Results of a species trial of cold tolerant eucalypts in south west England

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Summary:
A trial of six cold-tolerant eucalypt species, planted in 1981 near Exeter in south west England, was assessed in 2010 for height, diameter at breast height and survival. The predicted soil moisture deficit on the site is low and it is relatively warm (AT 1662.5) and sheltered (DAMS 126), although it experienced a succession of cold winters in the six years following planting. The growth of some *E. delegatensis* was very rapid; the productivity of the seedlot having best survival (48%) was 38$m^3ha^{-1}yr^{-1}$ although this seedlot was collected from one mother tree and was unrepresentative of the broader population at that location. Of the closely related species *E. johnstonii* and *E. subcrenulata*, seedlots recorded as *E. johnstonii* had poor average survival (26%) and growth (7$m^3ha^{-1}y^{-1}$), while *E. subcrenulata* seedlots from Mount Cattley, Tasmania exhibited both good average survival (68%) and growth (25$m^3ha^{-1}y^{-1}$), with progenies from individual mother trees performing substantially better. Based on the results of this assessment, selected sources of *E. subcrenulata* appear suitable for woody biomass production in sheltered sites in south west England. Of the closely related *E. coccifera* and *E. nitida*, the former showed better survival, at 18% against 5%. The poor performance of these species is surprising, as the latter species, which is less cold-tolerant, has grown and survived well elsewhere in south west England, and overall survival of both species at Exeter in 1995 was 60%. The good cold-tolerance and growth of certain seedlots from single mother trees within provenances suggests that much of the variation in performance of all species is genetically determined at family rather than provenance level. The larger surviving trees in the trial could provide germplasm for further trials, with the possibility of later conversion of parts of the Exeter trial to seed stands.

Introduction

In this study the performance of six cold-tolerant eucalypt species was assessed at a research trial established in 1981 near Exeter in south west England. This formed one of a series of experimental *Eucalyptus* trials established across Great Britain (Evans, 1980 p.2) with the aim of being able to:

- Evaluate the potential of eucalypts as forest trees throughout Britain.
- Identify the most suitable (if any) provenances of each species.

This trial is of particular interest for two reasons: first it remains in reasonable condition, in contrast to most of the eucalypt trials established during the 1980s, and second it contains multiple origins of five species that could be of importance to production forestry in Britain. Eucalypts have been a focus of recent attention in the UK being fast growing exotic hardwoods that are under consideration for planting for short rotation forestry, a specific niche role in the provision of woody biomass for the generation of electricity and heat (Hardcastle, 2006). In addition, some of the species may also have potential as timber species and could provide an alternative, in southern England, for productive exotic conifer species such as Corsican pine (*Pinus nigra* var *maritima* (Ait.) Melville), stands of which are being damaged or killed by red band needle blight (*Dothistroma septosporum*) (Brown and Webber, 2008) and Japanese larch (*Larix kaempferi* Carr.), which are under pathological attack from the fungal pathogen *Phytopthora ramorum* (Webber et al, 2010). However, risks to the successful establishment and growth of eucalypts also exist, primarily due to the poor cold tolerance of the genus. In addition, there are concerns about the impacts on biodiversity should widespread adoption of new exotic plantations of *Eucalyptus* be considered. Plantings of *Eucalyptus nitens* (Deane and Maiden) Maiden at a series of Defra trials in England and Forestry Commission Scotland trials in Scotland were devastated by the extreme low temperatures experienced during the winter of 2009/2010 (Harrison, 2010), and again in 2010/11. In a planting in Nottinghamshire of 30ha of *E. nitens* and *Eucalyptus gunnii*, the *E. nitens* were killed by a long spell of extremely cold weather in the winter of 2010/2011. The *E. gunnii* stems were killed to ground level but many have subsequently coppiced (Woodisse, 2011). Therefore, there is a pressing need to identify suitable origins of eucalypts for planting commercially and to refine information on their site tolerances.

The choice of species and seed sources planted at the trial was informed by results of earlier trials of eucalypts in Britain, and by availability of new seed of provenances collected from high altitudes by CSIRO and a private collector in Australia. The species at the trial originate from temperate, montane parts of Australia and represent both the Symphyomyrtus and Eucalyptus sub-genera. Table 1 describes some of the characteristics of the species at the trial.

The aim of the study of which the Exeter trial is a part was to:

1. Identify potential species and origins of eucalypts that could be used in production forestry in Great Britain.

2. Contribute to knowledge of the climatic tolerances of eucalypts in Great Britain.

Materials & Methods

Description of the trial

The trial is located near Chudleigh, Devon, at Haldon Forest (50° 37' 59'' N, 3° 34' 56''W) and is situated on a gentle south westerly slope at an altitude of 170m a.s.l. The soils are fertile brown earths overlying greensands and the site was previously under a stand of 1932 Douglas fir (*Pseudotsuga menziesii* Mirb. Franco.), Yield Class 16, which was felled due to windthrow damage. The trial was planted in May 1981 in four distinct blocks, each block containing a particular species or species group; block one with *E. delegatensis*, block two with *E. nitida*, block three with *E. nitens* and block four with plots of *E. johnstonii* and plots of *E. subcrenulata* together. Within these species blocks each origin is represented in three, randomly located, line plots of nine trees. The details of the origins are provided in Appendix 1. Some of the origins were collected from a single mother tree, while others are bulked seed lots from several parents. There is some uncertainty about the species and origin of some of the species at the trial; these aspects are reviewed in the Discussion.

