Growth and survival of provenances of snow gums *(Eucalyptus pauciflora)* and other hardy eucalypts at three trials in England

Leslie, A.D[1].; Mencuccini, M[2]. and Perks, M.P[3].
[1]Head of School, National School of Forestry, University Of Cumbria, Penrith Campus at Newton Rigg, Penrith, CA11 0AH, UK. Telephone: +44 1768 893683. Email: Andrew.leslie@cumbria.ac.uk
[2]Professor, School of Geosciences, University of Edinburgh, Crew Building, The King's Buildings, West Mains Road, Edinburgh EH9 3JN, UK.
[3]Programme Leader, Centre for Forestry and Climate Change, Forest Research, Northern Research Station, Roslin, Midlothian, EH25 9SY, UK.

Summary

Three trials of snow gums (*Eucalyptus pauciflora*) and other cold-tolerant eucalypts, planted in 1985, were assessed for height, diameter at breast height and survival. The trial sites were in southern England but differed in their climate, particularly maritime influence, summer moisture deficit, and in their altitude and soils. Patchy survival and windthrow within the trials posed constraints on the identification of trees of different locations (origins) that performed better. There were, however, some origins that showed good growth and survival across two or three trials. *E. pauciflora* ssp *debeuzevillei* from Mount Ginini (Australia) showed superior growth and survival at Thetford (East Anglia) and Torridge (Devon), while *E. pauciflora* ssp *niphophila* from Mount Bogong (also Australia) exhibited high survival across all three trials. If biomass production is the objective, many of the origins are too slow growing and faster growing species are available, including other eucalypts. The Mount Ginini origin of *E. pauciflora* ssp *debeuzevillei* was estimated to produce 7 $m^3 ha^{-1} y^{-1}$ at Thetford and 10 $m^3 ha^{-1} y^{-1}$ at Torridge at 26 years old, while Sitka spruce is estimated to yield 13$m^3 ha^{-1} y^{-1}$ on a similar rotation. A eucalypt species other than snow gum that showed some promise was *E. perriniana*, origin 'Smiggin Hole' (New South Wales, Australia) which yielded a mean annual increment of 25 $m^3 ha^{-1} y^{-1}$ over 24 years at Chiddingfold (Sussex). However, survival was poor at Thetford and so it may be suited to only the warmest of sites (above accumulated temperature (AT5) of 1900).

Introduction

The UK Government has made a commitment to increase the proportion of energy from renewable sources from 2.25% in 2008 to 15% in 2020 (DECC 2009). The use of biomass is central to this transition to a more carbon lean economy (DEFRA 2007) and woody energy crops will play a role. The Read Report (Read *et al.* 2009) on the potential contribution of forestry to mitigate climate change, identified short rotation forestry, through the rapid production of woody biomass that will substitute for fossil fuels, as being a particularly attractive forestry option for reducing greenhouse gas emissions in the UK.

A genus of trees that has attracted some interest recently as a source of biomass, is Eucalyptus (Hardcastle 2006, Leslie *et al.* 2012), but only a limited range of the seven hundred species can survive the cold of British winters (Leslie *at al.* 2012, Evans 1986). The extreme winter of 2009-2010 was the coldest in thirty years and temperatures in parts of the Midlands and south west England dropped to less than -17°C (Prior and Kendon 2011). This was followed by another severe winter in 2010-2011, which was the second coldest (after 2009-2010) since 1985-1986 (Met Office 2011); December temperatures were the lowest for 100 years, being over 5°C lower than the thirty year average (1971-2000) for England. These extreme temperature events have highlighted the importance of selecting trees adapted to the British climate and, with cold-hardy eucalypts, there seems to be a trade-off between growth rates and hardiness.

The Forestry Commission trials of the 1980s represent a useful research resource for examination of the potential of eucalypts, although there were problems associated with establishment, such as weed control (Purse and Richardson 2001). The first set of trials were planted in 1981 and the following winter was one of the coldest in decades, with temperatures at the trials in January 1982 falling to between -7°C and -23°C (Evans 1986), eliminating a number of eucalypt species and origins from consideration for production forestry in Britain. From these results, a second set of trials was established in 1985. These focused on species and origins that were considered to be particularly hardy. They included subspecies of the snow gum (*Eucalyptus pauciflora*), a eucalypt known for its cold-tolerance (Green 1969a) and used in several studies of the effects of cold on eucalypt physiology (e.g., King and Ball 1998). Booth and Prior (1991) gave a lower limit for survival of *E. pauciflora* ssp. *pauciflora* of -14°C, based on observations of the climate in its natural range in Australia. In 1985 four trials were established across England to test the growth and survival of origins of *E. pauciflora* and other species with a high degree of cold-tolerance. These trials are of particular interest more broadly because *E. pauciflora* is not a species that has been considered elsewhere for production forestry, instead being used in investigations of cold-hardiness in eucalypts (Green 1969b, King and Ball 1998). Evans (1986) noted that early results from these trials showed that there were significant differences in growth and survival between origins. Of the three subspecies of *E. pauciflora*, *E. pauciflora* ssp. *niphophila* was found to be most hardy, followed by *E. pauciflora* ssp. *debeuzevillei* and then *E. pauciflora* ssp. *pauciflora*.

The taxonomy of *E. pauciflora* has been reviewed several times (e.g. Green 1969a) and the species can be divided into three subspecies: *E.pauciflora* ssp. *pauciflora*, *E. pauciflora* ssp. *debeuzevillei* and *E. pauciflora* ssp. *niphophila*. This classification is adopted in this article and characteristics of each subspecies are described in Table 1.

