Soil requirements for *Eucalyptus globulus* plantations - preliminary results and recommendations

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1. Summary

Widespread deaths occurred in *Eucalyptus globulus* plantations, across the south-west of Western Australia, last summer. Deaths also occurred in some plantations in the summer of 1992/93. Accurate assessments of the areas affected by drought deaths are not currently available, however in some plantations deaths exceed half the planted area. Although in many of the plantations the deaths are due to drought, caused by shallow soils, in other plantations deaths may be due to other influences on rooting patterns such as salinity and waterlogging.

The soils of three P89 plantations (Hagen, George and Eckersley) on dissected granitic terrain on the Darling Scarp, near Harvey and Waroona, were examined with sixty back-hoe pits. Tree survival two years after planting (1991) was independent of all soil and site factors and averaged 79% of those trees initially planted. Deaths occurred in all plantations in the summers of 1992/93 and 1993/94. In May 1993 mean tree survival in each plantation was 52, 67 and 75%, and in May 1994 40, 34 and 71%, respectively. Tree survival following last summer can be related to several soil factors. Rates of survival were less on soils (a) <2 m deep compared to >2 m deep (42 vs 69%), (b) with weak sub-soil structure compared to strong structure (43 vs 61%) and (c) where ironstone gravels were absent (41 vs 70%). Mean predominant height and basal area at age four were related to sub-soil structure, but not to soil depth or the occurrence of ironstone gravels. A similar pattern was also clear in auger surveys of two other P89 plantations at Mumballup (Gardiner) and Unicup (Johnson), with deaths again generally associated with shallower soils. Each of the soil factors (soil depth, sub-soil structure and the occurrence of ironstone) is related to the soil water storage volume, the latter factor as an indicator of deep weathering profiles, rather than affecting water storage *per se*. This study was restricted to stands of one age-class, on soils with broadly similar geology, and in areas with relatively high rainfall (>800 mm); to further develop these relationships a larger array of plots should be studied. Such a study will determine whether the recent drought deaths were a function of abnormal seasonal conditions, or of stand age.

Reconnaissance studies were made of other plantations on the Swan Coastal Plain and north-west of Mt Barker. Deaths in the plantations near Harvey may have been due to drought, but this was induced by water-logging and/or impenetrable sub-soils which had limited sub-soil root exploration. Although some deaths in the Mt Barker plantations were undoubtedly due to shallow soils, others were due to salinity.

There are a number of problems in prescribing a definitive soil depth for *E. globulus* plantations across the south-west of WA. These include (a) difficulties in determining soil water holding capacity (defining what actually constitutes a root-limiting horizon, differences in WHC with different soil textures, methods of routinely measuring these across

paddocks), (b) variations in the effective moisture supply (rainfall-evaporation) across the south-west (such that the critical soil depth at Augusta may be quite different to that at Darkan, this water supply will also vary from year to year), and (c) differences in the likely transpirational demand of different stands (related to site fertility, age of stand and planting conformation). A modelling approach to solving this problem has been initiated by the CSIRO Division of Forestry (BIOMASS model), however a simplified, operational version is required.

It is clear that modifications are required to the criteria and methods for land selection for *E. globulus* plantations. Research currently aimed at meeting this requirement includes projects within CALM to relate soil and site factors to *E. globulus* performance, these being funded by NLP[1], LWRRDC[2] and SID. Bunning's Treefarms have also commenced a similar research programme.

As a major requirement is to quickly refine site-selection standards for *E. globulus* plantations, and the incidence of deaths can be related to soil conditions, it is suggested that the soils of a large number of inventory plots (~1000) be characterised across the range of plantations in the south-west. Many of these plots already exist, however in some areas many more will need to be established. Factors important in determining tree survival and performance can then be identified. This approach should be combined with more detailed studies of questions such as what constitutes a root impenetrable horizon, and by undertaking water balances of a range of sites along environmental gradients. Additional funding, and the allocation of additional staff are required if these important tasks are to be rapidly accomplished.

