A climate analysis of the current and potential future *Eucalyptus nitens* and *E. globulus* plantation estate on Tasmanian State forest

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Abstract

Plantations of Eucalyptus globulus *and* E. nitens *have been developed on Tasmanian State forest, with their combined area currently totalling 50,246 ha. The climatic envelope for this plantation estate was described by spatial interpolation of long-term climatic averages from an array of weather stations, using as parameters the mean minimum temperature of the coolest month, and effective rainfall (rainfall minus evaporation). Reanalysis of existing trial data suggested that growth reduction in* E. globulus *would begin to occur on sites with a mean minimum temperature of the coolest month below 1.8°C, and this threshold was thus chosen to segregate warmer areas of Tasmania suitable for planting either* E. globulus *or* E. nitens, *from cooler areas suitable only for planting* E. nitens. *This segregation based on temperature predicts that 53% by area of the current* E. nitens *and* E. globulus *plantation estate on State forest (26,607 ha) is suitable to plant either* E. globulus *or* E. nitens. *However, only 29% of this area is currently planted to* E. globulus, *a proportion which could potentially be increased to take advantage of the superior wood properties of* E. globulus.

There was strong overall agreement between segregation based on the 1.8°C temperature threshold, and segregation based on the previous altitudinal cut-off for E. globulus *of 350 m, with 87% of the State forest eucalypt plantation estate being classified similarly under both systems. However, there were significant differences among State forest Districts in the relationship between the mean minimum temperature of the coolest month and altitude. The altitude corresponding to the 1.8°C temperature threshold was substantially below 350 metres in Districts at a more southerly latitude or with plantations situated at greater distances from the coast. Two-thirds of the disparity between the temperature and altitudinal segregation (4,204 ha) was due to sites colder than the 1.8°C temperature threshold occurring at altitudes below 350 m. Currently 49% of this plantation area is under* E. globulus, *although the sites could be more suitable for* E. nitens.

Introduction

The current eucalypt plantation estate on State forest in Tasmania consists of predominantly *Eucalyptus nitens* and *E. globulus* with an area ratio of 80:20. The dominance of *E. nitens* in this estate relative to *E. globulus* is due to several factors, including the greater tolerance of *E. nitens* to low temperatures (Tibbits and Reid 1987,Volker *et al*. 1994, Tibbits *et al*. 2006), its greater resistance to Mycosphaerella leaf disease (Mohammed *et al* 2003) and its perceived early growth advantages. However, on frost-free sites, and where water is not limiting, growth rates of the two species are similar, at least for the first few years (Turnbull *et al*. 1993, Worledge *et al.* 1998). Increasing importance is being given to the superior wood properties of *E. globulus* for both pulpwood and solid wood (Wardlaw and Willams, 2010), with price premiums for these properties beginning to appear in the marketplace. The optimal choice of eucalypt species for State forest plantations during the transition into the next rotation is thus being re-evaluated.

Lower cold-tolerance of *E. globulus* limits the species choice decision to the warmer parts of the estate, where the risk of injury to *E. globulus* from frost or low temperature is reduced, and where *E. globulus* and *E. nitens* both grow well in the absence of pest and disease impacts. Historically, this has been achieved by restricting *E. globulus* to sites below approximately 350 m altitude: 98% of the current area of State forest planted to *E. globulus* occurs at elevations of 350 m or less. This altitudinal limit is applied throughout the State despite the plantation estate spanning more than 2.7 degrees of latitude, and its proximity to the coast varying between 1 and 100 km. Both latitude and proximity to the coast will influence site temperatures, augmenting the effect of altitude on temperature (Commonwealth of Australia 2008).

Spatial interpolation of climate data (typically rainfall and temperature) is used to create climate surfaces from a network of weather stations (e.g. Hijmans *et al*. 2005). Interpolated climate surfaces explicitly account for the influence of a range of factors such as elevation, latitude, longitude, and distance from the coast. Here, a spatially interpolated climate surface is used to describe the climatic attributes of the current *E. nitens* and *E. globulus* plantation estate on Tasmanian State forest, identify those parts of the estate likely to have climatic (particularly temperature) conditions suitable for *E. globulus*, and inform the *E. globulus* / *E. nitens* species-choice decision.