Table 1 Characteristics of subspecies of Eucalyptus pauciflora

Subspecies	Growth form	Distribution
debeuzevillei	A medium or sometimes large tree up to 18m (Green 1969a). Smaller than *E. pauciflora* ssp. *pauciflora* with strongly angled, glaucous and warty buds (Brooker and Kleinig 1990).	Restricted distribution in south eastern New South Wales (Brooker and Kleinig 1990).
niphophila	Differs from *E. pauciflora* ssp. *pauciflora* as it is a straggly small tree with a height up to 6m (Green 1969a), has smaller adult leaves and glaucous buds and fruits (Brooker and Kleinig 1990). Multi-stemmed after fire damage, but considered single-stemmed if undamaged (Green 1969a).	Alpine areas (altitude >1500m) in New South Wales and Victoria (Brooker and Kleinig 1990).
pauciflora	Small, medium or occasionally tall woodland or forest tree (Brooker and Kleinig 1990), growing up to a height of 18 m (Green 1969a).	Wider distribution than other subspecies across tablelands and mountain areas in south eastern Queensland, New South Wales, south western Victoria and Tasmania and a small population in south eastern Australia (Brooker and Kleinig 1990).

The objective of this paper is to:

- *Identify sub-species that are well adapted to the British climate.*
- *Identify any origins within sub-species that show superior performance*
- *Estimate mean annual increments of the better performing origins, using volume functions for cold-tolerant eucalypts.*

The intention is that the results from this study will help to identify eucalypt origins that can be considered for planting in Great Britain. Given the poor survival of some species of eucalypts (Harrison 2010) in the severe winter of 2009/2010 across both Scottish and English trials, this is of considerable current interest.

Materials and Methods

Site description

The four trials were planted across England in 1985, with the most northerly being at Wark (55° 6' 15"N, 2° 19' 28"E), near Kielder. The other three were in southern Britain, respectively at Thetford in Norfolk, in the East of England, at Chiddingfold in Sussex, in the South East of England and at Torridge in Devon, in the South West (Figure 1). The trial at Wark was omitted from this study as overall survival was very poor, reflecting the low temperatures and high levels of exposure experienced at that site. A description of the trials included in this study is shown in Table 2.

The climate of the three trials was characterised using the Forestry Commission's Ecological Site Classification (ESC version 2) software (Table 2). Accumulated temperature above 5°C (AT5) ranges in Great Britain from 0 to 2000 (Pyatt, Ray and Fletcher 2001), so all three sites are warm. The 'Detailed Aspect Method of Scoring' (DAMS) – a measure of wind risk – is low, ranging from less than 10 in sheltered areas to more than 22 in the exposed highlands, and so the sites are sheltered. Continentality (CT) varies from 1 to 13 in Britain and represents the variation in temperature over the year. Torridge in the south west of England has a more maritime climate, while Chiddingfold and Thetford are more continental. Moisture deficit (MD) ranges in Great Britain from <20mm in very wet, cold

Table 2 Site description (Forest Research no date a, Forest Research no date b, Forest Research no date c) and climate variables for Thetford, Torridge and Chiddingfold generated by ESC (Pyatt, Ray and Fletcher 2001).

Location	Thetford, Norfolk, 52° 28' 45" N, 0° 38' 57" E	Torridge, Devon 50°47' 55" N, 4° 14' 39" E	Chiddingfold, Plaistow 51° 03' 49" N, 0° 35' 19" W
Elevation/ Aspect	15m/ south west	152m/ north west	60m/ south west
Exposure	Open to most directions	Moderately exposed	Open to most directions
Slope	Nearly flat, slight slope to the south west corner.	Gentle	Gentle to south west
Geological formation/soil	Gipping till over chalk/ well (excessively) drained calcareous brown earth of at least 1m over chalk.	Permian upper carboniferous geology/ Brown gleyed intergrade over culm measures	Weald clay/ clay
AT5	1802.1	1769.5	1935.1
CT	10.6	7.8	10.2
DAMS	11.6	13	11.4
MD	221.9	132.3	209.7
Summer Rainfall (mm)	308.9	478.1	351.2
Winter Rainfall (mm)	312.2	712.5	463.8

AT5 = accumulated temperature above 5°C, CT = continentality, DAMS = Detailed Aspect Method of Scoring and MD = moisture deficit.

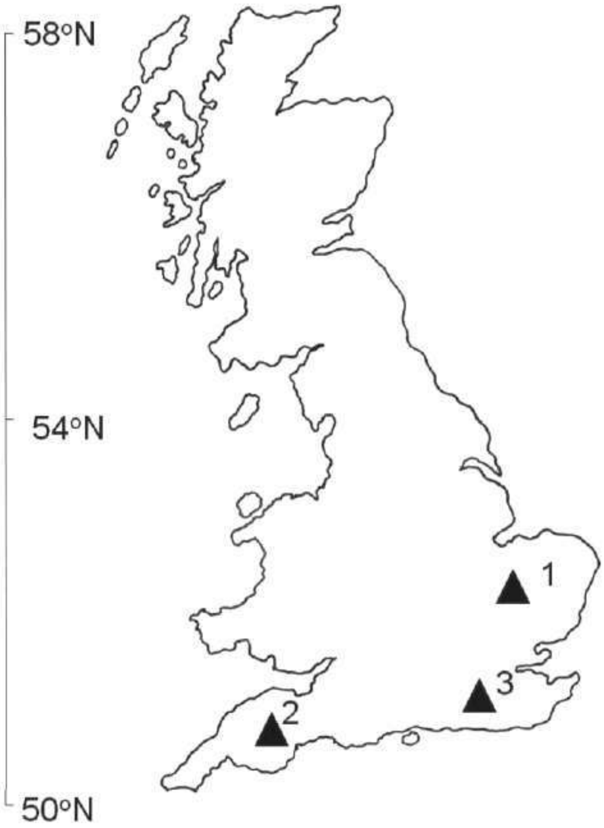

Figure 1 Location map of trials: 1 Thetford, 2 Torridge and 3 Chiddingfold.

areas to >200 mm in the hotter areas of South East England, with moderate values at Torridge, and high values for Chiddingfold and Thetford .

