Genetic variation in survival and growth of *Eucalyptus globulus* ssp. *globulus* in Ethiopia

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Summary

A provenance/progeny trial of *Eucalyptus globulus* ssp. *globulus* was established at Ilalaa Gojo in the central highlands of Ethiopia in 1990 to identify superior provenances and establish a breeding population for genetic improvement programs. The trial tested a total of 299 open-pollinated families from 52 localities within 17 natural sub-races in Australia, and one local landrace from Ethiopia. Nine years after planting, more than 61% of trees had survived and the overall mean height and diameter at breast height (dbh) of surviving trees were 21.2 m and 16.4 cm respectively. Significant ($P < 0.001$) differences in survival, height and dbh per tree were found between sub-races; differences among localities within the sub-races were also significant. Eastern and Western Otways, Cape Patton and Strzelecki Ranges in Victoria were the fastest-growing sub-races, and also displayed above-average survival. Sub-races from the Tasmanian mainland performed poorly; the Wilsons Promontory sub-race was the slowest-growing and displayed poor survival. The Ethiopian landrace performed well although it was not adequately represented in the trial. Assuming a coefficient of relationship of 0.4 for open-pollinated families, individual-tree within-sub-race heritabilities for height and dbh were 0.20 ± 0.03 and 0.16 ± 0.02 respectively. We conclude that there is substantial potential for genetic improvement of *E. globulus* in Ethiopia.

Keywords: provenance trials; growth; survival; heritability; *Eucalyptus globulus*; Ethiopia

Introduction

Eucalyptus globulus Labill., also commonly known as blue gum, is a forest tree occurring naturally in Tasmania, Victoria and New South Wales (NSW), Australia (Brooker and Kleinig 2006). It was one of the first eucalypt species to be both validly named and brought into cultivation within Australia and overseas. The species is planted widely in southern Australia, Portugal, Spain, Chile and the equatorial highlands of Africa and Latin America for a range of uses including firewood, pulpwood and timber (Eldridge *et al*. 1993). *Eucalyptus globulus* was amalgamated with three closely related species by Kirkpatrick (1975) and the sub-species *globulus*, *maidenii*, *bicostata* and *pseudoglobulus* recognised, with extensive intergrade zones between them. *Eucalyptus globulus* ssp. *globulus* is the most widely planted of the four subspecies (Eldridge *et al*. 1993). In this paper we follow Brooker and Kleinig (2006) in preferring to use the name *E. globulus* rather than *E. globulus* ssp. *globulus*.

Eucalyptus globulus was one of the first eucalypt species introduced to Ethiopia and is currently the most popular, and is now perceived as 'indigenous' among local communities. Commencing in 1895, plantations were established to supply poles and fuelwood to the city of Addis Ababa and other major towns in the Central Highlands (Davidson 1995). Community woodlots and plantations are managed by groups of farmers. The total area of plantations of *E. globulus* exceeds 100 000 ha. Most of the plantations appear to be *E. globulus* ssp. *globulus*, on the basis that their inflorescences are single-fruited (Kirkpatrick 1975). Results of previous species elimination trials in Ethiopia have confirmed *E. globulus* to be the best-performing species in the central highlands, with mean annual productivity of plantations 10–30 m^3 ha^{-1} (Pohjonen and Pukkala 1990). The ever-increasing demand for fuelwood and construction wood in Ethiopia, and the continually declining wood supply from natural forests, necessitate wood production from fast-growing plantation species. Notwithstanding an ongoing public argument for and against the use of eucalypts as plantation species, *E. globulus* plantations are attractive from an economic viewpoint (Pohjonen and Pukkala 1988).

Despite the importance of the species to Ethiopia, information on the genetic status of the Ethiopian populations is scant. Although the first introductions of *E. globulus* to Ethiopia were successful, the provenance origins and genetic base of the introductions are unknown and probably sub-optimal, and there could be a high degree of inbreeding in the land races that have developed (Ethiopian Forestry Action Plan 1994; Davidson 1995).

A tree improvement program for *E. globulus* in Ethiopia was initiated by FAO in 1990 in collaboration with the Ethiopian Forestry Research Centre. A provenance/progeny trial was established in the central highlands, testing progenies from an extensive range of provenances from across the natural range of *E. globulus* in Tasmania and Victoria. The objective of the program was to establish a base population from which a breeding population could be selected for genetic improvement programs. This paper describes genetic variation in survival and growth, 9 y after planting.