Despite the problems in clearly defining the critical values for important soil and site attributes, temporary standards can be applied now. For example soils should be at least 2 m deep, and this depth should be determined with observation densities of at least 1 hole/ha. These critical values have to be applied across areas of land, and this can be done with the standard techniques of soil survey and land evaluation. Basically such surveys define the attributes of the targeted area (what is there), the distribution of these attributes (where it is) and the likely importance of these attributes for tree survival and performance. Such surveys can also provide broad indications for silvicultural management. Consequently it is suggested that such surveys be undertaken, by trained personnel, in advance of plantation establishment.

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[1]National Landcare Project: a three year project with Research Scientist Ms Justine Edwards

[2]Land and Water Resources Research and Development Corporation: a small project ($10 000) in the Kent River Catchment

2. Introduction

This report (a) presents a brief summary of results of the current CALM research programme into this problem, which is most likely caused by drought, (b) discusses factors which should be considered prior to plantation selection, (c) presents a series of recommendations for further work.

3. Current CALM Research Programme Into *E. globulus* Deaths

3.1. Aims

This work has the following aims:

- Attempt to explain the cause of deaths in *E. globulus* plantations
- Produce objective site selection guidelines for new plantations
- Encourage adoption of existing techniques of soil and site survey, as a framework for site selection for new plantations

3.2. Study 1: Darling Range Plantations (Hagen, George and Eckersley)

3.2.1. Introduction

This project was aimed at determining the cause of deaths within three P89 *E. globulus* plantations. This commenced in November 1993 at the request of Mr Simon Penfold, then Afforestation Manager.

3.2.2. Methods

3.2.2.1. Location

Sixty existing inventory plots were examined in three plantations, all established in 1989 (Hagen, George and Eckersley). These are located near Harvey and Waroona, on ex-farmland, on the Darling Scarp.

3.2.2.2. Trees

Plots (400 m^2) were established in 1991, and re-measured in May 1993. Where existing plots did not encompass all environmental gradients, additional temporary plots were established. Mean predominant height (MPH) was based on the heights of the three tallest trees, basal area was calculated from the trees alive at the time of measurement. Tree survival was re-assessed in May 1994. Inventory data therefore includes indications of mean predominant height (1993), basal area (1993) and tree survival (1991, 1993, 1994).

3.2.2.3. *Soils*

In each of these plantations backhoe pits were dug to depths of up to 2.5 m in, or adjacent to, existing inventory plots. Soils were described (McDonald and Isbell 1990), with particular reference to those factors likely to limit the exploration of sub-soils by roots (structure) or the occurrence of materials, such as saprolite which had been reported as being important elsewhere (McGrath *et al.* 1991). Bulk samples were also taken from within the profile, and from within the plot (0-10 cm). Soil analysis is currently limited to measurements of pH and electrical conductivity (salinity) on surface and deep samples.

Duplicate bulk density samples were taken at 20 cm intervals down the profile. Bulk density data were presented in two ways (a) as mean values for discrete soil depths and (b) as the constants of third-order polynomial

Table 1 Mean survival (%) for three P89 *E. globulus* plantations in the Darling Range, near Harvey and Waroona.

Plantation	Nº plots	Initial Stocking (Stems/ha)	Mean tree survival (%) 1991	1993	1994
Eckersley	24	1104	83	75	71
George	24	1200	76	67	34
Hagen	12	1250	81	52	40
*P**		*0.05*	*n.s.*	*0.04*	*0.0001*

* One-way ANOVA; P is the probability that the differences are due to chance

equations fitted to the depth distributions.

3.2.3. *Results*

3.2.3.1. *Differences in tree survival between plantations*

Mean tree survival (76-81%) was similar for all plantations in 1991 (Table 1). In the summer of 1992/93 there were marked deaths in Hagen's plantation, with mean survival decreasing from 81 to 52%, whereas the effect in George's and Eckersley's was less marked. Further deaths occurred in Hagen's last summer, however there was a marked increase in tree deaths in George's, with a reduction in mean survival from 67 to 34%. Eckersley's plantation was again relatively unaffected.

What are the differences in these plantations that cause such differences in survival? Apart from the lower initial stocking (Table 1), Eckersley's also has deeper, and better structured soil (Table 2). Whereas Hagen's and George's occur mainly in areas where soils have formed on fresh rock in dissected river valleys, Eckersley's has been less stripped with remnant deep lateritic profiles.