Winter cold is an important factor in the survival of eucalypts in Britain but the climatic profile from ESC does not show the coldness of the three sites. Table 3 provides information on other important climatic variables, such as absolute minimum temperatures and mean frost days. Chiddingfold has the lowest absolute minimum temperature, followed by Thetford and then Torridge. The origins at the three trials were exposed to a number of severe frost events, including those in their early years of establishment, when they were most vulnerable.

Thermometers originally on the site at Torridge, showed the lower part of the trial (Block II and III) experienced lower temperatures, by as much as 3°C in winter due to cold air drainage, however the higher part of the trial (Block I) experienced greater exposure.

The three trials were designed as randomised complete block designs with three replications. They tested the same 66 origins at Thetford and Chiddingfold and 65 at Torridge (*E. viminalis* 221 was not planted at Torridge), mainly of *E. pauciflora* but also including four other species of cold-tolerant eucalypts. Details of the origins are shown in Appendices 1 and 2. Two small blocks of *E. nitens* (94) from Mount St Gwinnear, Victoria were planted at Torridge as a filler. In total, 57 origins of *E. pauciflora* were tested, comprising 31 origins of *E. pauciflora* ssp. niphophila, 24 origins of *E. pauciflora* ssp. *pauciflora* and two origins of *E. pauciflora* ssp. *debeuzevillei*. Line plots were established of ten trees, closely spaced at 1.4 m within lines and around 1.6m between lines, resulting in a stocking density of about 4,464 stems ha^{-1} at Thetford and Torridge. At Chiddingfold the trees were planted at approximately 1.3m within lines and 2m between lines, giving a stocking density of 3,600 stems ha^{-1}. The sites were given pre-planting herbicide application and the planting material, raised in Japanese paper pots, was planted in May 1985. The standard practice at the time was to raise seedlings in greenhouses enabling transplants to be of a size suitable (15-25 cm tall) for planting after only nine weeks after sowing (Evans, Haydon and Lazzeri 1983). Manual cultivation was practised followed by manual, mechanical and chemical weeding.

Measurement Protocol

Measurements followed the conventions described in Matthews and Mackie (2006). Measurements at the Chiddingfold trial took place in May 2009, when the trees were 24 years old, prior to the cold winters of 2009-2010 and 2010-2011 and at Torridge and Thetford in June 2011 when the trees were 26 years old. Two variables were measured on trees in the trial: diameter at breast height (dbh) and total vertical height. Dbh of all stems of standing trees was measured, while for the more time-consuming measurement of height, three trees were randomly selected from the plot. If fewer than four trees were present in the plot the heights of all trees were measured. Where trees were leaning they were subjectively categorised as leaning (<15°) or heavily leaning (>15°).

Volume estimation

Volumes were estimated for trees using a volume function developed for cold-tolerant eucalypts by Shell in South America (Purse and Richardson 2001). This adopted a form factor of 0.35, which was applied to the mean height and mean dbh data. This gave a mean tree volume estimate, which was then multiplied by the mean percentage survival and the stocking density (stems/ha) in the plots to obtain an estimate of standing volume per hectare for the origins of interest. This in turn was divided by the number of growing seasons to get a mean annual increment (MAI).

Table 3 *Temperature and frost days information for meteorological stations near Thetford, Torridge and Chiddingfold.*

Data for this table were summarised from daily data from 1985 to 2010 obtained from the MIDAS land surface stations data set (British Atmospheric Data Centre no date).

	Met Station	Mean Min Temp (°C)	Min Temp (°C)	Grass Min (°C)	Days at or below 0°C
Thetford	Cambridge	6.5	-12	-16	43
Torridge	North Wyke	7.1	-11	-14	31
Chiddingfold	Alice Holt	5.4	-14	-19	64

Statistical Analysis

The means for plots were used in all the analyses except where data were not normally distributed, when median was used as a measure of centrality. Basal area was used rather than dbh in the analysis as many of the origins displayed a proportion of multiple stems. However, survival was variable across the trials which, in addition to origin, will have influenced plot basal area.

The original objective was to identify whether there were statistically significant differences among origins and blocks using a two-way ANOVA. This was not possible due to:

- *Complete mortality of some plots making the experiment unbalanced*
- *Poor survival in many plots resulting in plot means being based on very few trees.*
- *The parameters measured not following a normal distribution*

For all site-based analysis, irrespective of whether at origin or block level, a Shapiro-Wilkes test (Dytham, 1999) was used to determine whether the plot means for percentage survival, basal area, number of stems and height were normally distributed. Where distribution of data for percentage survival was significantly different from a normal distribution an arcsine transformation was applied. Where distribution of basal area data was significantly different from a normal distribution a log transformation was applied. Data for height, basal area and number of stems by origin were then tested for homogeneity of variance using Levene's test. Where an unbalanced design was still evident or where the data were not normally distributed, differences were assessed using a Kruskal Wallis test. Where data were normally distributed but variances differed a Games-Howell multiple comparison test was used to identify where differences lay. When data were distributed in a way that differed from normal, Mann Whitney U tests were used to identify where the differences occurred, such as for tree height between blocks at Thetford. In the analyses, the threshold has been set at $p \leq 0.05$ for a significant difference and at $p \leq 0.01$ for a highly significant difference. Data were analysed in SPSS version 15 (IBM, no date).