An overview of the climate at the trial, based on 1961 to 1991 climatic data and generated by Forest Research's Ecological Site Classification (ESC) system is shown in Table 2. Accumulated temperature above 5°C (AT5) in Great Britain ranges up to 2000 degree days (Pyatt, Ray and Fletcher, 2001), so with AT5=1663 degree days, the site is very warm, while the 'Detailed Aspect Method of Scoring' (DAMS) wind risk scale, which ranges from around 3 to 36 in Britain, is 12.6 and can be considered to be low, indicating the site is sheltered (although the previous stand was windthrown). Continentality (CT) uses the Conrad Index which varies from 1 to 13 in Britain and represents the difference between the

Table 1. Notes on the natural habitat and silvicultural characteristics of eucalypt species at the trial. The species attributions are those given in Evans (1980).

Species (sub-genus)	Natural habitat	Relevant silvicultural attributes
E. nitida (Eucalyptus)	A sub-alpine species endemic to Tasmania that forms an altitudinal cline with *E. coccifera*, which it replaces at lower altitudes (Williams and Potts, 1996).	Wide range of intraspecific variation in size and form (EUCLID, 2006) although some trees have wonderful form and large dimensions in the wild.
E. delegatensis (Eucalyptus)	A widespread species on mountains of NSW and eastern Victoria. Also found throughout Tasmania, occupying a wide altitudinal range from 160m to 1500m. The species is distributed in patches of one to many hundred hectares with most populations being exposed to snow for several months each year (Boland and Moran, 1979).	One of the most important timber trees in Australia It favours well-drained soils on moderate slopes on a range of parent material (Boland and Moran, 1979). Timber from New Zealand-grown trees has been used on a modest commercial scale (Barr, 1996).
E. johnstonii (Symphomyrtus)	Occurs in south-eastern Tasmania, generally at elevations up to 900m. In the north-west of its distribution, it overlaps with *E. subcrenulata*, and populations with intermediate characteristics occur (Nicolle, 1997).	Growth form largely dictated by habitat and in forest conditions grows into a tall tree (Williams and Potts, 1996). Exhibits rapid growth and good survival in trials in Ireland (Neilan and Thompson, 2008).
E. nitens (Symphomyrtus)	Montane parts of Victoria and New South Wales. Scattered populations with considerable genetic variation between and within populations (Tibbits and Reid, 1987).	Fast growth, known wood properties and silviculture. Possibly the fastest growing tree in Great Britain (Evans, 1980).
E. subcrenulata (Symphomyrtus)	Closely related to *E. johnstonii*, but occurs at higher elevations (to 1100m) in the west and centre of Tasmania (Nicolle, 1997).	Highly variable in form and size in the wild. It tends to be a small multi-stemmed tree on exposed sites, but can be a single-stemmed forest tree up to 60m height in sheltered valleys (Nicolle, 1997).

mean temperature (°C) of the warmest and coldest months modified with respect to site latitude: the trial site has a value of 7.9 and so has a moderately continental climate. Moisture deficit (MD) at 128.3mm is moderate, the range in Great Britain is from <20mm in very wet, cold areas to >200 mm in the hotter areas of south east England. Moisture Deficit is an index of climatic dryness and also an important factor in determining the Soil Moisture Regime (SMR). It is expressed as the mean maximum accumulated monthly excess of evaporation over rainfall (1961-1990 period). As such, moisture should not be limiting for much of the year. Therefore Chudleigh can be considered a productive site for tree growth. Early establishment operations at the site are described in Table 3 below.

The survival within the trial in June 2010 was very patchy, with few trees in the *E. delegatensis* block, and almost complete mortality in the *E. nitens* block. Within these areas of poor survival, natural regeneration of other tree species had occurred.

Trial Assessments

In June 2010 height and diameter at breast height were measured, the trees having grown for 28 seasons. Diameter at breast height (cm, dbh) of all stems was assessed. The height of all trees was measured for *E. nitida* (n=34), *E. delegatensis* (n=50) and *E. nitens* (n=4). For the plots within the *E. johnstonii* / *E. subcrenulata* block, where survival was better (at 26% and 62% respectively), the height of three randomly sampled trees (n=88) were measured per plot. Height was measured using either a hypsometer (Measurement Devices Ltd (UK) Laserace) or a clinometer (Hagloff AB (Sweden)Vertex III).