Materials and methods

The Australian seedlots used in the trial were from the 1987 and 1988 CSIRO collections (Gardiner and Crawford 1988). A total of 299 open-pollinated families from 52 CSIRO local provenance seed collections (hereafter termed localities) were raised for planting in the trial. The localities are described in Appendix 1. Localities have been grouped into 17 sub-races according to the racial classification of *E. globulus* made by Dutkowski and Potts (1999). A bulk seed collection from a local Ethiopian landrace was also included as a single treatment in the trial, giving a total of 300 experimental treatments.

The trial was established at Ilalaa Gojo, in the Ethiopian central highlands (latitude 38°30'E, longitude 9°30'N, altitude 2400 m). The site is located in the tepid cool humid plateau sub-agro-ecological zone (Ministry of Agriculture 1998) and is representative of the major *E. globulus* plantation sites in Ethiopia. The area receives a mean annual rainfall of 2400 mm and has a mean annual temperature of 14°C. Of the total annual rainfall, 70% occurs in the long rainy season between June and September, and there is a second short rainy season in March–April. The trial site is situated on relatively flat terrain between mountain slopes and gently ascending plateaux. The soil at the trial site is reddish-brown in colour, of light clay texture in the upper horizons and heavy clay in the lower horizons, with pH 5–6. Nearby vegetation not under agricultural cropping consists mainly of remnant natural forest, herbaceous flora and eucalypt plantations.

The experimental design employed for the 300 treatments was an incomplete block with ten replicates and two-dimensional incomplete blocking provided by 15 rows and 20 columns within replicates. Each entry was represented by a square plot of four trees in each replicate. Initial spacing was 3 m × 3 m. Replicates were separated from one another by 6 m. Seedlings were raised in the nursery in plastic bags for about 5 months before planting out in July 1990. Prior to out-planting the site was fully cultivated using manual labour. Weed control was carried out manually as necessary. No fertiliser was applied.

Diameter at breast height over bark (dbh) was measured to the nearest 0.1 cm and total height was measured to the nearest 0.25 m for all surviving trees at 9 y of age, using diameter tapes and height poles respectively.

Data screening was carried out by scrutinising plot means and variances (Williams *et al.* 2002). Six trees < 5 m in height or < 5 cm in dbh were omitted from the data set. The plot means for survival, height and dbh were analysed using the software package Genstat (Genstat 2003) to obtain sub-races means and the average standard errors of differences between sub-races. A linear mixed model was used, with replicates and sub-races as fixed effects, and incomplete blocks (rows and columns within replicates) and open-pollinated families within sub-races as random effects. The significance of differences between sub-races was tested using Wald tests. A further analysis examined the significance of differences among localities within sub-races, by incorporating localities within sub-races as an additional fixed effect in the model and declaring open-pollinated families within localities rather than within sub-races as a random effect.

Narrow-sense heritabilities for height and dbh and their standard errors were estimated from the individual-tree data using ASReml (Gilmour *et al.* 2002, Chapter 11), using a linear mixed model with replicates and sub-races as fixed effects and incomplete blocks (rows and columns within replicates), plots and open-pollinated families within sub-races as random effects. Heritability was computed as $h^2 = 1/r \times \sigma_f^2/\sigma_p^2$, where h^2 denotes individual-tree heritability, r denotes coefficient of relationship, σ_f^2 denotes variance of families within sub-races and σ_p^2 denotes phenotypic variance, which was the sum of the variance components for open-pollinated families within sub-races, plots and residual variance. To take account of selfing and relatedness within open-pollinated families, known to occur in *E. globulus*, a coefficient of relationship of 0.4 was assumed in the computation of heritabilities (Williams *et al.* 2002; Potts *et al.* 2004). Heritabilities were also calculated on a within-locality basis using a model in which locality was declared as a fixed effect.

Results

Overall growth was excellent, with a mean height of 21.2 m and mean dbh of 16.4 cm attained at age 9 y (Table 1).