Results

Comparison of trials

Overall, median plot survival at the trials was low, at 20% at Torridge, 34% at Thetford and 40% at Chiddingfold. Differences between height, basal area, number of stems and survival of the treatments at the three trials were highly significant ($P<0.01$). In general growth across the trial was greater at Thetford than at Torridge whilst surviving origins exhibited a greater tendency to being multi-stemmed at Thetford, which might be the result of more frequent frost damage. The trees at Chiddingfold were measured when two years younger, yet their average size was still larger than those at Torridge (Table 4) .

Thetford results

Analysis by origin

Basal area and survival of the species were examined and some trends were apparent, i.e. the large basal area but very poor survival of *E. stellulata* and *E. viminalis* and the better survival and high basal area of *E. perriniana*, but there were no obvious differences in terms of basal area and survival in the subspecies of *E. pauciflora*. Differences between origins in terms of basal area, number of stems and survival were highly significant. A selection of better performing origins was made by excluding origins with a median plot survival of less than 50% and where there was complete mortality in at least one plot. This reduced the number of origins for testing to 19. For most origins there were no significant differences in basal area or stem number. However, there were significant differences between origin 283 and origin 239 in respect of numbers of stems (1.17 versus 2). The mean plot basal area for origin 267 (7.68 $m^2 ha^{-1}$) was also significantly different to that of origins 283 (18.39 $m^2 ha^{-1}$) and 256 (15.98 $m^2 ha^{-1}$).

Torridge results

Analysis by origin

Initial examination of survival and mean plot basal area gave no obvious trends by species, although it highlighted good growth of certain origins of *E. pauciflora* ssp. *niphophila* and high basal area but poor survival of an origin of *E. stellulata*, the result of a few, very large trees. Significant differences were found in height, basal area, survival and number of stems between origins. Eight origins had adequate survival to allow cross comparison and there were no significant differences in height or number of stems between the selected origins. However, some significant differences were found in plot basal area by origin. The plot basal area of *E. pauciflora* ssp. niphophila origin 239 (46.51 $m^2 ha^{-1}$) was found to differ from that of origins 267 (8.48 $m^2 ha^{-1}$), 271 (7.28 $m^2 ha^{-1}$) and 303 (15.6 $m^2 ha^{-1}$).

Table 4 Median height, plot basal area, survival and number of stems summary for each trial.

	Thetford	Torridge	Chiddingfold*
Height (m)	12.1	9.0	11.5
Basal area ($m^2 ha^{-1}$)	18.48	8.35	7.25
% plot survival	34	20	40
Number stems/tree	1.695	1.17	1.50

* *Data for trees that were 24 years old, other trials trees were 26 years old.*

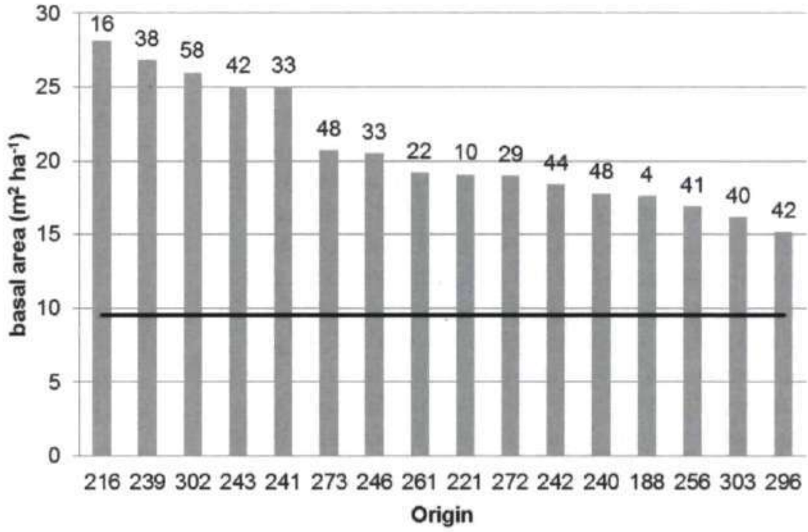

Figure 2 Basal area per hectare of the top 16 origins in comparison with the median across the three trials (solid line). Median percentage survival of each origin is shown by the numbers at the top of each bar.

Chiddingfold results

Analysis by origin

The relationship between mean survival and mean plot basal area showed no obvious trends in growth or survival of species, although one origin of *E. perriniana* showed particularly high survival and a moderate basal area, whereas three origins of *E. stellulata* exhibited high basal areas yet poor survival. There were no significant differences in survival between origins but highly significant differences in basal area, height and number of stems.

Differences between origins were examined further. Those origins with a median plot survival of more than 50% and with all three plots having at least one tree surviving were used as a dataset. This left 14 origins. There were highly significant differences in basal area and in number of stems and differences in basal area were found between *E. perriniana*, origin 302 (16.23 m^2 ha^{-1}) and origins of *E. pauciflora* ssp *niphophila* 278 (5.33 m^2 ha^{-1}) and 287(4.42 m^2 ha^{-1}) and *E. pauciflora* ssp *pauciflora* 281(3.19 m^2 ha^{-1}). For number of stems, *E. pauciflora* ssp *niphophila* 283 (1.06 stems) was significantly different from *E. pauciflora* spp *niphophila* 278 (1.84 stems) and 291 (2.08 stems). *E. pauciflora* ssp *niphophila* 291 (2.08 stems) and 289 (1.34 stems) also differed. A one way analysis of variance showed that there were no significant differences in survival between origins.