Table 3: Early establishment operations undertaken at the Chudleigh trial (Forestry Commission, no date)

Date	Operation
07/81	Hand weeding and cutting bramble with chemical weeding in near future.
09/81	After heavy rain and high winds 60-70mph trees of *E. nitens* and *E. delegatensis* blew over and were staked up. The instability was due to their heavy, dense crowns with lots of foliage
07/82	Chemical weeding of *E. johnstonii*/*E. subrenulata* replacement plots and beat ups. Note in file “My goodness they look nice”.
05/84	E. nitens brashed to 2m as bramble growing up the stems.
06/84	Chemical weeding glyphosate at high concentrations due to rampant bramble growth.
09/85	107 dead *E. nitens* felled – more likely to be dead before Spring. Also 102 *E. delegatensis* felled which were either dead, windthrown or of poor form.

Table 2. Climatic parameters for Chudleigh generated by ESC for 1961-1990.

AT5	CT	DAMS	MD	Summer Rainfall (mm)	Winter Rainfall (mm)
1662.5	7.9	12.6	128.3	353.1	583.3

AT5 = Accumulated temperature above 5°C, CT = continentality, DAMS = Detailed aspect measurement of scoring, MD = moisture deficit

Statistical Analysis

Initial analysis involved using the data from all origins, then origins were grouped by species and finally differences between individual origins were examined.

Analysis between & within origins

The means were calculated for percentage survival, plot basal area and height. The quadratic mean dbh was also calculated as this is a useful measure of tree size in forestry. Furthermore, a tentative calculation of volume per hectare and mean annual increment was made using a form factor of 0.35 as described in Purse and Richardson (2001). From measurements at the trial, plot size was approximately 49m^2 for nine trees, giving a stocking density equivalent of 1,837 stems ha^{-1}. The results are shown in Table 4.

A linear regression was used to investigate the relationship between mean survival, mean basal area and mean height against altitude of origin. For *E. delegatensis* and *E. nitida* the relationship between height or basal area and altitude of origin was poor (Table 5). However, for *E. subcrenelata* and *E. johnstonii* combined, altitude explained 57% of the variation in survival and 59% of the variation in plot basal area and the p values were highly significant suggesting that the relationship was not random (Table 5).

The *E. delegatensis* origins were then separated into *E. delegatenis* ssp. *tasmaniensis*, which is found only in Tasmania and *E. delegatensis* ssp. *delegatensis*, which is found only on the main part of Australia. There was a significant and positive relationship between basal area of *E. delegatensis* spp. *tasmaniensis* and altitude of origin, with a linear relationship explaining over 90% of the variation.

The origins attributed to *E. nitida* at the trial were likely to be a mix of *E. nitida* and *E. coccifera* (see Discussion). A regression was performed on all origins, with basal area giving a strong but non-significant relationship with altitude. Origins were then separated based on the location at which they were collected, with the origins from the Hartz Mountains (134) and from St Clements (24) being reclassified as *E. nitida* and the others being considered *E. coccifera*. Regression analysis was performed on the *E. coccifera*

Table 4. Summary of survival, dbh, height, basal area and volume at 28 years old for origins at the trial.

Species	Origin	Mean % Survival	Quadratic mean dbh (cm)	Mean height (m)	Basal area (m^2ha^{-1})	Volume (m^3ha^{-1})	MAI ($m^3ha^{-1}y^{-1}$)
E. nitida	21	19%	41.1	22.3	45.2	352.7	12.6
E. nitida	23	26%	43.9	23.6	72.1	595.0	21.3
E. nitida	24	11%	32.0	20.6	16.4	118.2	4.2
E. nitida	48	0	0	0	0	0	0
E. nitida	134	7%	32.1	19.2	11.0	73.9	2.6
E. nitida	135	11%	48.7	26.8	38.1	357.4	12.8
E. nitida	136	22%	37.2	19.1	44.4	296.0	10.6
E. nitida	137	30%	30.9	20.2	40.7	288.3	10.3
E. johnstonii	229[1]	7%	28.1	21.6	8.5	64.0	2.3
E. johnstonii	121	22%	26.9	22.3	23.2	181.0	6.5
E. johnstonii	122	30%	24.0	16.0	24.6	138.0	4.9
E. johnstonii	123	19%	29.3	22.7	23.0	182.2	6.5
E. johnstonii	124	22%	31.1	24.5	31.1	266.2	9.5
E. johnstonii	125	56%	25.0	21.6	50.2	379.3	13.5
E. subcrenulata	115	81%	22.4	20.0	59.0	412.8	14.7
E. subcrenulata	116	67%	37.2	20.3	132.9	944.1	33.7
E. subcrenulata	117	44%	30.3	20.7	58.8	426.6	15.2
E. subcrenulata	118	81%	30.8	20.3	111.8	796.1	28.4
E. subcrenulata	119	63%	33.7	25.8	103.0	931.4	33.3
E. subcrenulata	171[2]	37%	28.3	19.7	42.7	294.8	10.5
E. delegatensis	30	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	131	48%	48.3	18.8	162.4	1068.0	38.2
E. delegatensis	132	11%	63.7	17.2	65.1	391.3	14.0
E. delegatensis	133	15%	42.6	23.4	38.8	317.1	11.3
E. delegatensis	228[3]	19%	60.8	20.7	98.9	717.6	25.6
E. delegatensis	149	26%	38.3	19.9	54.9	382.2	13.7
E. delegatensis	150	26%	40.6	21.2	61.6	456.9	16.3
E. delegatensis	151	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	152	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	153	7%	59.9	22.0	38.3	295.2	10.5
E. delegatensis	154	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	155	19%	44.1	18.7	52.0	339.6	12.1
E. delegatensis	156	0%	0.0	0.0	0.0	0.0	0.0
E. delegatensis	157	4%	41.6	20.0	9.2	64.7	2.3
E. delegatensis	158	11%	66.1	20.8	70.1	508.8	18.2

