Drought deaths in *Eucalyptus globulus* (Labill.) plantations in relation to soils, geomorphology and climate

R. J. Harper · K. R. J. Smettem · J. O. Carter · J. F. McGrath

Abstract The occurrence of tree deaths in young, 3 to 6 year old *Eucalyptus globulus* plantations established on farmland in south-western Australia was found to be strongly related to factors indicative of poor soil water storage capacity. Seven years after planting tree survival was significantly less on soils <2 m deep compared to >2 m deep (22% vs 70%). This is due to the limited ability of some soils to store a sufficient proportion of the annual rainfall within the root-zone to meet the plant water demand in a region with a recurrent annual summer drought. There are practical difficulties in routinely surveying soils to depths in excess of 2 m over broad areas, to predict the likelihood of tree death. On the granitic basement rocks of south-west Western Australia, the occurrence of ferricrete gravels provides a useful surrogate indicator for 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 (~30-50 m deep); whereas along drainage lines the regolith has been completely stripped, the soils are shallow and plantations are most susceptible to drought. Knowledge of the relationship between soil depth and plantation performance allows regional indications of drought risk to be developed from regional soil mapping and the production of more efficient sampling designs for site assessment.

Keywords Eucalyptus globulus · Reforestation · Climate change · Soil constraints · Soil water storage capacity

R. J. Harper (✉) · J. F. McGrath
Forest Products Commission,
Locked Bag 888,
Perth Business Centre, WA 6849, Australia
e-mail: richard.harper@fpc.wa.gov.au

K. R. J. Smettem
Centre for Ecohydrology,
School of Environmental Systems Engineering,
The University of Western Australia,
Nedlands, WA 6907, Australia

J. O. Carter
Queensland Climate Change Centre of Excellence,
Environmental Protection Agency,
80 Meiers Rd,
Indooroopilly, Queensland 4068, Australia

Introduction

Much reforestation has occurred in south-western Australia, with 281,329 ha of Tasmanian blue-gum (*Eucalyptus globulus* Labill.) planted between 1985

and 2006, with this representing 35% of the Australian total (Parsons and Gavran 2007). This reforestation is driven by several factors, including investment for the production of pulp and timber, predominantly in higher rainfall areas (>600 mm mean annual rainfall), and an increasing investment for environmental benefits (Harper et al. 2009) and carbon sequestration (Harper et al. 2007).

Future reforestation may comprise additional species, have a wider geographic distribution, and have different aims including carbon sequestration, fuel for bioenergy, or enhanced habitats for wildlife. For example, it is estimated that by 2050 up to 17 million hectares of land will be affected by dryland salinity (National Land and Water Resources Audit 2001) and several million hectares of reforestation will be required to restore the hydrological balance across southern Australia. Plantations may also be established to off-set emissions of carbon dioxide from industry in response to the Kyoto Protocol and successor arrangements (Harper et al. 2007) or to produce bioenergy (Sochacki et al. 2007).

Irrespective of purpose, the benefits of reforestation can only be realised if the trees survive and growth is adequate. Growth and survival depend on good silvicultural management but are also strongly related to soil conditions. Soil surveys at an appropriate scale for management (1:10,000) are often recommended as a prelude to reforestation (Valentine 1986; Ryan et al. 2002). An important requirement is to identify the key soil properties that should be assessed in soil surveys for reforestation and then refine methodologies to allow surveys to be undertaken at a reasonable cost and speed.

Widespread deaths of trees in plantations in response to drought occur periodically in south-western Australia in response to periods of 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, indicating a possible link to soil properties.

A study of the relationship between soil properties and drought deaths was thus undertaken to identify major soil properties associated with tree mortality, and their critical values. By identifying the key soil constraints to tree growth and survival and incorporating these properties into soil survey procedures for reforestation it should be possible to identify and avoid poor sites, thereby minimising plantation losses due to drought deaths.

Methods

Measurement plots

Fifty six permanent inventory plots around 400 m^2 (20 m x 20 m) were randomly sited in three plantations approximately 100 km south of Perth, Western Australia in 1991. The plantations were all established in 1989 (Fig. 1), with initial planting densities of 1250 trees ha^{-1}. Plots covered the range of health, productivity, landscape position and soils found within the plantations. At each plot measurements were made to assess tree height using a measurement tape and clinometer and basal area (BA) using a diameter tape. 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. Standing tree volume was estimated from the cone formula BA x TH/3.