Performance of origins across all three trials

A ranking of plot basal area, (which combines tree size and survival) by origin was undertaken across all three trials. Differences in ranking of basal area by origin were highly significantly different (P=0.0001) across all three trials. Figure 2 shows the median basal area per hectare and median survival of those origins in the top quartile by plot basal area. The median basal area per hectare for all origins is also shown as a comparison.

The survival of some of the origins with highest plot basal area was poor and so a further analysis was conducted, focusing instead on origins that had more than 50% survival (Table 5).

Discussion

Deficiencies of the trials

The growth of the trees in these three trials may underestimate their potential. The experimental files show that, on the whole, weed control was good, but that there were periods early in establishment when the trees faced weed competition. Kerr and Evans (2011) noted that at the time of establishment of these experiments the focus was on fertiliser application rather than weed control. At Chiddingfold the young trees also suffered from serious rabbit damage post establishment. The close spacing at the trials has created problems. Competition between trees will have been considerable and it is likely that competition led to self-thinning; as early as 1987 the trees at Thetford were already exhibiting crown competition. Instability of the trees has been a problem from the early years of the trials and remains so, possibly exacerbated by the close spacing which may have restricted root development or root spiralling in containers in the nursery, resulting in poor root architecture.

Differences between the trials

There were differences in growth and survival between the trials and differences in climate are likely to have had a strong influence. Thetford has a more continental climate with colder winters than Torridge (Table 3) but also with warmer summers (indicated by the higher accumulated temperature – Table 2) and lower summer rainfall, resulting in a higher moisture deficit (Table 2) and is less exposed than Torridge (see DAMS score, Table 2). Chiddingfold is similar in climate to Thetford but has higher rainfall and lower moisture deficits and experiences lower minimum winter temperatures and for longer periods. The variables generated in ESC are based on 1961-1990 climatic data. Since 1990, the climate in the south of England has become appreciably warmer in all seasons, but particularly in spring and winter. Between 1990 and 2004 there was a mean increase in annual temperature of 0.62°C in south west England and Wales and 0.78°C in south central and

Table 5 Origins with good (>50%) survival in each trial. Those in bold have good median plot survival in two trials and those in bold with underlining good survival across all three trials.

Trial	**E. pauciflora ssp. debeuzevillei**	**E. pauciflora ssp. niphophila**	**E. pauciflora ssp. pauciflora**	**E. perriniana**
Thetford	**239**	243, **248,** 251, 264, **267, 271,** 276, 277, **283, 288,** 291, 292,	256, **273, 281,** 290, 293, 295, 296	
Torridge	**239,** 240	242, **248, 267, 271**		**302, 303**
Chiddingfold		241, 243, **248,** 278, **283,** 287, 288, 289, **291**	**273, 281,** 294	**302, 303**

E niphophila block, Thetford.

south eastern England (Perry 2006). This general warming is likely to be beneficial to eucalypts, provided it is not accompanied by the same or greater incidence of occasional extreme periods of cold.

Of the sites, overall survival was best at Chiddingfold, despite high mortality in the first four years of establishment (the best origins at the trial only exhibited 65% survival at age four years). The latest assessment at Chiddingfold was made two years earlier than at the other trials and was before the severe winters of 2009-10 and 2010-11. The different date of assessment makes direct comparison of survival and growth across all three trials difficult. Focussing on differences between Torridge and Thetford, origins tested in the trials exhibited better survival and performance at Thetford but also showed a higher incidence of multiple stems, possibly a response to frost damage. The milder conditions at Torridge favour less hardy species; *E. nitens* planted as a filler at Torridge had grown exceptionally well, yet plantings of several origins of *E. nitens* in the early 1980's at another trial at Thetford had failed completely (Bennett and Leslie 2003).

Differences between species and origins

Observations soon after planting indicated the poor adaptation of some species and origins to the extremes of the British climate. Soon after planting, in June 1985, all three sites experienced frost. At Thetford there were five severe ground frosts but this only resulted in minor browning of leaves. During the winter of 1985 at Torridge the temperatures dropped to -7°C at the top of

General view of edge of the trial at Chiddingfold.

the site and to -10°C at the bottom. At both sites, the subspecies of *E. pauciflora* and origins of *E. perriniana* remained undamaged but individuals of *E. camphora* and *E. stellulata* were badly damaged or dead. At Thetford further cold temperatures were experienced in the winter of 1985, with a -16°C grass minimum and -10°C air minimum temperature (Forest Research, undated c).

Since then the trees have been exposed to many unseasonal frosts and abnormally cold winters, including the recent ones of 2009-2010 and 2010-2011. It is clear that the majority of origins tested at the two sites are not sufficiently well adapted to be used in the UK as woody biomass plantation species, showing poor survival and growth. There were a small number of origins that exhibited good survival and growth, with nineteen origins at Thetford, eight origins at Torridge and fourteen origins at Chiddingfold exhibiting more than 50% mean plot survival and with trees surviving in all three replicates of the trial.

The results do not conform to the rankings of hardiness in *E. pauciflora*, proposed by Evans (1986) based on early performance in these trials. In earlier trials, origins of *E. pauciflora* ssp. *niphophila* from Smiggin Hole (1,550 m altitude) and from Smoker's Flat (1,400m altitude) were particularly hardy (Evans 1982). These subspecies were not tested at the three trials in this study. Other origins that showed good cold-tolerance in earlier trials included two from Mount Ginini (Evans 1982), and the one origin tested at these trials (origin 239) showed good survival and superior earlier growth at Torridge. As such, if snow gums are to be planted in future on sites similar to Torridge then this origin should be preferred. However, it did not perform well at Chiddingfold. Why this should be the case is not clear as it performed well at Thetford and Torridge. The only origin of snow gums that has consistently high survival across all three trials was *E. pauciflora* spp. *niphophila* (248) originating from an altitude of 1830m at Mount Bogong in Victoria, but rate of growth was disappointing, with a mean increment of 10.7 m^3 ha^{-1} yr^{-1}.