Methods

The ESOCLIM© module of ANUCLIM© 5.2 (Houlder *et al*. 2000) was used to predict a range of climatic values for each eucalypt plantation stand on State forest (excluding King Island), based on a large number of weather stations across Tasmania. Australian Map Grid coordinates for the centroid of each stand, and the corresponding spot elevation at that point, were extracted from Forestry Tasmania's PAS (Plantation Area System) Database. These grid-co-ordinate and elevation data were used as independent variables in ESOCLIM to generate predictions of mean minimum temperature of the coolest month, rainfall and evaporation for each stand. These climatic variables were chosen because they were considered most likely to provide useful discrimination of sites likely to be unsuitable for *E. globulus* (too cold) or *E. nitens* (too dry). The ESOCLIM variables were then simplified and combined as the mean minimum temperature of the coolest month, and effective rainfall (annual rainfall minus annual evaporation). The climatic envelope for the plantation estate on Tasmanian State forest based on these derived parameters was plotted, with each plot point discriminated according to the species (*E. globulus* or *E. nitens*) currently planted in that plantation.

The low-temperature threshold for *E. globulus* was identified by reference to stands of known field performance, based on the results of an altitudinal study of planted eucalypt species in the Esperance Valley (Hallam *et al*. 1989). In that study, growth of *E. globulus* was a maximum at 240 m elevation, declined sharply at 440 m elevation, and was severely impacted by frost / snow damage at 650 m elevation (data for the 60 m site was not used as it was situated in a frost hollow). The altitude of 340 m (the mid-point altitude between the 240 and 440 m sites) was thus chosen to represent a conservative low-temperature threshold, i.e. the threshold at which growth of *E. globulus* would start to decline but before that at which cold injury would be likely to occur. The mean minimum temperature for the coolest month corresponding to an altitude of 340 m in the Esperance Forest Block was then determined from the ESOCLIM data, and used as a state-wide low-temperature threshold for *E. globulus*.

While *E. nitens* is regarded as being more drought-intolerant than *E. globulus* (Nielsen 1990, White *et al*. 1996), a dryness threshold could not be determined in a similar way to that done for temperature. Instead, the climatic envelope was partitioned into dry and moist zones based arbitrarily on a threshold of the 33rd percentile of the estate-wide frequency distribution of effective rainfall.

The predicted mean minimum temperature of the coolest month for each plantation, and the effective rainfall of each plantation, were tested against the above threshold values. Plantations were classified as either warm or cool based on the minimum temperature threshold, and moist or dry based on the effective rainfall threshold. The combination of these two classifications was used to define four climate zones: warm-moist, warm-dry, cool-moist and cool-dry. Chi-squared tests were used to determine whether there were significant departures from independent assortment in the proportions of current *E. nitens* and *E. globulus* plantations among the climate zones. The 'comparison of regression lines' procedure in Statgraphics Plus (Statistical Graphics Corporation 1996) was used to test the significance of differences in the slope of the linear regressions of mean minimum temperature versus altitude for plantation sites among the Districts.

For these analyses, Derwent district was divided into its two administrative sections, Derwent (East) and Derwent (West).

Results

The climatic envelope of the *E. globulus* and *E. nitens* plantation estate on Tasmanian State forest was determined from temperature and rainfall parameters, namely the mean minimum temperature of the coolest month, and effective rainfall (rainfall minus evaporation). The range of mean minimum temperature of the coolest month for the current plantation estate was -0.5°C to 5.7°C, and the range of effective rainfall was -377 to 1669 mm (Figure 1). Despite considerable overlap, sites occupied by *E. globulus* were significantly warmer (3.2°C versus 1.9°C, average mean minimum temperature of the coolest month; $t = -12.1$; $P < 0.001$) and drier (238 mm vs 359 mm, effective rainfall; $t = -6.78$; $P < 0.001$) than sites occupied by *E. nitens*. This result is not surprising because the species were originally selected for sites based on perceptions of their performance and climatic requirements.