The fraction of living trees included in the assessment was 61%. Overall survival was slightly higher than this, because a few of the plots were not fully stocked at the time of planting. The sub-races differed significantly ($P < 0.001$) for survival, height and dbh. The fastest-growing sub-races were Western and Eastern Otways, Cape Patton and Strzelecki Ranges from Victoria, all of which had heights of > 22 m and dbh >17 cm. These sub-races also displayed above-average survival, except for Cape Patton which was slightly below average at 59%. The Strzelecki Ranges sub-race displayed the highest survival at 79%. The worst-performing sub-race was Wilson's Promontory, with height of 15.7 m, dbh of 11.5 cm and survival of 37%. Sub-races from southern and eastern Tasmania also performed poorly, all being well below the trial mean in survival, height and/or dbh. The Ethiopian land race performed relatively well, with height and dbh close to those of the Otways and Strzelecki Ranges sub-races, but its performance was estimated from only 21 surviving trees. Localities within sub-races also differed significantly in their performance ($P < 0.001$ for survival, $P = 0.01$ for height and $P < 0.01$ for dbh).

Estimated individual-tree within-sub-race heritabilities for height and dbh were 0.20 ± 0.03 and 0.16 ± 0.02. Individual-tree within-locality heritabilities were lower, at 0.17 ± 0.03 and 0.13 ± 0.02 respectively.

Discussion

The trial had not been thinned up to the age of assessment at 9 y. Volume estimates (not presented here) indicate that the best-performing sub-races had a mean annual increment of 29 m^3 ha^{-1}, which is close to the maximum observed in Ethiopia (Pojonen

Table 1. Mean height, diameter and survival of *Eucalyptus globulus* sub-races at age 9 y at Ilalaa Gojo, Ethiopia

Sub-race (no. of families tested)	State	Height (m)	Diameter (dbh, cm)	Survival (%)
Western Otways (52)	Victoria	22.5	17.6	66.8
Strzelecki Ranges (32)	Victoria	22.3	17.7	79.1
South Gippsland (5)	Victoria	19.0	14.7	22.0
Wilsons Promontory (7)	Victoria	15.7	11.5	37.2
Cape Patton (17)	Victoria	22.2	17.5	58.8
Eastern Otways (23)	Victoria	22.3	18.2	71.3
Western Tasmania 19)	Tasmania	20.5	14.7	60.1
St Helens, Tasmania (2)	Tasmania	19.6	14.1	76.8
Southern Furneaux (35)	Tasmania	21.3	16.6	66.5
King Island (10)	Tasmania	21.5	16.0	52.1
Flinders Island (37)	Tasmania	20.9	16.0	67.2
SE Tasmania (26)	Tasmania	19.8	14.6	45.5
Southern Tasmania (15)	Tasmania	21.4	16.0	42.1
Dromedary (4)	Tasmania	19.9	15.1	44.8
NE Tasmania (5)	Tasmania	19.6	13.9	30.9
Inland NE Tasmania (5)	Tasmania	19.6	14.5	42.1
Tasman Peninsula (5)	Tasmania	20.3	15.7	35.6
Ethiopian land race (bulk)		22.1	18.0	52.5
Overall mean		21.2	16.4	60.8
Average standard error of difference of means		0.86	0.87	11.1
Significance of differences between sub-races		$P < 0.001$	$P < 0.001$	$P < 0.001$
Significance of differences between localities within sub-races		$P = 0.01$	$P < 0.01$	$P < 0.001$

and Pukkala 1990). Intense competition between adjacent plots would have accentuated differences between fast-growing and slow-growing families, through suppression of the slower-growing families. Support for this interpretation is provided by the much poorer survival of the slowest-growing sub-race, Wilsons Promontory. *Eucalyptus globulus* is known to have variable but generally high levels of selfing and neighbourhood inbreeding in natural populations (Hardner *et al*. 1996), and these inbred individuals typically become suppressed when growing under competition (Hardner and Potts 1995). Poorly performing individual trees within plots would thus be likely to die following suppression, contributing to the mortality observed in the trial. Additional complicating factors were that the trial was not surrounded by external buffer rows and that replicates were separated from one another by 6 m, creating edge effects. The incomplete block design used enables adjustment for edge effects; row incomplete-block variance components were more than twice the magnitude of their standard errors for survival, height and dbh.