[1]Originally *E. johnstonii* (37), replaced at beat up in 1982.
[2]Originally *E. johnstonii* (69) replaced at beat up in 1982.
[3]Originally *E. delegatensis* (148), replaced at beat up in 1982.

origins, whilst there was insufficient data (mean plot values) for statistical analysis of the response of *E. nitida* at this site.

Analysis between species

An analysis was performed to examine whether differences in survival, basal area and height between origins were statistically significant, combining all plot means for each species. Due to very poor survival *E. nitens* was excluded from the analysis. The mean basal area, mean height, mean survival, quadratic mean dbh and estimates of volume and mean annual increment (MAI) for each species are shown in Table 6.

Basal area

Following a log transformation, mean plot basal area by species was distributed in a way that was not significantly different from normal and the variances across the species were not significantly different and so ANOVAR was used to determine whether differences existed between species. Differences in log mean plot basal area by species were found to be highly significant ($p = 0.0001$). A Tukey's HSD test showed that log basal area of *E. johnstonii* was significantly different from that of the other species, except *E. nitida*.

Height

ANOVA was used to determine differences between species as arcsine height distribution was not significantly different from normal and variances were equal. There were no significant differences between species.

Survival

Percentage survival even after an arcsine transformation was not normally distributed, and so a Kruskal Wallis test was used to detect whether there were differences in survival between species and highly significant differences were found. Mann Whitney tests were used to identify significant differences between pairs of origins. The results of significance are shown in Table 7.

Analysis of growth and survival for the origins with high survival

There were thirteen origins with consistently good survival across the trial where trees survived in all three replicates. Five *E. subcrenulata* origins (origins 115, 116, 117, 118, 119) were considered one grouping as they were collected from individual trees from the same location. The remaining origin (origin 171) was treated as a separate group. *E. johnstonii* origins 121, 122, 123, 124 and 125 were clumped together as they were also single tree collections from the same location.

There were two origins (131 and 133) of *E. delegatensis*, both from Tasmania that met the survival criteria and were treated as separate groupings. The mean basal area, mean height, mean survival and quadratic mean dbh for each species is shown in Table 8.

Table 5. Relationships for linear regressions of mean survival, mean height and mean plot basal area against altitude of origin.

	Mean % survival		Mean height (m)		Mean plot basal area (m^2)	
	r^2	p	r^2	P	r^2	p
E. 'nitida'[1]	(-) 0.000	0.974	(+) 0.136	0.416	(+) 0.366	0.150
E. coccifera[2]	(-)0.515	0.108	(-) 0.028	0.789	(-) 0.492	0.187
E. delegatensis	(+) 0.027	0.559	(+) 0.017	0.717	(-) 0.000	0.958
E. delegatensis (t)[3]	(+) 0.230	0.229	(-) 0.132	0.548	(+) 0.908	0.033
E. delegatenis (d)[4]	(+) 0.080	0.864	(+) 0.001	0.957	(-) 0.002	0.944
E. subcrenulata /E. johnstonii	(+) 0.575	0.007	(-) 0.050	0.510	(+) 0.586	0.006

[1]This includes all origins identified as either *E. nitida* or *E.coccifera*. [2]This only includes those origins that are *E. coccifera*, not origins 24 and 134 which are likely to be *E. nitida*. [3]Comprises *E. delegatensis* ssp *tasmaniensis*. [4]Comprises *E. delegatensis* ssp *delagetensis*.

Basal area

Basal area was found to be normally distributed but variances were not equal. A log transformation produced data where variances were not significantly different and an ANOVA was applied. A Tukey's range test was used to examine differences between the groups and *E. delegatenisis* (131) exhibited a significantly larger basal area than *E. subcrenulata* (171) and than *E. johnstonii*, while *E. subcrenulata* from Mount Cattley (115-119) yielded a significantly larger basal area than *E. johnstonii*.

Height

No statistically significant differences in height between species/origins were observed.

