Effect of differences in climate on growth, wood, and pulp properties of nine eucalypt species at two sites

CHARLIE R. E. CLARKE, MIKE J. P. SHAW, ANTON M. WESSELS, AND WAYNE R. JONES

ABSTRACT

Growth and wood properties of trees from nine eucalypt species in trials at two different sites were measured to evaluate the influence of environment. A large difference in mean annual temperature between the two sites had little effect on species ranking for most properties. There were significant differences between sites for growth (diameter, height, and volume), wood (lignin, pentosans, and density) and pulp (yield, alkali consumption, rate of delignification, and brightness) properties, but a greater proportion of the variation occurred between and within species for all properties except wood density.

E. fraxinoides, E. smithii, *and* E. oreades *were the most desirable species because of high pulp yield, fiber yield, and brightness but low kappa number and alkali consumption. There was a significant site-by-species interaction for mass of fiber per tree as well as a significant difference between species, suggesting that improvement could be best achieved through a combination of selecting between trees and species as well as by matching the species to the growing site. Improvements in the other important pulp properties mostly depended on species selection for a particular site.*

Application:

This paper provides information on some of the variation (genetic and environmental) that occurs in eucalypt timber and suggests how it is best managed.

Environmental variation influences the growth of most tree species, and it is likely that wood, pulp, and papermaking properties are similarly affected. Although the majority of pulp mills use the wood of a number of different species from a wide range of sites, very little is known about the effects of growing environment on pulp and paper properties. With strong genetic influence, improvements are best accomplished through tree breeding, or alternatively, environmental effects can be exploited by matching species or genotypes to sites. Variations in growth, wood, pulp, and paper properties of provenances and trees of nine eucalypt species grown on two different sites were used to investigate the impact of environment on some of these properties.

METHODS

The trees in this study were in species trials at the Shafton and Helvetia plantations in South Africa. Site descriptions are shown in **Table I.** The high-altitude Helvetia site was colder than Shafton, and frost was common during the winter months. Mean annual precipitation was less at Helvetia, but the effective moisture at the two sites was similar as Helvetia had a lower evapotranspiration rate. Both trials were 6 years old and planted as 11×11 balanced lattice squares with six replications. Plots were three rows of five trees, spaced 1 m apart within the row and 3 m between rows. Trees were selectively thinned at 2 years to leave nine trees (typically three rows of three trees). Evaluation at each site was restricted to three randomly selected trees out of nine in each plot in the three replications showing the best growth and survival.

Although there were 121 seed sources representing 13 different species in each trial, only 27 sources of 9 species were evaluated. Species and their sources included in the evaluation are shown in **Table II.**

GROWTH

The diameter under bark at breast height and the height to 7-cm top diam. were recorded for each tree after felling. Underbark diameters were also recorded at the bottom, middle, and top (7-cm-diam.) of each tree.

Usable tree volume (in m^3) was estimated using the following formula for the frustum of a neiloid *(1)*:

$$V = \pi h / 6(D_1^2 + 4D_2^2 + D_3^2) \quad (1)$$

where

V = usable tree volume, m^3
h = height to 7-cm top diam., m
D_1 = underbark radius at the bottom of the tree, m
D_2 = underbark radius at the middle of the tree, m
D_3 = underbark radius at the top of the tree, m

CHEMICAL COMPOSITION

Wood chemical composition was assessed by the Sappi Research and Development Laboratory, Enstra, Springs, South Africa.

A 50-cm log removed at 1.3 m from the base of each of the 243 trees was cross cut with a circular saw (blade thickness: approximately 3 mm) to generate sawdust. The

Parameter	Shafton	Helvetia
Latitude	30° 14′	25° 31′
Longitude	29° 25′	30° 20′
Altitude, m	1220	1700
Soil classification	Hutton	Hutton
Mean annual precip., mm	950	775
Mean annual temp., °C	16.0	14.8
Mean max. temp. of hottest month, °C	24.9	24.1
Mean min. temp. of coldest month, °C	4.8	1.8

I. Description of species trial sites

chemical composition of the sawdust from a subsample of 47 trees representing all nine species was measured by wet chemistry, and these values were used to calibrate a near-infrared spectrophotometer, which in turn was then used to predict the properties of all 243 trees.