The differences between sub-races measured at age 9 y are probably somewhat exaggerated by competition effects. However, the four best-performing sub-races (Western Otways, Eastern Otways, Strzelecki Ranges and Cape Patton) are well represented in the trial, together contributing 124 out of 300 progenies, so their superiority has been clearly established. The ranking of sub-races for growth is in agreement with results from trials in north-western Tasmania of the same CSIRO seed collections (Jordan *et al*. 1994; Dutkowski and Potts 1999) in which Strzelecki Ranges and Otways were outstanding performers. In earlier trials in Victoria, Australia, *E. globulus* provenances from the Otway Ranges also showed superior growth (Eldridge *et al*. 1993).

The study reported here also demonstrated significant differences among localities within sub-races in height, dbh and survival. This is to be expected, as the local collections within sub-races are separated by considerable geographic differences in many cases, although a few of the localities were repeat collections from virtually the same site (Appendix 1). In Tasmanian trials, Jordan *et al*. (1994) similarly reported significant variation in growth among collection localities within twelve geographic races of *E. globulus* subsp. *globulus*. The variation in locality performance accounts for some of the family-within-sub-race variance, leading to the reduction in individual-tree heritabilities for height and dbh when these are calculated on a within-locality basis.

The observed major differences among sub-races and localities and the significant heritabilities for height and dbh within localities in the present trial support the findings of other researchers that there is substantial variation between provenances of *E. globulus* in survival and growth parameters, and that there is an opportunity for genetic gain by selection and breeding. Estimated within-sub-race, individual-tree heritabilities (0.20 for height and 0.16 for dbh) are within the range found in open-pollinated progeny trials of *E. globulus* (Eldridge *et al.* 1993; Potts *et al*. 2004). However, differences in family performance arising from variable levels of inbreeding tend to inflate these estimates, even when a coefficient of relationship of 0.4, rather than 0.25 (appropriate for half-sib families), is used (Hodge *et al*. 1996).

The trial did not effectively resolve the performance of the Ethiopian landraces of *E. globulus* relative to natural provenances of the species, as it tested only a single bulk from the Addis

Ababa region, represented by only 21 surviving individual trees. It is possible that the genetic status of the landrace varies considerably in different parts of the country, as seed collection and seed distribution is not carried out in any systematic way.

The genetic resources established in this trial have broadened the genetic base of *E. globulus* ssp. *globulus* in Ethiopia available for use in breeding programs. The information on sub-race rankings presented here was used by the Ethiopian Forestry Research Centre to establish new seed production areas based on the superior Otways and Strzelecki Ranges sub-races.

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Appendix 1. *Eucalyptus globulus* localities tested in the trial at Ilalaa Gojo, Ethiopia, grouped according to the sub-race classification of Dutkowski and Potts (1999)