The upper altitude threshold of 340 m for *E. globulus* in the Esperance Valley, selected as an optimum combination of growth and frost risk, corresponded at this location to a mean minimum temperature in the coolest month of 1.8ºC. The temperature threshold derived from this single field-performance measurement was applied across an interpolated climate surface for the State based on long-term climatic averages. The validity of this approach depends on how typical the weather conditions were during the period over which the Esperance Valley field trial was assessed. Field measurements reported in Hallam *et al*. (1989) were made during the years 1982-84. Winter (June-September) temperatures at Cape Bruny Lighthouse (Bureau of Meteorology station 094010, 29 km south-east of the approximate mid-point along the Esperance Valley trial) were slightly warmer than the long-term average during these years (+0.7, +0.1 and +0.6°C, respectively). This suggests that, had the Esperance gradient study of Hallam *et al*. (1989) been done at a time when the winter minimum temperatures were average or below average, cold damage may have occurred at elevations lower than the 650 m, and growth reduction may have occurred at elevations lower than 440 m. However, the selected altitude threshold of 340 m was 100 m below the 440 m elevation plot, which represents a 0.98°C temperature difference at the dry adiabatic temperature lapse rate (http://en.wikipedia.org/wiki/Lapse_rate, accessed 21/12/2010). Thus the long-term average mean minimum temperature of the coolest month at 340 m would still be warmer than temperatures experienced at 440 m during the three slightly warmer years over which the Esperance trial was assessed.

The 33rd percentile of the frequency distribution for effective rainfall across the eucalypt plantation estate on State forest was 233 mm (Figure 1), and this value was used as a threshold for separating moist and dry sites. Consistent with the significant differences in characteristics of sites occupied by *E. globulus* and *E. nitens*, there were significant departures from independent assortment of current *E. globulus* and *E. nitens*

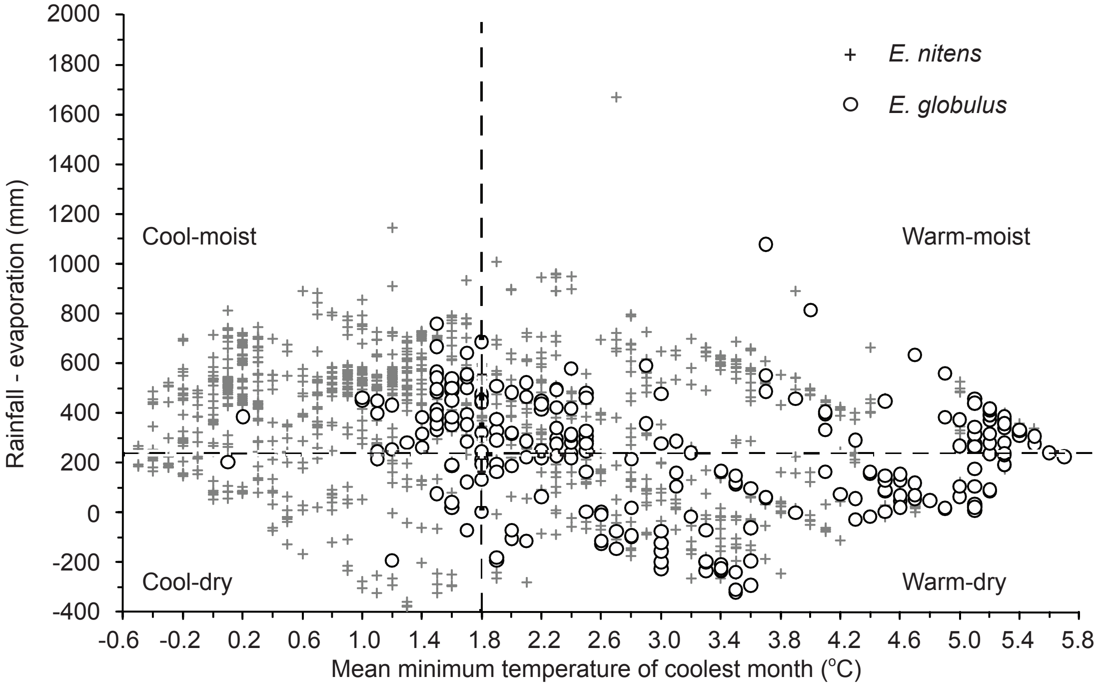


Figure 1. Climatic distribution of E. globulus *and* E. nitens *plantations on State forest. Horizontal and vertical dashed lines represent the thresholds in temperature used to define 4 climate zones (mean minimum temperature of the coolest month: cool, ≤1.8°C; warm, >1.8°C) and effective rainfall (rainfall minus evaporation: dry, ≤233 mm; moist, >233 mm).*