An assessment at Torridge and at Thetford at one year old showed origins of *E. pauciflora* ssp. *pauciflora* from Currango Plain (origins 255 to 260) to be superior in terms of growth and survival at both trials but this is no longer the case. At Torridge *E. pauciflora* ssp. *niphophila* origins from Neengar Plain (origins 283 and 286) were also promising and origin 283 showed good survival at Thetford and Chiddingfold.

Those that were in the top quartile in the ranking of basal area (Figure 1) and which showed consistently good survival across the trials (Table 5) were: *E. pauciflora* ssp. *debeuzevillei* (239), Mount Ginini; *E. pauciflora* ssp. *niphophila* (243) Mount Ginini; *E. pauciflora* ssp. *pauciflora* (273), Kiandra; *E. perriniana* (302), Smiggin Hole and *E perriniana* (303), Kiandra. From these results that combine growth with survival, origins of *E. pauciflora* from the high altidude (c1700 m) site at Mount Ginini in the Australian Capital Territories appear well adapted to conditions in southern England.

The original aim for testing *E. pauciflora* in this trial was to test its performance as a potential timber species (Evans 1986), being a member of the 'ash' group, which contains important timber species such as *Eucalyptus fastigata* and *Eucalyptus fraxinoides*. However, the highly variable stem form and the tendency to be multi-stemmed are unlikely to make *E. pauciflora* an attractive timber species in British conditions. For use as biomass, characteristics of stem form and number are less important, yet poor form and multi-stems do increase the costs of processing and handling compared with straight single stemmed trees. Some of the individuals within the trial show good stem form and thus there is potential to improve for this trait through selection of superior performing genotypes. However, the results from these experiments show that snow gums are relatively slow growing for eucalypts, even though they still compare favourably with other genera. These findings are confirmed by the small plots of *E. nitens* (origin 94 from Mount St Gwinnear, Victoria) used as a filler at the Torridge trial. These have grown considerably faster than the snow gums at an estimated MAI of over 30 m^3 ha^{-1} yr^{-1}, compared with about 10 m^3 ha^{-1} yr^{-1} from *E. pauciflora* ssp. *debezevillei* (239). While the growth of *E. nitens* was impressive at Torridge, several origins of *E. nitens* failed to survive in an earlier trial at Thetford (Bennett and Leslie 2003), highlighting the sensitivity to cold of this species.

Using the plot data for *E. pauciflora* ssp. *debezevillei* origin 239 at Thetford, where growth was poorer for this origin, the standing volume was estimated at 180 m^3 ha^{-1} and the mean annual increment was calculated at 6.9 m^3 ha^{-1} y^{-1}. It is likely that on many sites exotic conifers would be more productive than snow gums over a 25-year rotation. An analysis using ESC version 2 in a UK decision support tool, EMIS, (Perks *et al.* 2006) indicated a very limited number of species that would be suitable at Thetford, given the moratorium on planting Corsican pine (*Pinus nigra* ssp. *laricio*), with only European larch (*Larix decidua*) being suitable. In the west of Britain, the future of this species as a commercial crop is also in question, given the potential impact of *Phytophthora ramorum*. Yield Class 8 European larch at 25 years old would grow at a rate of around 5.5 m^3 ha^{-1} y^{-1} (Edwards and Christie 1981). At Torridge a wider range of conifers can be planted as a productive crop and Sitka spruce (*Picea sitchensis*) will grow at an estimated Yield Class 20. At 25 years of age Sitka spruce would have an average annual growth rate of approximately 13 m^3 $ha^{-1}y^{-1}$ (Edwards and Christie 1981), considerably higher than the best of the snow gums.

A species that may be suitable for wood production on milder sites is *E. perriniana*, which has shown good survival at Torridge and Chiddingfold but poor survival at Thetford. In the Chiddingfold trial, origin 302 (Smiggin Hole) attained a mean height of 15.7m and dbh of 22.1 over 24 years, equivalent to a mean tree volume of 0.212 m^3 and at the trial stocking of 3,623 stems ha^{-1} and a percentage survival of 83%, an estimated a standing volume of 638 m^3 ha^{-1} or a MAI of 26 m^3 ha^{-1} y^{-1}. Given the small plots and patchy survival across the trial the volume per hectare and growth per hectare should be viewed with caution but it may be that on specific sites this species may have some potential.

Some of the other species tested at the trials had consistently poor survival, although sometimes the few survivors grew to large dimensions. A few individuals of one of two origins of *E. camphora* survived only at Chiddingfold, while there was poor survival of the one origin of *E. viminalis* at Chiddingfold and Thetford. There were individuals of *E. stellulata* across all three trials, but survival was poor. Growth of some of the remaining individuals, however, was impressive. The poor and patchy survival of these species, even in relatively benign sites like Torridge, makes them unsuitable for production forestry in Britain.