Soils

Soils were examined to depths of up to 3 m, via pits prepared with an excavator. Soil profile and landscape attributes were described using standard procedures (McDonald et al. 1990). Landscape positions ranged from lower slope to crests. Soil depth was described as depth to saprolite, as identified by partially weathered or unweathered feldspars and micas, and expressed as three depth intervals (<1 m, 1–2 m 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 using standard techniques (Rayment and Higginson 1992). Duplicate bulk density cores were taken at 20 cm intervals down the soil profiles. Ferricrete gravel was considered in terms

Fig. 1 Location of the three plantations
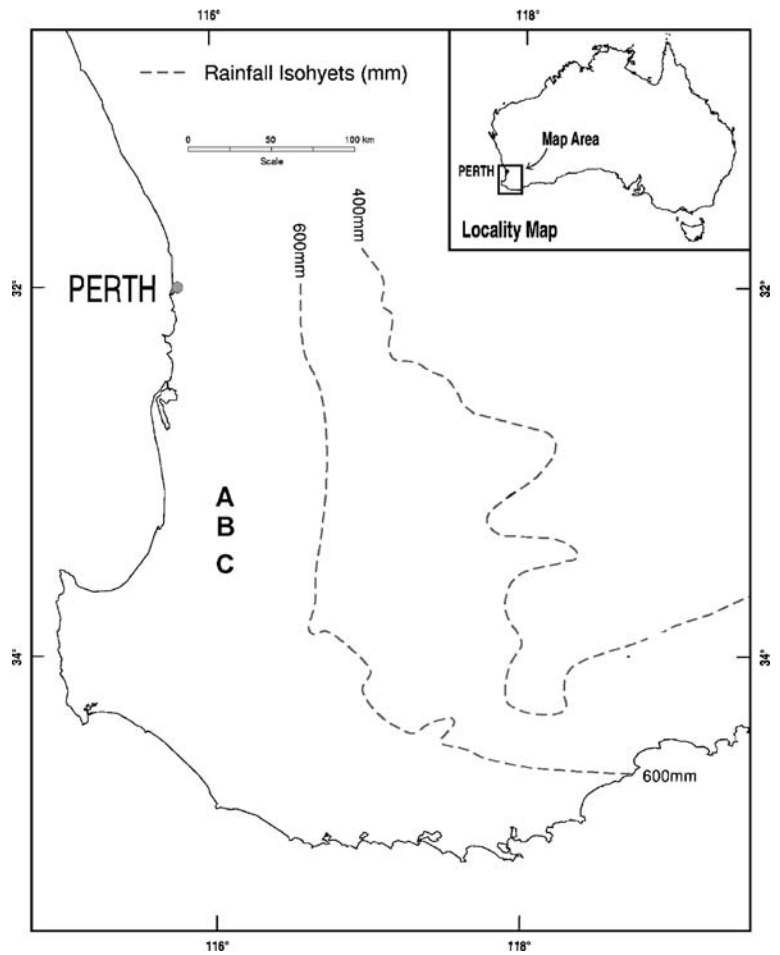
of presence or absence anywhere within the soil profile.

Climate

South-western Australia has a Mediterranean environment, with a predominance of winter rainfall and an annual summer drought. For the three plantations daily rainfall (R) and evaporation (E) data were obtained from the SILO climate data base (Jeffrey et al. 2001). This system 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, with the earlier data being used for model spin up of initial soil water balance. Approximate annual and summer water deficits were estimated with a simple water balance calculated from R – 0.7E, where R is the

rainfall and E is the pan evaporation over the period of interest (annual or summer). The 0.7 crop factor was taken from a study that produced estimates of potential evapotranspiration from pan evaporation for Australian conditions (Chiew and McMahon 1992).