Table 1. Area of State forest E. nitens *and* E. globulus *plantations in each of four climate zones by District,* E. globulus:E. nitens *area ratios in that climate zone by District, and the area percentage of each climate zone in each District.*

District		Cool-dry	Cool-moist	Warm-dry	Warm-moist
Bass	Plantation area	853 ha	9,045 ha	9,004 ha	1,440 ha
	E. globulus: E. nitens area ratio	3:97	0:100	22:78	10:90
	% of Statewide area for that climate zone	18%	48%	67%	11%
Derwent (East)	Plantation area	624 ha		1,424 ha	
	E. globulus: E. nitens area ratio	1:99		50:50	
	% of Statewide area for that climate zone	13%		11%	
Derwent (West)	Plantation area	955 ha	3,643 ha		
	E. globulus: E. nitens area ratio	4:96	0:100		
	% of Statewide area for that climate zone	21%	19%		
Huon	Plantation area	452 ha	3,338 ha	458 ha	2,813 ha
	E. globulus: E. nitens area ratio	66:34	54:46	63:37	48:52
	% of Statewide area for that climate zone	10%	18%	3%	22%
Mersey	Plantation area	1,774 ha	2,224 ha	251 ha	124 ha
	E. globulus: E. nitens area ratio	6:94	0:100	64:36	0:100
	% of Statewide area for that climate zone	38%	12%	2%	1%
Murchison	Plantation area		761 ha	2,396 ha	8,697 ha
	E. globulus: E. nitens area ratio		0:100	26:74	28:72
	% of Statewide area for that climate zone		4%	18%	67%
Total	Plantation area	4,629 ha	19,901 ha	13,533 ha	13,073 ha
	E. globulus: E. nitens area ratio	10:90	10:90	28:72	30:70
	% of Statewide area for that climate zone	100%	100%	100%	100%

plantations when these were classified according to both the mean minimum temperature threshold (χ^2_1=13.5, P<0.001) or the effective rainfall threshold (χ^2_1=76.0, P<0.001). In both cases, the assortment of *E. globulus* plantations was the main contributor to the significant chi-square results. There were fewer *E. globulus* plantations on cool sites (≤1.8°C) than expected from random assortment, and more than expected on warm sites (>1.8°C). There were also more *E. globulus* plantations on dry sites (≤233 mm effective rainfall) than expected from random assortment, and fewer than expected on moist sites (>233 mm effective rainfall). This distribution again reflects the historical preference for planting *E. nitens* on cooler sites and for avoiding *E. nitens* on drier sites.

The cool-moist section of the climate envelope contained the largest proportion (38%) of the plantation estate (19,910 ha; Figure 1, Table 1). The warm-moist and the warm-dry sections of the climate envelope contained similar but smaller proportions of the plantation estate (13,073 ha and 13,533 ha, 26% and 27% of the total respectively) and together represented just over half of the plantation estate. Only a small proportion of the plantation estate (4,629 ha, 9%) occurred in the cool-dry

Table 2. Areas of State forest E. nitens *and* E. globulus *plantations, the percentage of total State forest plantation area, and* E. globulus:E. nitens *area ratios. Data are segregated by altitude and by mean minimum temperature of the coolest month.*

		≤350 m	>350 m	Total
>1.8°C	Plantation area	24,261 ha	2,345 ha	26,607 ha
	% of total State forest plantation area	48%	5%	53%
	E. globulus:E. nitens area ratio	32:68	0:100	29:71
≤1.8°C	Plantation area	4,204 ha	19,436 ha	23,639 ha
	% of total State forest plantation area	8%	39%	47%
	E. globulus:E. nitens area ratio	49:51	1:99	10:90
Total	Plantation area	28,465 ha	21.781 ha	50,246 ha
	% of total State forest plantation area	57%	43%	100%
	E. globulus:E. nitens area ratio	34:66	1:99	20:80