Conclusion

Most of the origins tested at the three trials proved unsuitable for production forestry in Britain exhibiting poor survival and growth in British climatic conditions. There are however a few origins that might have potential as a source of biomass: notably: *E. pauciflora* ssp. *debeuzevillei* (239), Mount Ginini; *E. pauciflora* ssp. *niphophila* (243) Mount Ginini; *E. pauciflora* ssp. *pauciflora* (273), Kiandra; *E. perriniana* (302), Smiggin Hole and *E perriniana* (303), Kiandra. One origin that was superior to some of the other origins with high survival at Torridge was *E. pauciflora* ssp. *debeuzevillei* (239). While the growth rate was poor compared with many other eucalypts it is greater than that achieved within 25 years by naturalised or native broadleaves, the best origin achieving 10 $m^3\ ha^{-1}\ y^{-1}$ at an age of 25 years at Torridge and around 7 $m^3\ ha^{-1}\ y^{-1}$ at Thetford. The growth and survival of snow gums was better at Thetford and Chiddingfold than Torridge and this might be explained by the lower accumulated temperature at Torridge or the higher DAMS score, indicating more exposure. Tentatively, it is suggested that snow gums perform best when accumulated temperature is above 1800 and DAMS is below 12. The accumulated temperature and DAMS figures, are based on climatic data from 1961-1990 and so these limits should be used only as a rough guide, given the increases in temperature in the UK since 1990 (Perry 2006). One origin, *E. pauciflora* spp. *niphophila* (248) from Mount Bogong had greater than 50% overall survival in all replicates across all trials, however, growth was unexceptional, attaining a height of 9.1m at Chiddingfold, compared with a nearby stand of *Eucalyptus gunnii*, which had grown to an average of 22.7 m at the same age.

The impressive growth of filler *E. nitens* at Torridge illustrates the potential of this species, but the complete failure at an earlier trial at Thetford highlights the importance of identifying the site limits for this species, which are likely to restrict planting to the more coastal sites around Britain. While Thetford has a higher accumulated temperature than Torridge, Torridge has a more maritime climate and experiences less extreme low winter temperatures.

Appendix 1: *Details of origins of Eucalyptus pauciflora subspecies (Forestry Commission Research and Development Division 1985)*

Alice Holt number	Species & CSIRO number	Locality	Latd	Longtd	Altitude
239	*debeuzevillei*	Mt Ginini ACT	35°32	35°35'	1745
240	*debeuzevillei*	Mt Gingera ACT	35°35'	148°47'	1750
241	*niphophila*	Mt. Coree, ACT	35°19'	148°49'	1390
242	*niphophila*	Mt. Franklin	35°30'	148°47'	1630
243	*niphophila*	Mt. Ginini ACT	35°30'	148°47'	1740-1760
245, 246, 247, 249, 252, 253, 254	*pauciflora*	Mt. Bogong	E,E,W,W,W,W, NW	1780, 1800, 1740, 1780, 1800, 1770, 1730	
248, 250, 251	*niphophila*	Mt. Bogong	W,W	1830, 1860, 1830	
255, 256, 257	*pauciflora*	Currango Plain	N, W, not specified	1320, 1300, 1340	
258, 259, 260	*niphophila*	Currango Plain	W,W,not specified	1310, 1270, 1260	
262, 263, 264, 266, 267, 268, 270, 271	*niphophila*	Mt. Hotham	SE, NE, E, SE, NE, E, N,N	1725, 1680, 1760, 1700, 1775, 1760, 1790, 1760	
265, 269	*pauciflora*	Mt. Hotham	SE, N	1660, 1765	
272, 273	*pauciflora*	Kiandra Plain	E,E	1454, 1300	
274, 275, 276	*niphophila*	Kiandra Plain	W,SW,E	1524, 1460, 1400	
277, 278	*niphophila*	Langford Gap	SW,SW	1650, 1620	
279, 280, 281	*pauciflora*	Langford Gap	NE, NE, NE	1640, 1660, 1680	
282	*pauciflora*	Nungar Place	E	1270	
283, 284, 285, 286	*niphophila*	Nungar Plain	E, SW, W,W	1300, 1300, 1280, 1330	
287, 288, 289, 291	*niphophila*	Ramshead	SE, SW, SE	1828, 1890, 1870, 1870	
290	*pauciflora*	Ramshead	N	1885	
292	*niphophila*	Ramshead Ridge	S	1890	
293, 294	*pauciflora*	Ramshead Ridge	S, S	1980, 1970	
295, 296	*pauciflora*	Thredbo Valley	S,S	1640, 1700	

Acknowledgements

The authors would like to acknowledge the financial assistance from the Scottish Forestry Trust and the University of Cumbria that made this study possible. Help through lending experimental files and providing support during the field work was provided by Forest Research and the authors would like to thank the following staff for their support; James Morison (internal Forest Research reviewer), Richard Jinks (for providing trial files and also for acting as the other internal Forest Research reviewer), Mark Oram (Chiddingfold), Liz Richardson (Thetford) and Dave Powell and Russell Collins (Torridge). We would also like to acknowledge the help in assessing the trials provided by Damien Garner and Luke Hemmings, who at the time were students at The National School of Forestry at the University of Cumbria. Finally we thank Bill Mason, a reviewer for this journal for useful comments on the initial version of this article.

References

Bennett, C.J. and Leslie, A.D. (2003) *Assessment of a Eucalyptus provenance trial at Thetford and implications for Eucalyptus as a biomass crop in lowland Britain.* Q J For 97 (4) p257-264

Booth, T and Pryor, L (1991) Climatic requirements of some commercially important eucalypt species. *Forest Ecol and Manage* 43, p47-60

British Atmospheric Data Centre. Data http://badc.nerc.ac.uk/data/ [accessed 20 June 2012]

Brooker, M.I.H and Kleinig, D.A. (1990) *Field Guide to Eucalypts, South-eastern Australia, Revised edition,* Inkata Press, Melbourne and Sydney.