Results

Climate

Table 1 summarizes the mean climate for the period 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) rainfall for Plantation A is plotted in Fig. 2a. It is evident that the annual rainfall to March

Table 1 Mean rainfall and evaporation (1970–2000), tree growth at 7 years of age and soil depth (m) for each of the three plantations

Plantation	n	Rainfall	Pan Evaporation	Top Ht	Volume	Survival	Soil depth
		(mm)		*(m)*	*($m^3\ ha^{-1}$)*	*(%)*	*(m)*
A	10	1010	1599	15.7	22	17	1.2
B	23	996	1555	17.1	28	16	1.3
C	23	980	1560	20.8	108	64	2.1
P				*0.001*	*0.0001*	*0.0001*	*0.003*

n number of samples, *P* is probability that the mean values are significantly different, using a one-way ANOVA

1994 and March 1995 were both below average, with the summer rainfall in Nov 1994–March 1995 being particularly low with only 19 mm received. This low rainfall coincided with a higher than average annual potential evaporation (Fig. 2b) with a resultant negative water balance for the year of −561 mm and

Fig. 2 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

−852 mm for the summer. Fig. 2 also shows the recurrent nature of drought in this environment.

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 medium clays (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 reddish 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 maximum soil depth increments (Fig. 3a). 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 $m^3\ ha^{-1}$.

In this region, soils containing ferricrete gravels are generally deeply weathered (McArthur 1991); hence this soil attribute may provide a useful field indicator, or surrogate, of soils with an adequate volume of root penetrable material. The occurrence of ferricrete
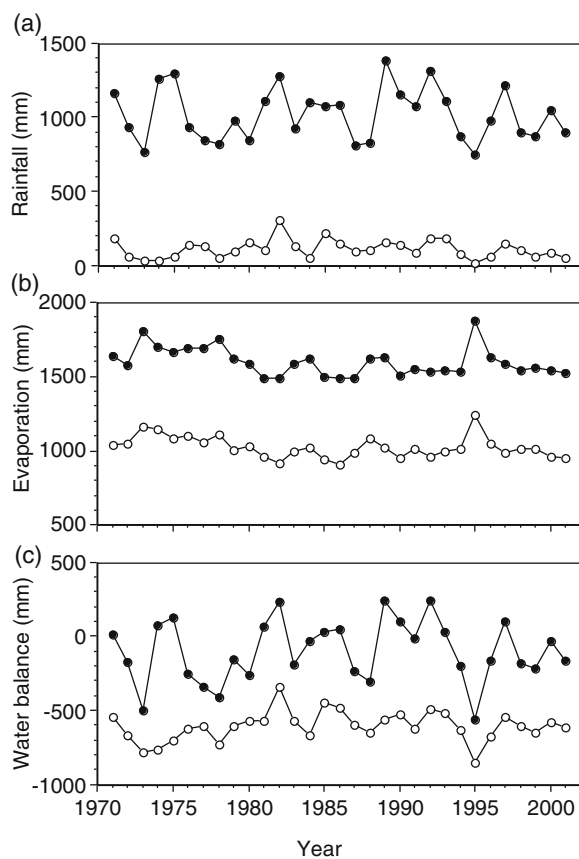
Table 2 Mean surface soil (0–10 cm depth) properties of a random sub-set of soils <2 m and >2 m deep

Soil depth	n	N	OC	Particle Size				EC	Exch. Cations				BD
				Clay	Silt	FS	CS		Ca	Mg	Na	K	
(m)				(%)				$(mS\ m^{-1})$	$(cmol\ p^+\ kg^{-1})$				$(Mg\ m^{-3})$
<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

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 (mS m^{-1}), BD Bulk density from 0.9 m deep (Mg m^{-3}), P is probability that the mean values are significantly different, using a one-way ANOVA

gravels gave a similar discrimination of tree survival as soil depth. Again there was no difference two years after planting but by seven years after planting the sites where ferricrete gravel was absent had markedly poorer survival than where it occurred (19% vs 68%) (Fig. 3b). There was again a small decrease in tree volumes between four and seven years of age (44 to 30 m³ ha⁻¹) where ferricrete was absent, whereas volumes increased markedly where it was present (50 to 121 m³ ha⁻¹). The mean soil depth, based on observations to 3 m, of sites without ferricrete was markedly less than where ferricrete was present (1.2 m vs 2.4 m, $P<0.001$). Across the study sites, the bulk density of the sub-soil clays ranged from 1.3 to 2.1 Mg m⁻³ but had no apparent effect on growth (wood volume increment) or survival.

Development of a drought stress index

A drought stress index was developed using a four-layer daily soil-water balance program (GRASP) that incorporated both pasture (before canopy closure) and tree transpiration. The GRASP model (Rickert et al. 2000) previously modified to provide for dynamic tree growth, (J.O. Carter unpubl.) was further modified in this study to calculate a water stress index related to tree death.