CSIRO seedlot	Location[a]	State[b]	Sub-race name[a]	Sub-race no.	No. of families	Latitude (S)	Longitude (E)	Altitude (m)
16223	19 km SW Apollo Bay PO	Vic	W Otways	1	3	38°77'	143°53'	200
16224	21.6 km SW Apollo Bay	Vic	W Otways	1	10	38°82'	143°57'	145
16225	17 km SW Apollo Bay PO	Vic	W Otways	1	2	38°78'	143°58'	200
16226	8.0 km SW Apollo Bay	Vic	W Otways	1	12	38°80'	143°62'	130
16227	9.5 km SW Apollo Bay	Vic	W Otways	1	2	38°78'	143°62'	150
16240	Otway State Forest	Vic	W Otways	1	18	38°75'	143°45'	150
16241	SW of Lavers Hill	Vic	W Otways	1	5	38°73'	143°30'	230
16319	Jeeralang North	Vic	Strzelecki Ra.	2	32	38°32'	146°55'	220
16398	1.5 km NW of Hedley	Vic	S Gippsland	3	4	38°63'	146°50'	20
16399	Wilsons Promontory	Vic	Wilsons Prom.	4	7	39°13'	146°42'	60
16400	8.5 km N of Toora PO	Vic	S Gippsland	3	1	38°62'	146°35'	180
16401	10.2 km W Kennett R.	Vic	Cape Patton	5	6	38°67'	143°80'	300
16402	5.4 km W Kennett R.	Vic	Cape Patton	5	6	38°65'	143°80'	250
16403	0.6 km W Kennett R.	Vic	Cape Patton	5	5	38°67'	143°83'	130
16405	12.1 km S Lorne PO	Vic	E Otways	6	7	38°60'	143°90'	200
16406	2.4 km NW Lorne PO	Vic	E Otways	6	5	38°52'	143°95'	210
16407	17.1 km W Lorne PO	Vic	E Otways	6	9	38°53'	143°93'	210
16408	6.5 km N Lorne PO	Vic	E Otways	6	1	38°50'	144°02'	60
16409	W of Lorne	Vic	E Otways	6	1	38°55'	143°97'	100
16410	Badgers Ck Quarry Rd	Tas	W Tasmania	7	7	41°98'	145°30'	120
16411	Near Binalong Bay	Tas	St Helens	8	2	41°27'	148°30'	120
16412	Little Henty River	Tas	W Tasmania	7	8	41°93'	145°20'	10
16413	W Cape Barren Is.	Tas	S Furneaux	9	2	40°40'	148°00'	60
16414	SW Cape Barren Is.	Tas	S Furneaux	9	1	40°45'	148°10'	30
16415	Clarke Is.	Tas	S Furneaux	9	3	40°53'	148°13'	40
16416	NE Cape Barren Is.	Tas	S Furneaux	9	4	40°32'	148°32'	60
16417	N Cape Barren Is.	Tas	S Furneaux	9	5	40°37'	148°22'	20
16418	W Cape Barren Is.	Tas	S Furneaux	9	2	40°40'	148°05'	220
16419	NW Cape Barren Is.	Tas	S Furneaux	9	8	40°35'	148°12'	20
16420	NW Cape Barren Is.	Tas	S Furneaux	9	5	40°37'	148°08'	60
16421	SW Cape Barren Is.	Tas	S Furneaux	9	5	40°43'	148°05'	40
16422	Maquarie Harbour	Tas	W Tasmania	7	4	42°33'	145°33'	20
16424	King Is.	Tas	King Is.	10	10	40°00'	144°00'	60
16425	S Flinders Is.	Tas	Flinders Is.	11	4	40°23'	148°13'	120
16426	NW Flinders Is.	Tas	Flinders Is.	11	2	39°77'	147°87'	20
16427	N Flinders Is.	Tas	Flinders Is.	11	4	39°75'	147°95'	40
16428	W Flinders Is.	Tas	Flinders Is.	11	2	39°85'	147°83'	20
16429	Central Flinders Is.	Tas	Flinders Is.	11	7	39°92'	147°95'	40
16430	Central Flinders Is.	Tas	Flinders Is.	11	1	39°92'	148°03'	20
16431	Central Flinders Is.	Tas	Flinders Is.	11	9	40°03'	148°02'	190
16432	E Flinders Is.	Tas	Flinders Is.	11	1	39°98'	148°18'	60
16433	Cent Flinders Is.	Tas	Flinders Is.	11	3	40°07'	148°07'	150
16434	S Flinders Is.	Tas	Flinders Is.	11	4	40°27'	148°17'	12
16470	Moogara	Tas	SE Tasmania	12	21	42°78'	146°92'	500
16471	NW of Dover	Tas	S Tasmania	13	5	43°27'	146°98'	190
16472	Ellendale	Tas	SE Tasmania	12	5	42°63'	146°70'	460
16473	NE of New Norfolk	Tas	Dromedary	14	4	42°72'	147°15'	300
16474	N of St Marys	Tas	NE Tasmania	15	5	41°57'	148°20'	400
16475	SW of Jericho	Tas	Inland NE Tasmania	16	5	42°42'	147°27'	500
16476	S of Geeveston	Tas	S Tasmania	13	7	43°20'	146°90'	250
16477	N of Geeveston	Tas	S Tasmania	13	3	43°13'	146°95'	200
16478	Koonya Tasman Pen.	Tas	Tasman Pen.	17	5	43°07'	147°83'	20
Local	Addis Ababa		Ethiopia		Bulk	9°03' (N)	38°42'	

[a]Ck = Creek; Is. = Island; Pen. = Peninsula; PO = Post office; R. = River; Ra. = Ranges
[b]Vic = Victoria; Tas = Tasmania