DECC. (2009) The UK Renewable Energy Strategy http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Renewable%20energy/Renewable%20Energy%20Strategy/1_20090717120647_e_@@_TheUKRenewableEnergyStrategy2009.pdf [accessed 9 July 2012]

DEFRA. (2007) UK Biomass strategy, DEFRA, London. http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/renewable%20energy/explained/bioenergy/policy_strat/1_20091021164854_e_@@_ukbiomassstrategy.pdf. Accessed 9 July 2012

Dytham, C. (1999) *Choosing and using statistics, a biologist's guide.* Blackwell Science.218pp.

Edwards, P.N. and Christie, J.M. (1981) *Yield models for forest management,* Forestry Commission Booklet 48, HMSO, London.

Evans, J (1986) A re-assessment of cold-hardy eucalypts in Great Britain. *Forestry* 59, (2), p223-242.

Evans, J. (1982) *Effects of 1981/82 winter on eucalypt provenance trials.* Forestry Commission internal report of 11 August 1982 6pp and Appcs.

Evans, J,, Haydon, L. And Lazzeri, M. (1983) Propagating and planting eucalypts in Britain. *Arboricultural Journal* 7. p137-147.

Forestry Commission Research and Development Division (1985) Provenance Trial of Snow gums and other hardy eucalypts. *Forest Experimental Plan.* 2p and Appcs.

Forest Research (no date a) Alice Holt 374 P85 Snow gums at Chiddingfold. *Experimental Record, Forest Research,* Alice Holt.

Forest Research (no date b) Alice Holt 38 P85 Snow gums at Torridge. *Experimental Record, Forest Research,* Alice Holt.

Forest Research (no date c) Alice Holt 233 P85 Snow gums at Thetford. *Experimental Record, Forest Research,* Alice Holt.

Green, J.W. (1969a) Taxonomic problems associated with continuous variation in Eucalyptus pauciflora (Snow gum) (Myrtaceae). *Taxon* 18. p269-277.

Green, J.W. (1969b) Temperature responses in altitudinal populations of Eucalyptus pauciflora Sieb ex Spreng. *New Phytol* 68. pp399-410.

Hardcastle, P.D. (2006) A Review of the impacts of short-rotation forestry. LTS International 2006 http://www.forestry.gov.uk/pdf/SRFFinalreport27Feb.pdf/$FILE/SRFFinalreport27Feb.pdf

Harrison A.(2010) Eucalypts – proceed with caution? *Forestry and Timber News;* October 2010, p. 15.

IBM (no date) SPSS software, Predictive analytics software and solutions [online] Last accessed on 17 January 2013 at URL: http://www-01.ibm.com/software/uk/analytics/spss/

Kerr, G. and Evans, J. (2011) Eucalypts for short rotation forestry: a case study from the 1980s. *Quarterly Journal of Forestry* Vol 105 No 2. p109-117.

King, D.A. and Ball, M.C. (1998) A model of frost impacts on seasonal photosynthesis of Eucalyptus pauciflora. *Austr J Plant Physiology* 25. p27-37.

Leslie, A.D. Mencuccini, M. and Perks, M. (2012)The potential for Eucalyptus as a wood fuel in the UK. *Applied Energy* 89 p176-182.

Matthews, R. and Mackie, E.D. (2006) *Forest Mensuration: A Handbook for Practitioners.* Forestry Commission, Edinburgh.

Met Office (2011)Winter 2010/ 2011. http://www.metoffice.gov.uk/climate/uk/2011/winter.html Accessed on 3 September 2011

Perks, M.P., Harrison, A.J. & Bathgate, S.J. (2006) Establishment Management Information System [EMIS]: delivering good practice advice on tree establishment in the uplands of Britain. In: Reynolds, K.M., Ray, D and Thomson, A.J. (eds.) Sustainable forestry: from monitoring and modelling to knowledge management and policy science, CABI International. p412-424.

Perry, M. (2006) *A spatial analysis of trends in the UK climate since 1914 using gridded datasets* The Met Office, Exeter.

Prior, J and Kendon, M (2011) The UK winter of 2009/2010 compared with severe winters of the last 100 years. *Weather* 66 (1). p4-10.

Purse, J.G. and Richardson, K.F. (2001) Short rotation single stem tree crops for energy in the UK- an examination with Eucalyptus, Biomass and Energy Crops II. *Aspects of Applied Biology* 65. p.1-8

Pyatt, D.G., Ray, D. and Fletcher, J. (2001) An Ecological Site Classification for forestry in Great Britain. *Bulletin* 124. Forestry Commission, Edinburgh.

Read, D., Freer-Smith, P.P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds) (2009) Combatting climate change, - a role for UK forests. *An assesment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change.* The Stationery Office, London.

Appendix 2: Details of origins of other *Eucalyptus* species (Forestry Commission Research and Development Division 1985)

Alice Holt number	Species & CSIRO number	Locality	Latd	Longtd	Altitude
187	*camphora*	Tamut	35°30'	148°06'	1100
188	*camphora*	Coree Flat	35°21'	148°44'	1000
221	*viminalis*	Big Badja Mts	36°01'	149°34'	1380
214	*stellulata*	Nimmitabel	36°33'	149°22'	1070
215	*stellulata*	W.Berridale	36°21'	148°46	1040
216	*stellulata*	S. Jerangle	35°54'	149°22'	1200
261	*stellulata*	Currango Plain	Not available	Not available	Not available
302	*perriniana*	Smiggin Hole	36°22'	148°24'	1555
303	*perriniana*	Kiandra	35°53'	148°24'	1500
304	*stellulata*	Cotter Flats	35°38'	148°24'	1000