The water balance component of GRASP is a simple tipping bucket model initially developed and tested in wheat lands of Western Australia (Rickert and McKeon 1982). A soil water index was calculated for each soil layer based on the available water ratio and a non linear function relating amount of moisture

Fig. 3 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
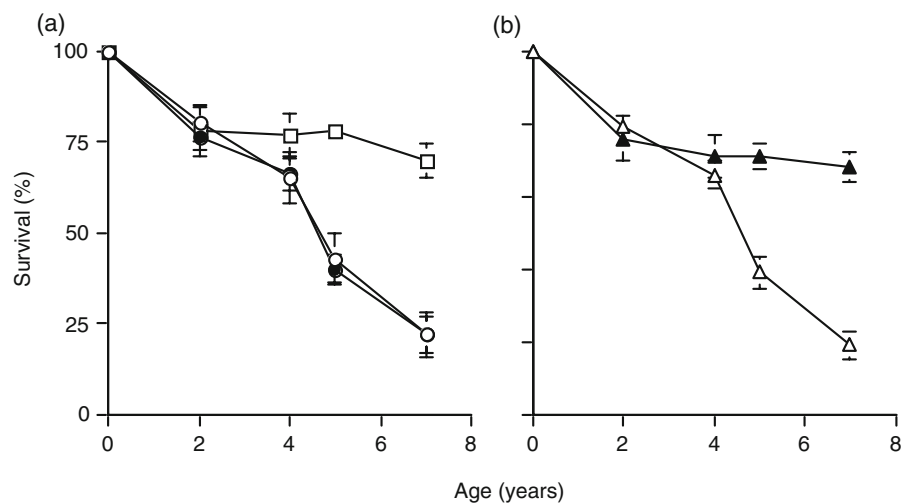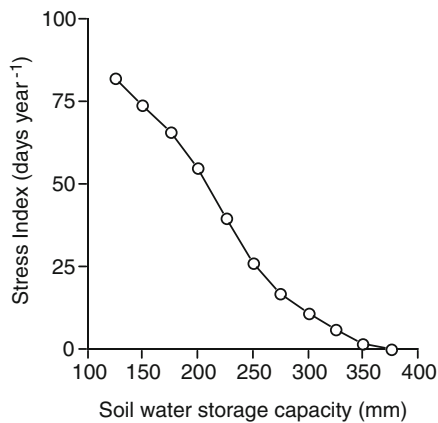
Fig. 4 Variation in nominal drought stress index (days year^{-1} beyond wilting point) compared to soil water storage capacity, modelled using 1990–2000 daily climate data from Plantation A using a derivation of GRASP

to its plant availability. The stress index for tree death was a simple function that counted the number of days in which soil water index in all four layers fell below a threshold value.

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 by modifying parameters that control nitrogen availability and transpiration use efficiency. Simulation studies were run where the stress index was calculated for soil water holding capacities in the range of 125–375 mm. For the climate regime studied there appeared to be no stress in the trees with 375 mm of soil water storage capacity, with the stress index increasing non-linearly with decreasing soil water storage capacity (Fig. 4).

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 this region in *P. pinaster* and *P. radiata* (McGrath et al. 1991), however the drought deaths in *E. globulus* occur at a much younger age than these 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 critical. Sites selected for plantations require rootzone soil moisture storage conditions that allow survival through extreme rather than average conditions.

The occurrence of ferricrete gravels is an indicator for deep weathering profiles, which in this region may be 30–50 m deep overlying bedrock (McArthur 1991). Subsequent drilling to 10 m at various plantations indicated water depletion to at least this depth under trees. By comparison, adjacent soils under agriculture contained plant available water below the top metre. Similar results were also reported by Robinson *et al*. (2006) for deeply weathered soils, elsewhere in this region. Although subsoil bulk densities approached values of up to 2.1 Mg m^{-3} such materials do not appear to be root impenetrable, where patterns of moisture depletion have been used to infer root activity (Robinson et al. 2006). Dell et al. (1983) reported the extension of roots to depths of up to 40 m depth under natural stands of *Eucalyptus marginata*, the natural vegetation of much of this region. This was explained as being the result of the occupation of root channels, fissures and voids that occurred throughout the deep soil profiles. Up to 1% of the horizontal surface at 6 m was occupied by these channels, and it is likely that the *E. globulus* trees have re-occupied these channels, following reforestation of farmland.