Survival

Survival, after arcsine transformation, was found to be distributed in a way that was significantly different from normal. A Kruskal-Wallis test showed differences in percentage survival between species/origins to be highly significant. Mann-Whitney tests, were used to compare pairs of species/origins and these showed statistically significant differences between *E. subcrenulata* and all other species/origins except *E. delegatensis* 131.

Table 6. Mean basal area, mean height, mean survival and quadratic mean dbh by species after 28 growing seasons.

Species	Mean % Survival	Quadratic mean dbh (cm)	Mean height (m)	Basal area (m^2ha^{-1})	Volume (m^3ha^{-1})	MAI ($m^3ha^{-1}y^{-1}$)
E. nitida[1]	4.6	32.0	20.0	13.7	95.9	3.4
E. coccifera[2]	17.9	39.5	21.3	40.3	301.0	10.8
E. delegatensis	15.6	49.3	20.1	43.4	305.3	10.9
E. delegatensis (t)[3]	17.3	51.9	19.2	67.1	452.4	16.2
E. delegatenis (d)[4]	10.4	42.5	19.1	27.3	183.1	6.5
E. subcrenulata	62.2	30.4	21.1	84.7	634.3	21.9
E. johnstonii	26.0	27.4	21.5	26.8	201.8	7.0

[1]This comprises origins 24 and 134, identified as *E. nitida*. [2]This comprises origins that are *E. coccifera*, not origins 24 and 134 which are likely to be *E. nitida*. [3]Comprises *E. delegatensis* ssp *tasmaniensis*. [4]Comprises *E. delegatensis* ssp *delagetensis*.

Analysis of growth and survival between origins of E. johnstonii

Most of the origins of *E. johnstonii* at the trial were from the Hartz Mountains in Tasmania. McGowen et al (2001) note that morphological variation in this species at this location is not continuous, which suggests there may be considerable differences between the individuals from which seed was collected. To test this possibility the survival, basal area and height of the five seed lots from the Hartz Mountains were compared. There were no statistically significant differences in basal area, height or survival between origins.

Discussion

This discussion draws upon the results from this assessment of the trial, unpublished historical archive records of the trial and also the performance of the species in trials elsewhere.

In Tasmania considerable topographic and climatic variation in habitat over short distances has lead to substantial genetic and morphological variation in eucalypts (McGowen et al, 2001; Davidson and Reid, 1987). Altitude may therefore be considered to have a strong influence on physiological attributes such as cold tolerance and frost resistance. However, the relationship between survival and growth of origins at the trial was found to be poorly related to altitude, except for survival and basal area of *E. subcrenulata* and *E. johnstonii*. The findings from this trial may reflect the variation in topography across the natural range of the species tested, for example some origins from lower altitudes may be subject to cold air drainage in frost hollows. The absolute minimum temperature reported in Australia of -22°C

Table 7. Statistical significance (p value) of differences in percentage survival between species.

	E. coccifera[2]	*E. delegatensis (t)*[3]	*E. delegatenis (d)*[4]	*E. subcrenulata*	*E. johnstonii*
E. 'nitida'[1]	0.454	0.743	0.932	<0.0001	0.036
E. coccifera[2]	...	0.587	0.494	<0.0001	0.165
E. delegatensis (t)[3]	...	...	0.611	<0.0001	0.004
E. delegatenis (d)[4]	...	...	...	<0.0001	0.001
E. subcrenulata	...	...	...	...	<0.0001
E. johnstonii	...	...	...	...	...

[1]This comprises origins 24 and 134, identified as *E. nitida*. [2]This comprises origins that are *E. coccifera*, not origins 24 and 134 which are likely to be *E. nitida*. [3]Comprises *E. delegatensis* ssp *tasmaniensis*. [4]Comprises *E. delegatensis* ssp *delagetensis*.

was in a hollow at intermediate altitude in Tasmania (Davidson and Reid, 1985). This is reflected by the distribution of one of the most cold-tolerant eucalypts, *Eucalyptus stellulata* which dominates, in its natural range, locations where frost hollows, rather than high altitudes, occur.

Furthermore, for species that have a wide distribution in Australia, the continentality of climate at the location of origin may be important in determining which provenances are adapted to the maritime climate across the UK. Evans (1982) identified continentality at the location of origin as being a factor likely to influence suitability of eucalypt species to the UK climate. The results of the trial showed that most of the origins tested are not sufficiently well adapted to the climate of south west England for them to be reliably used in UK forestry. However, the growth rate and form of some make them of interest for production of biomass.

Eucalyptus delegatensis and Eucalyptus nitens

Eucalyptus nitens and *E. delegatensis* exhibited rapid early height growth of approximately $1my^{-1}$; some individuals were 1.75m tall in September 1981, four months after planting. However, this growth was associated with poor rooting leading to instability, and some trees were staked in the early years. Furthermore, during three cold winters from 1981/82 to 1984/1985 there was considerable mortality of trees of these two species. By 2010 only four individual *E. nitens* remained out of 351 planted, and the mean survival for *E. delegatensis* across the trial was only 16%. Observational notes contained within the research experimental file (September 1985) noted that all provenances of *E. nitens* were damaged in the winter of 1984-1985 when temperatures dropped to -8°C and were below 0°C for extended periods. Those from altitudes of between 1100-1300m in Victoria were described as being least damaged.