Table 2 Mean values for several site and soil attributes for three P89 *E. globulus* plantations in the Darling Range, near Harvey and Waroona.

Plantation	Nº plots	Slope (%)	Effective Depth (cm) [1]	Structure [2]	Ironstone [3]
Eckersley	24	14	210	2.2	0.67
George	24	19	135	1.8	0
Hagen	12	11	122	1.3	0
*P**		*0.001*	*0.003*	*0.005*	*0.001*

[1] Effective depth from soil observation - mostly depth to saprolite

[2] Structure - weak =1, moderate = 2, strong = 3

[3] Occurrence of ironstone gravel = 1, absent = 0

3.2.3.2. *Differences in tree performance with soil depth*

Are these differences in tree survival therefore due to differences in soil depth? In Table 3 the mean survival and performance of trees is related to three different depth classes, with a marked difference in the survival of trees following last summer with soils which were >2 m deep (69% survival) compared to those <2 m deep (42% survival). There were no significant differences in mean tree survival, with differences in soil depth, at two (1991) or four years (1993). Hence the effects of soil depth may be related to the increased transpirational demand of larger trees and/or the effects of last summer's drought. These results support those of previous studies into drought deaths in *P. pinaster* (Havel 1968) and *P. radiata*

Table 3 Tree performance for different depth classes in *E. globulus* plantations in the Darling Range, near Harvey and Waroona.

Depth Class (cm)	Nº plots	MPH (m)[1]	BA (m^2/ha)[1]	Mean tree survival (%) 1991	1993	1994
<100	22	12.7	9.1	77	65	44
100-200	19	13.1	10.1	81	70	41
>200	17	13.9	11.7	82	72	69
P		*n.s*	*n.s*	*n.s.*	*n.s*	*0.003*

[1] Mean predominant height (m)

[2] Basal area (m^2/ha)

(McGrath *et al.* 1991), however the drought deaths in *E. globulus* occur at a much younger age.

Although there are general trends of increasing height and basal area with increasing soil depth, these differences are not significant.

There are some difficulties in actually defining "soil depth". This is related to two factors (a) actually defining what represents a barrier to roots and (b) being able to measure that barrier across the landscape. Even in relatively simple situations such as shallow soils overlying bedrock there are complications - these include marked differences in soil depth over short distances and sometimes the occurrence of root impenetrable layers such as saprolite, such as reported by McGrath *et al.* (1991) in the Blackwood Valley. The former can of course be overcome with adequate sampling.

3.2.3.3. *Differences in tree performance with difference in sub-soil structure*

What about the effects of sub-soil structure? Differences in the mean survival and performance of trees is related to three different structural classes in Table 4. Soil structure was qualitatively assessed on soil profile faces, and is an estimate of macropores and hence ability of tree roots to explore subsoils. This ranged from no, or poor structure (i.e. like concrete), to very well structured clays, with evidence of prior root penetration.

Table 4 Tree performance as related to different soil structural classes in *E. globulus* plantations in the Darling Range, near Harvey and Waroona.

Structural Class	Nº plots	MPH (m)[1]	BA (m^2/ha)[1]	Mean tree survival (%) 1991	1993	1994
Weak	24	12.5	8.5	75	62	43
Medium	14	13.2	11.4	82	76	53
Strong	17	14.3	12.6	83	76	61
P		*0.003*	*0.02*	*n.s.*	*0.03*	*n.s*

[1]Mean predominant height (m)

[2]Basal area (m^2/ha)

Trees grew less well on soils with weak structure. When measured in 1993 these were 1.8 m shorter and had basal areas only 67% of those with strong structure (Table 4). Both these differences were highly significant. Similarly, tree survival increased with better soil structure. These differences were less apparent in 1994, possibly due to the poorer tree growth, and hence transpirational demand, from the soils with weak structure.

