of increasing soil water storage capacity to the minimization of tree stress is shown clearly in Figure 3.

It is expected that *E. globulus* plantations will be coppiced or replanted in 10 year rotation. Depletion of soil moisture may result in reduced second rotation growth and survival, however the modelling suggested a similar stress index for the 1990-2000 climate sequence for both initially dry or moist soil profiles. Rainfall appears to recharge the soil profile in the early stages of plantation growth, before tree canopies re-establish. The occurrence of drought in these years may be crucial to future productivity.

While it is recommended that pre-planting surveys concentrate on defining overall regolith volume there are significant practical difficulties in doing this, particular where this involves routine evaluation of soils to depths of 2-3 m or more. Issues involve being able to define what soil materials represent a barrier to roots, and thus the effective soil volume, and being able to portray the distribution of these materials across the landscape. The presence of ferricrete gravels in the soil profile may provide a rapid indicator of adequate soil volume, if combined with other observations such as the exposure of bedrock.

Regional pattern of soil depth in relation to regolith stripping

Another approach to determining the regional distribution of soil volume is to recognise its geomorphic basis, with this being related to patterns of regolith stripping (Mulcahy, 1967). Thus, regional indications of drought risk may be developed from regional soil mapping. The regional pattern of soils is strongly controlled by the prior deep weathering of the underlying bedrock, resulting in the formation of the characteristic deeply weathered ("laterite") profile, and subsequent regolith stripping. Deep weathering has resulted in regolith profiles often 30-50 m deep with a surface cover of sands and ferricrete gravels.

Along the western and southern margins of the Yilgarn Craton, drainage lines are prominent and the regolith has been variably stripped, the extent depending on the local drainage patterns. In each case the parent materials for contemporary soils comprises the different horizons of the original laterite profile. Thus, along some valleys the weathering profile has been completely stripped, bedrock is often exposed and the soils are often shallow. In contrast, deeply weathered profiles remain on the interfluves.

As a result of this landscape stripping, there are thus regional patterns in soil volume and soil fertility. Patterns of fertility in relation to stripping have been previously reported (Turton *et al.,* 1962), with primary minerals occurring in the stripped soils but not in the deeply weathered soils, which are dominated by quartz and sesquioxide clay minerals.

Plantations on the shallow soils consistently succumb to drought. When confronted with similar problems with *Pinus radiata* plantations, the management response was to substantially reduce tree stocking. In contrast pulpwood plantations rely on rapid early growth, with high rates of stocking. The conservative management strategy in this case is to avoid planting such soils or only use strips of trees in conjunction with agriculture.

Conclusions

This study has demonstrated the importance of soil volume in explaining the onset of drought deaths in *Eucalyptus globulus* in south-western Australia. Deep soils are important with small and erratic summer rainfall to provide a store for winter rainfall. They may also provide extra water for the plantations in their early years of growth, this having accumulated under agriculture. The ultimate success of reforestation in such seasonally water limited environments depends on water management through both rigorous site selection and subsequent plantation management.

Surrogates such as the occurrence of ferricrete gravel and broad landscape interpretation provide a means of defining where drought risk is greatest. While these specific findings are likely to be region specific it does reiterate the need to undertake site surveys prior to plantation establishment to minimize the risk of failure. For plantations, soil observations are required to depths much deeper than those made in agricultural soil surveys. Some soil properties that are routinely described in soil surveys (colour, texture) may not be immediately important in terms of plantation importance, although they may be important for other aspects of site management.

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