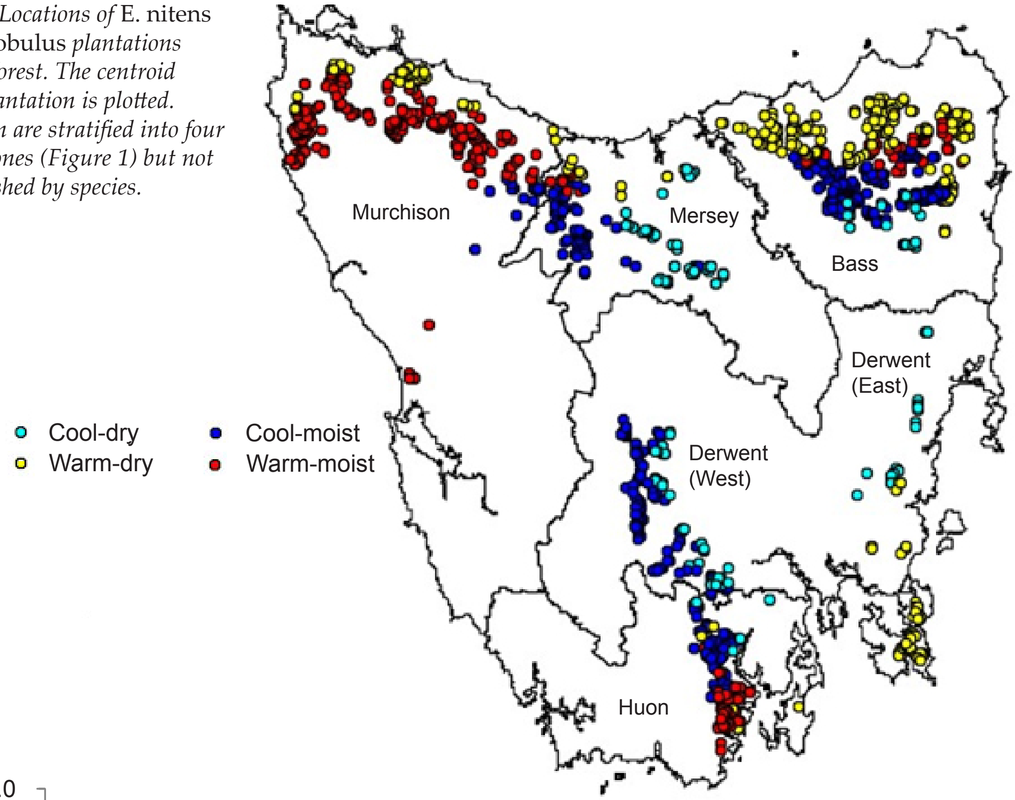
section of the climate envelope (Figure 1, Table 1).

Plantations in the cool-moist climate zone were concentrated in the north-eastern highlands of Bass District, Derwent (West), the upper Mersey Valley sections of Mersey District, and inland plantations in Huon District (Figure 2, Table 1). The small component of the plantation estate situated in the cool-dry climate zone was concentrated in low-altitude, inland plantations in Mersey District, the eastern fringes of the Derwent Valley in Derwent (West), and the eastern highlands in Bass and Derwent (East) Districts. Plantations occupying the warm-moist climate zone were concentrated in the interior lowland of Murchison District, the coastal sections of Huon District and mid-altitude areas of Bass District. The warm-dry climate zone encapsulated coastal lowland plantations extending along the north and east coasts of the state in all Districts (Figure 2, Table 1).