Davidson and Reid (1987) in a study of frost tolerance of sub-alpine eucalypts found *E. delegatenisis* to be susceptible to cold, including from winter frost and spring frost in trials and from observations from natural stands. This relative lack of cold hardiness was borne out from the results from this assessment. In 1985 two subspecies of *E. delegatensis* were recognised (Boland, 1985); *E. delegatensis* ssp *tasmaniensis*, found only in Tasmania and *E. delegatensis* ssp *delegatensis*, which is found in other parts of Australia. Tasmanian origins appeared to be better adapted to the climate at the trial, exhibiting better growth and survival (Table 6), although differences were not statistically significant. Following the cold winter of 1984-1985 continued survival of higher altitude origins was observed, with greatest damage from cold being in low altitude Tasmanian origins. In the most recent assessment, growth was greatest in origins from higher elevations in Tasmania.

Of the origins of *E. delegatensis* tested, the origin with most consistent survival and also exceptional plot volume in 2010 was seedlot 131 from a single mother tree at 1200m on Ben Lomond, Tasmania. However, in Evans' (1986) review, this origin was indicated as being only relatively cold-tolerant, while another origin from the same location was highly tolerant. Furthermore, no trees of seedlot 154, which was from nine mother trees at 1220m at the same location (Clarke, 2012), remained alive in 2010. These findings suggest that there is considerable within-provenance variation for cold-tolerance.

Table 8. Performance of origins with survival in all three replicates at the trial.

Species	Mean % Survival	Quadratic mean dbh (cm)	Mean height (m)	Mean plot basal area (m^2ha^{-1})	Mean plot volume (m^3ha^{-1})	Mean plot MAI ($m^3ha^{-1}y^{-1}$)
E. delegatensis (131)	48.3	48.3	18.8	162.4	1068.4	38.2
E. delegatensis (133)	14.7	42.6	23.4	38.8	317.4	11.3
E. subcrenulata (115, 116, 117. 118. 119)	67.5	31.1	21.4	93.1	697.3	24.9
E. subcrenulata (171)	36.7	28.3	19.7	42.7	294.7	10.5
E. johnstonii (121, 122, 123, 124,125)	31.2	26.7	21.2	32.2	239.1	8.5

Eucalyptus nitida/Eucalyptus coccifera

E. coccifera was introduced to Britain in 1840 (Benson, 1994) and was noted by Davidson and Reid (1987) as being highly cold tolerant, although Martin (1950) in his review of plantings in Great Britain and Northern Ireland describes it as being moderately cold-tolerant. Trial records state that the inclusion of *E. nitida* in the trial at Exeter and elsewhere was due to the good growth, form and cold tolerance of this species in a single experiment planted in 1953 near Truro, Cornwall, England (Evans, 1980a; Evans and Brooker, 1981).

The crowns of the trees at the Truro site were killed by a severe winter in 1978-79, with a temperature of -18°C being recorded locally, but the trees subsequently recovered vigorously from stem epicormic buds. The trees also survived the severe and prolonged cold conditions in early 1963. Twelve of these trees still exist in 2012, and all have excellent form. The original seedlot was identified as *E. coccifera*, originating from a collection made in 1947 at 900m in Cradle Mountain Reserve, Tasmania; taxonomic studies in 1979-80 on the trees at Truro indicated that the correct attribution was *E. nitida*. At this time other related seedlots in the Exeter trial were also assigned as *E. nitida*, although it is unclear whether this was appropriate as the higher altitudes from which some originated are more typically populated with *E. coccifera* (Nicolle, 1997). Those origins attributed to *E. nitida* have performed poorly compared with those attributed to *E. coccifera* (Table 6).

The poor survival of all seedlots of this taxon, including the very poor survival of trees raised from seed from the Truro trial (seedlot 24), is surprising in light of the performance of the trees at Truro. Over the period 1981-85 assessments indicate that the species had good winter survival and between 1993 and 1995 records show 18 of the *E. nitida* plots remaining, with approximately 60% stocking. These records also indicate that apart from seedlot 24, the form of the taxon was poor, with many multi-stemmed trees. Thus, the reason for the poor survival in 2010 remains unclear.

Eucalyptus subcrenulata/johnstonii

The species that has performed best at the trial, in terms of a balance between growth and survival, is *E. subcrenulata*. This forms a cline with the closely related species *E. johnstonii* and *E. vernicosa* in Tasmania. In this environment small shrubs of *Eucalyptus vernicosa* at high altitude are replaced at lower altitudes by small trees of *E. subcrenulata*, which in turn are replaced by tall trees of *E. johnstonii*. (McGowen et al., 2001). The hardiness of this species agrees with Benson (1994) who described the species as hardy and capable of tolerating exposure, and Evans (1986) who, from assessment of Forestry Commission trials, considered that this species had potential as a timber tree in south west England.