If structure is important in tree survival how can we routinely assess it, prior to establishing a plantation? This is a real problem. There was no significant relationship between soil bulk density and tree performance, or indeed between soil bulk density and soil structure. This was despite bulk density increasing in a general manner with depth in most soils, and these patterns being well described with third-order polynomial functions. If soils are examined with an auger, structure is destroyed. If examined with a probe, or penetrometer, there is no indication of what is being probed; moreover the force required to insert the probe is related to moisture content.

3.2.3.4. Differences in tree performance with the occurrence of ironstone gravels

Soils containing such gravels are generally deeply weathered; hence this soil attribute may provide a useful field indicator of soils with reasonable depths of root penetrable soil.

Table 5 shows that drought deaths are less prevalent on soils with ironstone gravels (70% survival) compared to soils in which they are absent (41% survival). The occurrence of ironstone gravels is related to landscape history, and hence to the likely depth of available soil.

Table 5 Tree performance related to the occurrence of ironstone gravels.

Ironstone Gravels	Nº plots	MPH (m)[1]	BA (m^2/ha)[1]	Mean tree survival (%) 1991	1993	1994
Absent	44	13.0	10.0	79	67	41
Present	16	13.7	10.7	80	73	70
P		*n.s.*	*n.s.*	*n.s.*	*n.s.*	*0.0002*

[1]Mean predominant height (m)

[2]Basal area (m^2/ha)

3.2.3.5. Soil factors unimportant for tree growth and survival

A number of other soil and site factors were assessed, however none of these was related to tree growth or survival. These include the field texture, pH and electrical conductivity of the surface and clayey sub-soil horizons, and the slope and aspect. This may be partly due to the relatively narrow range of soils and sites considered within this study.

3.3. Study 2: Brief inspections of various plantations (April-July 1994)

3.3.1. Introduction

Inspections have also been made, in the last 2-3 months, of a range of *E. globulus* plantations through-out the south-west.

3.3.1.1. *Muir's Plantation - Waroona*

This P89 plantation has a mean rainfall of 884 mm and occurs on the Swan Coastal Plain, 16 km south-west of Waroona. Soils have formed on sand dunes and adjacent swales.

Deaths in this area mainly occurred on the poorly drained swales, apart from where these had been mounded. Swales had up to 120 cm of grey sand overlying an iron-organic hardpan. There was no indication of salinity. Although there were no recent deaths on the dunes, these areas had poorer survival and growth, than trees planted on mounds in the swales.

3.3.1.2. *Gardiner's Plantation - Mumballup*

This P89 plantation has a mean rainfall of 901 mm. It occurs in the Preston River valley 25 km east of Donnybrook. Soils have formed on exposed basement rock on valley sides and remnants of deep weathered laterite profiles on ridge crests.

Several transects were made along slopes, temporary plots established and soil depth determined by auger. Tree survival was generally related to soil depth, and possibly aspect. On north and west facing slopes there was a requirement for at least 1.6 m of soil for full survival whereas on south facing slopes the critical depth was only around 0.9 m. Deaths occurred on sandy soils with depths in excess of 2 m. It should be stressed that these depths are based on limited sampling.

3.3.1.3. *Johnson's Plantation - Unicup*

This P89 plantation has a mean rainfall of 830 mm, and is located 5 km north of Muir's Highway, 60 km ESE of Manjimup. Here the depth of soil required for full survival was around 2.4 m of moderately structured loamy soil.

3.3.1.4. *Mt Barker plantations*

Several plantations north of the Muir Highway, north-west of Mt Barker were inspected in late April. Here deaths were likely to be due to a number of causes such as drought on shallow soils (Ahern's, Shepherd's), salinity and waterlogging (Struther's, Boyle's).

3.4. Discussion

Deaths in *E. globulus* plantations last summer were mostly due to drought, induced by planting trees on shallow soils. In some plantations, however, deaths may have been caused by salinity and waterlogging.

There are a number of problems in prescribing a definitive soil depth for *E. globulus* plantations across the south-west of WA. With quite fertile loamy surfaced soils, in areas with rainfall >800 mm, a soil depth of at least 2 m of soil is required to avoid widespread drought deaths, however deaths also occurred on soils >2 m deep. For example at Hagen's, Georges and Eckersley's Plantations 31% of the trees died between establishment and 1994, with 13% between 1991 and 1994. Deaths on these soils last summer were, however, minimal (3%[3]) compared to those soils <2 m deep (25%).