On an area basis, therefore, 26,607 ha (53%) of the current State forest eucalypt plantation estate occurs on sites where the mean minimum temperature of the coolest month is above the 1.8°C threshold (warm-moist plus warm-dry) and thus suitable for *E. globulus* (Table 2). This segregation of the plantation estate was in reasonable agreement with a segregation based on altitude (Table 2), with 43,697 ha (87%) classified the same way by both classifications. Nearly two-thirds of the disagreement between the two classifications (4,204 ha) related to areas at or below 350 m altitude that were predicted to have a mean minimum temperature of less than 1.8°C and that thus may not be suitable for *E. globulus.*

The slopes and y-axis intercepts of the linear regression of mean minimum temperature of the coolest month and altitude differed significantly among the districts ($F_{11,\ 1386}$ = 2114, MSE = 0.1475; P <0.001) (Figure 3). These differences derived from the confounding influences of latitude and proximity to the coast on the otherwise simple relationship between temperature and altitude. Districts with a predominance of plantation sites at higher latitudes or greater distance from the coast, namely Huon, Mersey and Derwent (West), have the minimum temperature threshold of 1.8°C well below

Figure 2. Locations of E. nitens *and* E. globulus *plantations on State forest. The centroid of each plantation is plotted. Plantation are stratified into four climate zones (Figure 1) but not distinguished by species.*



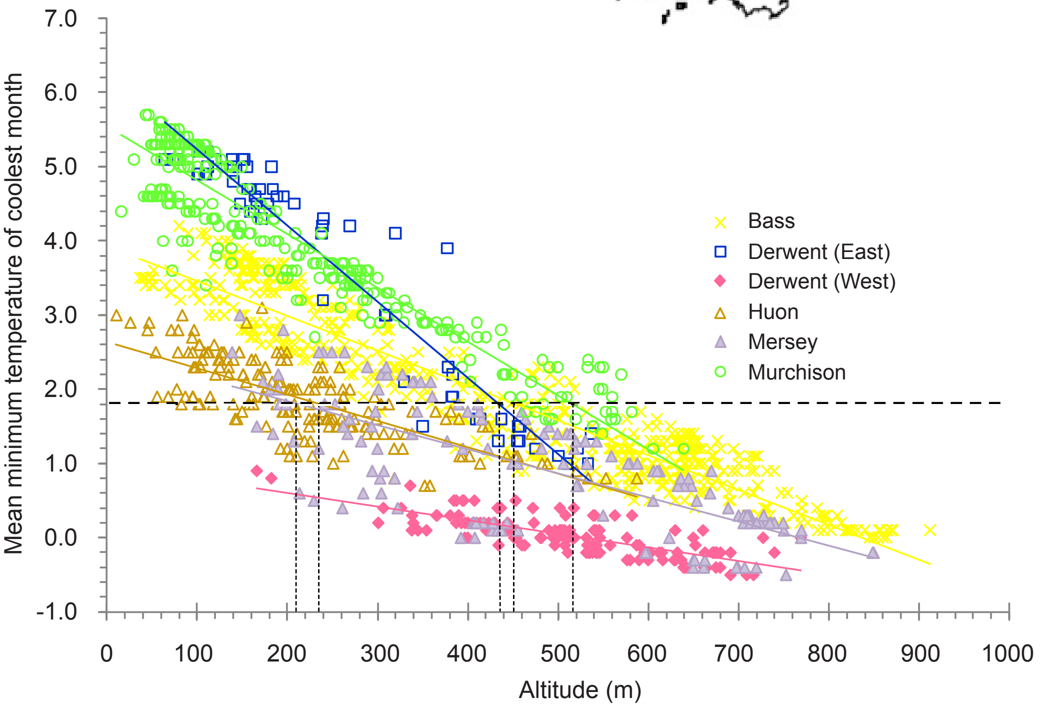


Figure 3. Relationship between altitude and mean minimum temperature of the coolest month for State forest plantation sites. Climate parameters for each plantation site on State forest were predicted using ESOCLIM©. Regression lines shown separately for each District. Vertical dotted lines indicate altitude for each District that corresponds to a predicted mean minimum temperature of the coolest month of 1.8°C (horizontal dotted line). All sites in Derwent (West) were below the 1.8°C threshold.

Table 3. Areas of eucalypt plantations on State forest, and percentage of each species area within a temperature cohort. Data are segregated by species and mean minimum temperature.