However, the seed sources of *E. subcrenulata* and the *E. johnstonii* used in the trial are atypical of the two species. Mt Cattley, the source of *E. subcrenulata* seedlots 115-119, lies at the extreme north-west of the limits of natural distribution of this species. The altitude from which the seedlots were collected (720m) is at the lower limit of natural occurrence of this species. The seedlots were single tree collections, and the dimensions of the parent trees (Evans, 1983, Appendix 2) were large by the standards of the species. By contrast, the *E. johnstonii* seedlots 121-125 were sourced from trees in the Hartz Mountains, close to the highest elevations at which the species occurs (760-800m), and at the extreme south-eastern limit of distribution of *E. subcrenulata*. Seedlots 121-125 were also single tree collections, and the parent trees were exceptionally small for *E. johnstonii* (Evans, 1983, Appendix 2). This suggests that the parent trees of seedlots 121-125 may have been an intermediate taxon. The lack of any seed capsules characteristic of *E. johnstonii* under the trees at the Exeter site, and an abundance of capsules characteristic of *E. subcrenulata*, supports this.

The survival of the origins classified as *E. johnstonii* was significantly poorer than that of *E. subcrenulata*, while differences in basal area and height were not significant. It is also noteworthy that the dimensions of the surviving trees

E. nitens 29 yrs old

attributed to *E. johnstonii* were substantially greater than those of the parent trees. Early records from the trial indicate that all sources of both species were essentially undamaged by cold winters until 1985, and that the height growth of the two species was similar. An undated Forest Research file note evidently written between 1993 and 1995 records 35 plots containing trees of the two species, with "probably over 60%" survival overall. Thus the seedlots appear to have relatively good cold tolerance. *E. johnstonii* has performed well in Ireland where it is considered a species with potential (McCarthy, 1979; Neilan and Thompson, 2008). As such, the reasons for losses occurring between 1995 and 2010 are unclear; mortality of weaker trees through self-thinning is a plausible explanation.

While it is not explicit in the original trial plan, it seems likely that the Mt Cattley and Hartz Mountains seedlots were deliberately chosen as likely to represent a balance between acceptable growth and acceptable cold tolerance in *E. subcrenulata/johnstonii*. Furthermore, the use of single tree collections for both sources, coupled with the trial layout used, would now allow for collection of seed from the best trees for further trials and progeny testing. The results presented here suggest that seed sources of *E. subcrenulata* originating from lower elevations deserve more extensive testing in milder parts of southern and western Britain.

Conclusion

Certain seedlots and individual trees in the trial grew very rapidly over a period that equates to a relatively short rotation and have survived a number of severe winters and thus appear well-adapted to the Exeter site. If such growth could be obtained consistently and on a significant scale, these origins would clearly be of interest for production forestry. The good performance of seedlots from certain single-tree collections strongly indicates that a considerable part of the explanation for this performance is the genotype of the trees concerned. The results of the trial presented here indicate that bulk seed of any provenance of any species examined could not be recommended for larger-scale deployment. As examples, contrasting performance of progeny from single mother trees of *E. subcrenulata* from the same location on Mt Cattley, and of seed origins of *E. delegatensis* from Ben Lomond, indicate the risks of using bulk seed from identified provenances. However, collections in Australia from superior trees from these provenances could provide well-adapted, genetically diverse material for trial plantings in Britain. These trials could later be converted into seed production stands. Parts of the Exeter trial itself could also be used for seed production, as the design has allowed testing of the genetic worth of half sib families.

E. delegatensis 29 yrs old.

Vegetative propagation of superior, well adapted individual trees by rooted cuttings could also provide an opportunity to evaluate their genetic worth across a range of sites. This approach has been used very successfully with other eucalyptus species and hybrids elsewhere in the world, and has led to large-scale deployment of clonal selections. Of the species discussed in this paper, a research study indicates that *E. coccifera* and *E. subcrenulata* may have good potential for rooting from cuttings (Orme, 1983). However, no further work on these species has been undertaken, and based on precedents with other *Eucalyptus* species and hybrids, a significant programme would be required to identify selections having both good field performance and ease of rooting. It is not clear how such an investment could be justified at this stage.

It is also noteworthy that *E. subcrenulata* and *E. delegatensis* have hardly featured in plantings elsewhere in the UK. Further trials with these species would clearly be of interest, especially on sites having a similar climate to that of the Exeter trial. The *E. johnstonii* from the Hartz Mountains, which may be *E. subcrenulata*, has shown much poorer performance, along with other origins that were identified as *E. johnstonii*. The poor performance of *E. johnstonii* contrasts with experience of the species in Ireland, where it has shown rapid growth and good survival (Neilan and Thompson, 2008). One possible explanation of this discrepancy is that the Hartz Mountain source in general, and/or the single mother trees that were the seed source for the Exeter trial, are not typical of the species. The small size of the mother trees (Evans, 1983) is consistent with this conclusion. For *E. nitens* it is recommended that it only be planted on sites with the mildest of climates in Britain. For *E. nitida* and *E. coccifera*, the situation is more complex as evidence exists of the former species having performed well on sites with a harsher climate. Thus they may be worth further investigation, particularly focusing on higher altitude origins of *E. coccifera* of good form.