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, but 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 volume decreasing with decreasing rainfall. The contribution of increasing soil water storage capacity to the minimization of tree stress is shown clearly in Fig. 4.

While it is recommended that pre-planting surveys concentrate on defining overall regolith volume there

are significant practical difficulties in doing this, particularly where this involves routine evaluation of soils to depths of 2–3 m or more. Issues involve the definition and spatial representation across the landscape of soil materials that represent barriers to roots, and thus constrain the effective rootzone soil volume. The presence of ferricrete gravels in the soil profile may provide a rapid field indicator of adequate soil volume, if combined with other observations such as the exposure of bedrock.

The chemistry and mineralogy of the weathered and unweathered soils are quite distinct (Turton et al. 1961) and such differences have been depicted with gamma radiometric soil surveys, elsewhere in the region (Pracilio et al. 2006). This opens the possibility that gamma radiometric surveys may provide a means of rapidly delineating the occurrence of soils of different depths, and thus potential drought risk.

Regional pattern of soil depth in relation to regolith stripping

Another approach to determining the regional distribution of soil volume is to recognise the geomorphic basis of regolith stripping. Thus, regional indications of drought risk may be developed from regional soil mapping.

In south-western Australia, 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, with subsequent removal of regolith to variable depths in response to fluctuations in base level (Mulcahy 1967). 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 (Bettenay and Mulcahy 1972; Finkl and Churchward 1973). In each case the parent materials for contemporary soils comprise the different horizons of the original laterite profile (Stephens 1946; Mulcahy 1967). 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.

The process of landscape stripping has led to regional patterns in soil profile water storage and soil fertility. Patterns of fertility in relation to stripping in this region have been previously reported (Turton et al. 1961; Webster 1979), with primary minerals occurring in the stripped soils but not in the deeply weathered soils, which are dominated by quartz and sesquioxide clay minerals. There were no significant differences in soil fertility, as measured by total nitrogen content and exchangeable cations, between shallow and deep soils in this study (Table 2). Across the region, there are strong reported relationships between the soil-landscape patterns and patterns of natural vegetation (Lange 1960; Havel 1975).

These regional soil patterns have been used to predict potential pulp-wood production and carbon sequestration for a type locality in this region by Harper *et al.* (2005), using existing regional soil survey information.

Pinus radiata plantations in this region are also affected by periodic droughts (McGrath et al. 1991), and here the management response is 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.

Implications for second rotation growth and survival

It is expected that the *E. globulus* plantations will be coppiced or replanted in a 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 as drought death is more probable if soil moisture profiles are depleted and tree death occurring in large patches is unlikely to be compensated by improved growth of neighbouring trees as might occur with death of scattered trees.

Conclusions

This study has demonstrated the importance of soil volume in explaining the onset of drought deaths in

Eucalyptus globulus in south-western Australia, with deep soils providing a store for winter rainfall. Deep soils 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 rigorous site selection.

Surrogates such as the occurrence of ferricrete gravel and broad landscape interpretation provide a means of defining where drought risk is greatest. While these 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 and demonstrate the application of knowledge of soil-geomorphic relationships to site selection. 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.

References

Bettenay E, Mulcahy MJ (1972) Soil and landscape studies in Western Australia. (2) Valley form and surface features of the south–west drainage division. J Geol Soc Aust 18:359–369

Chiew FHS, McMahon TA (1992) An Australian comparison of Penman's potential evapotranspiration estimates and class A evaporation pan data. Aust J Soil Res 30:101–112. doi:10.1071/SR9920101

Dell B, Bartle JR, Tacey WH (1983) Root occupation and root channels of jarrah forest subsoils. Aust J Bot 31:615–627. doi:10.1071/BT9830615

Finkl CW, Churchward HM (1973) The etched landsurfaces of southwestern Australia. J Geol Soc Aust 20:295–307

Harper RJ, Smettem KRJ, Tomlinson RJ (2005) Using soil and climatic data to estimate the performance of trees, carbon sequestration and recharge potential at the catchment scale. Aust J Exp Agric 45:1389–1401. doi:10.1071/EA04186