	Area (% of total in that temperature cohort)		
	≤1.8°C	>1.8°C	Total
E. globulus	2,271 ha (10%)	7,691 ha (29%)	9,962 ha (20%)
E. nitens	21,368 ha (90%)	18,916 ha (71%)	40,284 ha (80%)
Total	23,639 ha	26,607 ha	50,246 ha

Table 4. Area of E. nitens *and* E. globulus *by District, in the current State forest eucalypt plantation estate and in a future scenario that plants* E. globulus *on all coupes with a predicted mean minimum temperature of the coolest month >1.8°C.*

District	Altitude (m) corresponding to a 1.8°C mean minimum temperature threshold	Current estate (ha)		Estate (ha) if *E. globulus* in all coupes above minimum temperature threshold	
		E. nitens	*E. globulus*	*E. nitens*	*E. globulus*
Bass	452	18,222	2,120	9,898	10,444
Derwent (East)	432	1,328	719	624	1,424
Derwent (West)	-	4,551	47	0	4,598
Huon	234	3,327	3,735	3,790	3,271
Mersey	215	4,085	258	3,698	374
Murchison	513	8,771	3,083	761	11,093
Total		40,284	9,962	23,639	26,607

the traditional altitudinal limit for *E. globulus* of 350 m: 234 m in Huon, 215 m in Mersey, and no "safe" altitude in Derwent (West). Overall, 2,271 ha of current *E. globulus* plantations occur on sites at or below the 1.8°C minimum temperature threshold, with the majority (2,096 ha) being in Huon District and mostly at altitudes <350 m. For Bass, Murchison and Derwent (East) Districts, the altitude corresponding to the 1.8°C minimum temperature threshold occurred above 350 m, considerably so in Murchison District: 432 m in Derwent (East), 452 m in Bass and 513 m in Murchison.

The current area ratio of *E. nitens* to *E. globulus* plantations in the warmer part of the estate (>1.8°C mean minimum temperature of the coolest month) is 71:29 (Table 3). A strategy of maximising the area of *E. globulus* by planting that species in all climatically suitable coupes would result in the *E. globulus* estate increasing from the current 9,962 ha to 26,607 ha (Table 4). The majority of the *E. globulus* estate under this scenario would then be in Murchison and Bass Districts, while the *E. globulus* plantation estate would decrease in Huon and Mersey Districts (Table 4).

Discussion

Spatially-interpolated climate data were used to determine climatic parameters for each current *E. nitens* and *E. globulus* plantation site on Tasmanian State forest, and thus to circumscribe the climatic envelope of the current *E. nitens* and *E. globulus* plantation estate. Similar approaches have been used previously to delinate the climatic envelopes of forest diseases in Tasmania (Podger and Wardlaw 1990; Podger *et al*. 1990). The aim in this case, however, was to understand the detailed distribution of *E. nitens* and *E. globulus* within the current eucalypt plantation estate, suggest a climate-based rule-set alternative to the current altitude-based rule-set for planting *E. globulus*, and then identify that subset of the estate that is climatically suited to *E. globulus*. Validation of this approach will require analysis of statewide inventory data on growth yields across sites with different climate parameters.

The mean minimum temperature of the coolest month was chosen as a temperature parameter with high temporal resolution. The decision to adopt a cut-off value of 1.8°C for this parameter was based on the field performance of *E. globulus* along a single altitudinal gradient in the Esperance Valley. This cut-off value corresponded to an altitude just above that giving peak early height growth for *E. globulus*, but below that at which growth reduction occurred, and well below that at which cold injury occurred. This conservative threshold for *E. globulus* would thus be below that likely to lead to cold injury associated with high altitudes, but still able to capture the full suite of sites where the growth of *E. globulus* is not limited by low temperatures. The conservativeness of the 1.8°C temperature threshold is attested by the significant number of existing *E. globulus* plantations on sites below the threshold, most notably in Huon District. Health surveillance records (Forestry Tasmania, unpublished data) provided no evidence of altitudinally triggered cold damage in *E. globulus* plantations on sites below the 1.8°C threshold. However, growth of *E. globulus* plantations below the 1.8°C threshold has not been examined, a factor that was clearly differentiated in *E. globulus* planted at 240 m and 440 m in the Esperance trial reported by Hallam *et al*. (1989). The stratification of the plantation estate into warm and cool zones based on mean minimum temperature of the coolest month was in good overall agreement with the previous stratification based on altitude. However, stratification by temperature also takes into account the significant influence of latitude and proximity to the coast.