This critical soil depth will be subject to the influence of (a) soil water holding capacity (i.e. storage), (b) variations in effective moisture supply, (c) transpirational demand and (d) the interactions between these variables. These will now be considered in turn.

3.4.1. Soil water holding capacity

The critical depth requirement will vary with soil texture. Plant available water generally increases with clay content, such that sandy soils contain less water per unit volume than loams and clays (Donahue *et al.* 1983). As described earlier, there are also difficulties in determining what actually constitutes a root-limiting layer and in routinely measuring such layers across paddocks.

These problems are not insurmountable - what are needed are calibrations of soil water holding capacity using surrogate variables that can be easily measured such as field texture or clay content. Similarly, once root impenetrable layers have been identified, methods for assessing their distribution in the field can be developed. The routine use of backhoe pits during site assessments will provide valuable information on the potential root exploration of sub-soils.

3.4.2. Variations in effective moisture supply

Variations occur in the effective moisture supply (rainfall-evaporation) across the south-west of the state, such that the critical soil depth at Augusta may be quite different to that at Darkan. This effective moisture supply will also vary from year to year; such variability should be taken into account in plantation planning.

The role of local hydrology in contributing to water supply should also be considered, again these contributions to tree growth and survival need to be quantified.

3.4.3. Tree transpirational demand

Whereas soil factors such as soil depth and structure may give an indication of potential tree growth and survival, the degree to which soil water is depleted will depend on the stand transpiration. This will be related to factors such as site fertility (more fertile sites have larger canopies), age of stand (up to a certain age transpiration may increase with age) and planting conformation (i.e strips vs blocks, stand density).

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[3]As % of initial trees planted

3.4.4. Interactions

The above factors will also interact with each other. Hence not only will soil water storage differ between sands, loams and clays of the same depth, but so will the transpirational demand, as the sandy soils will be the least fertile.

Such factors have been integrated in the BIOMASS model, currently being calibrated for local conditions by the CSIRO Division of Forestry, however a simplified, operational version is required.

4. Soil and site factors which should be considered for *E. globulus* plantation selection

Although the specific relationships between soil and site attributes and tree performance are often not known in Western Australia, general relationships are known from studies elsewhere. The roles of soils can thus be considered in terms of their effects on water supply (deficiency or excess), tree nutrition and stability (Carmean 1975; Valentine 1986; Turvey *et al.* 1990).

4.1. Water supply

In south-west WA both water deficiency (drought) and excess (waterlogging) are important for tree performance. Deficiency will be related to the volume of the soil, its moisture holding capacity and rainfall, as seen earlier in this report. Factors which control the rooting capacity of the soil include the depth to any root impeding layer and soil texture.

In many cases it is not clear what actually constitutes a root inhibiting horizon. Despite deep weathering profiles being common, and reports of the roots of native vegetation penetrating this material to depths of several metres, it is by no means certain that all deep weathering profiles, or indeed the clayey B horizons of the texture contrast (duplex) soils will be penetrable to the roots of plantation species. Similarly hardpans of varying composition (ferricretes, silcretes and iron-organic matter) and structure commonly occur within soil profiles. It is clear that the importance of such differences in structure, and hence root exploration of sub-soils, should be resolved and this information incorporated into soil surveys.

Waterlogging has been recognised as a problem in agricultural regions of south-western Australia (McFarlane *et al.* 1989), particularly on duplex soils. An excess of water can lead to anaerobic conditions, mortality of tree roots, and paradoxically drought deaths (Avery 1962). Similarly trees in such sites can suffer from wind-throw. The pattern of water supply is often related to landscape position (Moore *et al.* 1991), with water logged sites most likely in lower slope positions and at the breaks of slope.