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Appendix 1. Details of origins of species other than *E. delegatensis* (Forestry Commission, no date; Evans, 1983)

Species	Alice Holt Number	Locality	Altitude (m)
E. nitens	45	Plot 209, Kilmun, Argyll, Scotland	
E. nitens	56	Barnewall Plain, Rubicon area, Victoria	1170
E. nitens	57	Macalister, Connors Plain, Victoria	1260
E. nitens	58	Macalister, Mt Wellington, Victoria	1280
E. nitens	87	Barrington Tops, NSW	1520
E. nitens	88	Barren Mt, NSW	1460
E. nitens	89	Point Lookout, NSW	1500
E. nitens	90	Badja Mt, NSW	1250
E. nitens	91	Tallaganda State Forest, NSW	1200
E. nitens	92	Anembo Trig, NSW	1400
E. nitens	94	Mount St Gwinear, Victoria	1175
E. nitens	95	Macalister, Connors Plain, Victoria	1310
E. nitens	97	Mount Torbreck, Rubicon, Victoria	1220
E. dalrympleana	169	Laura Gap, ACT	1320
E. dalrympleana	170	Smokers Flat, ACT	1400
E. johnstonii	37[1]	Kirroughtree Forest S, Scotland	
E. johnstonii	69[2]	Misery Plateau, Tasmania	747
E. johnstonii	121	Hartz Mountains, Tasmania (Tree 1)	800
E. johnstonii	122	Hartz Mountains, Tasmania (Tree 2)	800
E. johnstonii	123	Hartz Mountains, Tasmania (Tree 3)	760
E. johnstonii	124	Hartz Mountains, Tasmania (Tree 4)	760
E. johnstonii	125	Hartz Mountains, Tasmania (Tree 5)	760
E. nitida	21	Arthur's Lake, Tasmania	1000
E. nitida	23[3]	Breona, Tasmania	1000
E. nitida	24	Kernow, St Clements, Cornwall, England	900
E. nitida	48	Mt Field W of Lake Dobson, Tasmania	1200-1300
E. nitida	134	Hartz Mountains, Tasmania	800
E. nitida	135	Lake Mackenzie, Tasmania (Tree 1)	1100
E. nitida	136	Lake Mackenzie, Tasmania (Tree 2)	1100
E. nitida	137	Lake Mackenzie, Tasmania (Tree 3)	1100
E. subcrenulata	115	Mount Cattley, Tasmania (Tree 1)	720
E. subcrenulata	116	Mount Cattley, Tasmania (Tree 2)	720
E. subcrenulata	117	Mount Cattley, Tasmania (Tree 3)	720
E. subcrenulata	118	Mount Cattley, Tasmania (Tree 4)	720
E. subcrenulata	119	Mount Cattley, Tasmania (Tree 5)	720

During the beat-up in 1982 the following replacements of origins were made:
[1]*E. johnstonii* 37 was replaced with 229, originating from the north end of Florentine Valley, Tasmania (altitude 1000m). [2]*E. johnstonii* 69 was replaced with *E. subcrenulata* 171 from east of Great Lake, Tasmania (altitude 1100-1200m). [3]*E. nitida* 23 was replaced with *E. nitida*, Mount Wellington summit (altitude 1200m).

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Appendix 2. Details of origins of E. delegatensis (Forestry Commission no date)

Species	Alice Holt Number	Locality	Altitude (m)
E. delegatensis	30	Hunterston, Tasmania	762
E. delegatensis	131	Ben Lomond, Tasmania	1200
E. delegatensis	132	Mount Barrow, Tasmania	1000
E. delegatensis	133	Steppes, Tasmania	900
E. delegatensis	148[1]	Yaouk Hill Range, NSW	1340
E. delegatensis	149	Laura Gap, ACT	1350
E. delegatensis	150	Mount Bogong, NSW	1525
E. delegatensis	151	The Pinnacle, NSW	1500
E. delegatensis	152	Mount Buffalo, Victoria	1350
E. delegatensis	153	Lake Mountain Victoria	1310
E. delegatensis	154	Ben Lomond, Tasmania	1220
E. delegatensis	155	Miena, Tasmania	960
E. delegatensis	156	Mount Dromedary, Tasmania	800
E. delegatensis	157	Forlorn Hope Track, Victoria	1400
E. delegatensis	158	Ben Lomond, Tasmania	1200

[1]Origin 148 was replaced a year after the initial planting because of complete failure with origin 228, East of Great Lake, Tasmania, altitude 1100m.

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