Segregation based on temperature predicted that 26,607 ha of the current *E. nitens* and *E. globulus* plantation estate on State forest is suitable to plant either species. However, only 29% of this area is currently planted to *E. globulus*. This proportion could be increased to take advantage of the superior wood properties of *E. globulus*. However, a total of 4,204 ha of sites were identified as colder than the 1.8°C temperature threshold but at altitudes below 350 m. Of this area, 49% is planted to *E. globulus*, although the sites could be more suitable for *E. nitens*.

By using mid-winter minimum temperatures, this study related to susceptibility to cold damage at the time when the trees have attained maximum tissue hardening. At maximum hardening, both *E. nitens* and *E. globulus* can tolerate much lower temperatures before tissue damage than they can in an unhardened state (Tibbits and Reid 1987). As temperatures warm during spring, trees begin dehardening and the temperature at which lethal damage from cold occurs begins to rise. Dehardening occurs more quickly in *E. globulus* than *E. nitens* (Tibbits *et al.* 2006), so *E. globulus* is more susceptible to unseasonal frosts than *E. nitens*, and cold damage in *E. globulus* can occur at altitudes below that corresponding to the 1.8°C threshold of mean minimum temperature of the coolest month. Chambers *et al* (1996), for example, observed frost damage at an altitude of 240 m at Meunna, north-western Tasmania, a location with a mean minimum temperature of the coolest month of approximately 3.2°C (data not shown). The spatial resolution of the interpolated climate surface used in this analysis was also not sufficiently fine to take into account localised topographic effects such as frost-hollows. Frost-hollows would render some plantations, or areas within plantations, colder than predicted, and coupes predicted to be suitable for *E. globulus* would, if they contain frost-hollows, actually have a high risk for cold injury for that species: adjustments based on local knowledge would be needed to account for such effects. Local frost events may also affect the form of *E. globulus*.

When temperature alone is considered, *E. nitens* is the best choice of eucalypt species on colder sites that are below the temperature threshold for *E. globulus.* However, this simple rule takes no account of moisture availability. *E. nitens* is considered less drought-tolerant than *E. globulus* (White *et al* 1996). This study made no attempt to link effective rainfall with field performance of *E. nitens* relative to *E. globulus*, instead simply using a threshold value of effective rainfall corresponding with the 33rd percentile for the entire estate. An *E. nitens* plantation in Blackwood Creek 368A (located at the base of the north-eastern end of the Great Western Tiers, Mersey District), which lies near the dry extreme of this cool-dry section of the climatic envelope, suffered significant mortality from stem borer attack following drought events in the mid-2000s (Wardlaw and Bashford 2007). Extensive areas of nearby *E. nitens* plantations on private land also suffered heavy mortality following the same drought event (unpublished records, Forestry Tasmania). *Pinus radiata* may be a safer choice on such sites, as this species survives better than *E. nitens* on low-rainfall sites in the Tasmanian Midlands. However, the area of the State forest eucalypt plantation estate occupying cool-dry sites is relatively modest (4,600 ha is below the 33rd percentile, with approximately 800 ha of this area in annual rainfall deficit), with the bulk concentrated in the Eastern Tiers (Swanport, Snow Hill and Tooms Blocks). The gains from averting the risk of drought damage by planting *P. radiata* instead of *E. nitens* on such sites may not outweigh the operational difficulties of managing small isolated pockets of *P. radiata* well beyond the main nodes of concentration of the *P. radiata* estate in the north-east, central-north and north-west of the State.

This study focussed on the cool-warm boundary separating areas suitable only for planting *E. nitens* from those where both *E. globulus* and *E. nitens* may be planted. The climate mapping has shown the eucalypt plantation estate on Tasmanian State forest occupies a wide climate envelope. Understanding the location within that envelope of particular plantation sites may give a better understanding of other attributes, such as relative growth rates, or risk in regard to particular pests or diseases. Further analyses would benefit from using additional topographic and climatic parameters to better predict relative growth rates and risks at finer spatial scales.

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