4.2. Nutrition

Deep weathering and deposition have resulted in soil parent materials comprised mainly of quartz with kaolinitic and sesquioxide clay minerals (Gilkes *et al.* 1973; Robson and Gilkes 1981). Consequently soils are infertile in terms of a range of plant nutrients, with forestry responses to both macro (N, P, K) and micronutrients (Cu, Zn, Mn). Boron responses have not been reported in Western Australia. Chemical fertility is invariably higher on soils under agricultural management, compared to native vegetation, with contents of nitrogen and phosphorus often related to past management. Soils with potassium deficiencies are often sandy, and excessively drained and may not be capable of producing economic timber crops. While calibrations between different chemical extractants and plant response have been developed for phosphorus and potassium for agricultural plants, such relationships are not available for commercial tree species.

4.3. Salinity

Salinity is a major agricultural land degradation problem in south-western Western Australia (Select Committee into Land Conservation 1990). This is a consequence of the storage of large amounts of salt within the deep weathering profiles; this salt is remobilized by movements in groundwater following land clearing for agriculture. Soil salinity contents critical for tree growth have not been adequately researched; although several studies have described the growth of trees on saline soils (Biddiscombe *et al.* 1981; Pepper and Craig 1986), actual soil analysis is minimal. Moreover, soil samples are rarely taken from below the surface horizons in the zone where most salt occurs.

Measurements of salinity at a site may be less important than understanding the likely response of deep groundwaters over time. In areas with ≈750 mm annual rainfall groundwaters can rise at rates of up to 1.4 m/year (Schofield *et al.* 1988), and salinity may even develop following tree establishment. Direct soil measurements of surface salinity, such as with electromagnetic induction (EM38 meters), will indicate the present situation, but not future risk, as groundwaters may rise over time.

5. Soil and site surveys can be implemented now

Objective guidelines for selecting sites for *E. globulus* plantations can be implemented now, and modified as research results are interpreted.

The observations and interpretations from individual points have to be extended over areas of land, and the techniques of soil survey have been developed to contend with these issues (Dent and Young 1981). Issues to be considered in designing guidelines for the soil survey component of a land evaluation package include the scale of survey (i.e. 1:10 000 or 1: 20 000), the intensity of sampling, the depth of soil assessment, the range of soil and site attributes which are recorded and the extent that laboratory analyses are used. The development of salinity is a major issue in some areas in which we are establishing trees and traditional techniques of soil survey cannot provide information about its likely risk. Some hydrological interpretation will therefore be necessary in any land evaluation package.

In 1991 I produced a set of guidelines for site selection for *P. radiata* sharefarms, across the south-west. These were based on standard techniques of soil survey and provided a framework for decision making. These guidelines paid particular recognition to the importance of soil depth, salinity and waterlogging. Where the survey indicated particular problems, it was complemented with examination of back-hoe pits, with an estimation of whether sub-soils were penetrable by plant roots. This contract was undertaken by Mr Bill McArthur over the period 1991-1993, at a cost of $10/ha. During 1993 I commenced training a CALM forester (Mr Ted Reilly) to continue this work for CALM. This system although not yet adopted for *E. globulus* plantations, is readily adaptable.

6. Research requirements

6.1. Regional soil and site investigation

A major research requirement is to quickly refine the site selection standards for *E. globulus* plantations. As seen earlier in this report the incidence of deaths can be related to soil conditions, hence it is suggested that the soils of a large number of inventory plots (~1000) be characterised across the range of plantations in the south-west. Ideas for a project outline are attached (Appendix 1).

Such a project will allow (a) the production of a set of guidelines for site selection, at broad scales such as rainfall and geomorphic zones, which can be used for broad planning and (b) indicate the critical values of the factors important in determining tree survival and performance. Such a framework will also allow different survey strategies within different geomorphic zones; for example in dissected terrain effort can be concentrated on soil depth, in flat terrain on waterlogging and salinity. Some of this work is already underway with the NLP and Bunning's Research programmes; however with increased resources these results can be obtained sooner.

Many of the inventory plots already exist, however in some areas many more will need to be established. These plots can also be used for yield estimation.

6.2. Detailed studies of soil/tree interactions

This approach should be combined with detailed studies of questions such as what constitutes a root impenetrable horizon, and by undertaking water balances of a range of sites across environmental gradients.

Additional funding, and the allocation of additional staff to this research programme are required if these important tasks are to be rapidly accomplished.

7. Acknowledgements

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