Harper RJ, Beck AC, Ritson P, Hill MJ, Mitchell CD, Barrett DJ, Smettem KRJ, Mann SS (2007) The potential of greenhouse sinks to underwrite improved land management. Ecol Eng 29:329–341. doi:10.1016/j.ecoleng.2006.09.025

Harper RJ, Smettem KRJ, Reid RF, Callister A, McGrath JF, Brennan PB (2009) Pulpwood Crops. In: Reid RF, Nuberg I (eds) Agroforestry for natural resource management. CSIRO, Melbourne

Havel JJ (1975) Site vegetation mapping in the northern jarrah forest (Darling Range). 2. Location and mapping of site—vegetation types. In For. Dep. West. Aust. Bull. Forests Department of Western Australia, p 105

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ Model Softw 16:309–330. doi:10.1016/S1364-8152(01)00008-1

Lange RT (1960) Rainfall and soil control of tree species distribution around Narrogin, Western Australia. J R Soc West Aust 43:104–110

McArthur WM (1991) Reference Soils of South-western Australia. Australian Society of Soil Science Inc. WA Branch, Perth, p 265

McDonald RC, Isbell RF, Speight JG, Walker J, Hopkins MS (1990) Australian soil and land survey field handbook. Inkata, Melbourne

McGrath JF, Ward D, Jenkins PJ, Read B (1991) Influence of site factors on the productivity and drought susceptibility of *Pinus radiata* in the Blackwood Valley Region of Western Australia. In: Ryan PJ (ed) Productivity in perspective. Third Australian forest soils and nutrition conference. Forestry Commission of New South Wales, Sydney, Melbourne, pp 65–66

Mulcahy MJ (1967) Landscapes, laterites and soils in south-western Australia. In: Jennings JN, Mabbutt JA (eds) Landform Studies from Australia and New Guinea. ANU, Canberra, pp 211–230

National Land and Water Resources Audit (2001) Dryland Salinity in Australia. A summary of the National Land and Water Resources Audit's Australian Dryland Salinity Assessment 2000. National Land and Water Resources Audit, Canberra

Parsons M, Gavran M (2007) National plantation inventory Australia — 2007 Update. Department of Agriculture, Fisheries and Forestry, Canberra, p 8

Pracilio G, Adams ML, Smettem KRJ, Harper RJ (2006) Determination of spatial distribution patterns of clay and plant available potassium contents in surface soils at the farm scale using high resolution gamma ray spectrometry. Plant Soil 282:67–82. doi:10.1007/s11104-005-5229-1

Rayment GE, Higginson FR (1992) Australian laboratory handbook of soil and water chemical methods. Inkata, Melbourne, p 330

Rickert KG, McKeon GM (1982) Soil water balance model: WATSUP. Proc Aust Soc Anim Prod 14:198–200

Rickert KG, Stuth JW, McKeon GM (2000) Modelling pasture and animal production. In: Mannetje L, Jones RM (eds) Field and Laboratory Methods for Grassland and Animal Production Research. CABI, New York, pp 29–66

Robinson N, Harper RJ, Smettem KRJ (2006) Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. Plant Soil 286:141–151. doi:10.1007/s11104-006-9032-4

Ryan PJ, Harper RJ, Laffan MD, Booth TH, McKenzie NJ (2002) Site assessment for farm forestry in Australia and its relationship to scale, productivity and sustainability. For Ecol Manage 171:133–152

Sochacki S, Harper R, Smettem K (2007) Estimation of woody biomass production from a short rotation bio-energy system in semi-arid Australia. Biomass Bioenergy 31:608–616. doi:10.1016/j.biombioe.2007.06.020

Stephens CG (1946) Pedogenesis following the dissection of lateritic regions in southern Australia. Council for Scientific and Industrial Research, p 21

Turton AG, Marsh NL, McKenzie RM (1961) Morphological, chemical and minor element data on lateritic and non-lateritic profiles from south-western Australia. CSIRO Australia Division of Soils

Valentine KWG (1986) Soil resource surveys for forestry. Soil, terrainand site mapping in boreal and temperate forests. Oxford University Press, Oxford, p 147

Webster R (1979) Exploratory and descriptive uses of multi-variate analysis in soil survey. In: Wrigley N (ed) Statistical Applications in the Spatial Sciences. Pion, London, pp 286–306