Alpha-cellulose was determined by degradation of noncellulosic material with peracetic acid *(2);* pentosan and lignin contents were measured according to TAPPI Test Methods T 19 ts-50 and T 22 om-83, respectively.

A Technicon Model InfraAnalyser 450R coupled to a computer was used to evaluate approximately 10 g of sawdust packed into an 80-mm diameter that was closed-cup fitted with a glass cover. Two readings were taken per sample; the cup was rotated 180° for each, and the results were averaged. This method of measuring wood chemical composition has been shown to be reliable in a number of studies *(2–5).*

DENSITY

Wood density was measured on disks cut from the bottom, middle, and top of each tree. The density was assessed as the ratio of wet volume to ovendry (o.d.) weight of timber, and wet volumes were measured by water displacement of saturated disks. Mean tree density was calculated as the average of the three measurements weighted by disk cross-sectional area (underbark) in units of kg/m^3. Extractives content was estimated as the wood component remaining following subtraction of alpha-cellulose, pentosans, and lignin, and this extractives content was used to determine a density minus extractives (extracted density).

PULP EVALUATION

Pulp evaluations were done at the Sappi Research and Development Laboratories in Springs, South Africa. The three basal logs (1.2-m) from each test tree were fed through an industrial Mowbark in-field chipper, and chips were mixed and divided to produce a consolidated sample of approximately 1 kg. The chips were cleaned to remove knots, bark, and oversized chunks of wood.

Separate aliquots of chips (100-g o.d. mass) representing the tree were cooked for 5, 15, or 40 min, respectively, to provide three different degrees of delignification. This enabled pulp yield and chemical consumption to be interpolated to a standard kappa number of 18. Cooking conditions are described in **Table III.** A kraft cooking liquor (400 g) of sodium hydroxide (NaOH), sodium sulfide (Na_2S), and water was added to the chips in a 1000-mL pressure vessel. Six cooking vessels at a time were inserted into holding slots of a revolving cage fitted inside a modified laboratory digester. The digester was filled with water, and heat was applied to produce steam at a

Species	Provenance	Latitude (S)	Longitude (E)	Altitude, m
E. grandis	Coffs Harbour	30° 24′	153° 00′	200
E. grandis	Coffs Harbour	30° 24′	153° 00′	200
E. grandis	Mtao landrace, Zimbabwe	-	-	-
E. saligna	Paddys Land SF	30° 06′	152° 08′	1100
E. saligna	Armidale	30° 46′	152° 02′	910
E. saligna	Wild Cattle Ck	30° 00′	151° 44′	970
E. dunnii	Unumgar SF	28° 24′	152° 41′	400
E. dunnii	Acacia Creek	28° 23′	152° 20′	700
E. dunnii	Moleton	30° 05′	153° 00′	300
E. macarthurii	Paddys River	34° 39′	150° 07′	600
E. macarthurii	Penrose SF	34° 39′	150° 14′	620
E. macarthurii	Local	-	-	-
E. nitens	Ebor	30° 31′	152° 20′	1500
E. nitens	Barrington Tp	31° 55′	151° 30′	1450
E. nitens	Tallaganda	35° 54′	149° 30′	1200
E. nitens	Brown Mt	36° 38′	149° 24′	1120
E. smithii	Mittagong	34° 27′	150° 27′	1070
E. smithii	Robertson	34° 40′	150° 40′	800
E. smithii	Nerrigundah	36° 05′	149° 55′	400
E. smithii	Mt Dromedary	36° 17′	150° 03′	305
E. fastigata	Tallaganda SF	35° 20′	149° 35′	850
E. fastigata	Nalbaugh SF	37° 02′	149° 21′	860
E. fastigata	Bendoc	37° 05′	148° 49′	960
E. fraxinoides	Tallaganda SF	35° 00′	149° 30′	650
E. fraxinoides	Pikes Saddle	35° 59′	149° 33′	1250
E. fraxinoides	Brown Mountain	36° 38′	149° 24′	1100
E. oreades	Newnes SF	38° 22′	150° 15′	1069

II. Latitude, longitude, and altitude of provenances representing the nine eucalypt species evaluated in the Shafton trial

Parameter	Condition
Wood charge, g o.d. chips	100
Active alkalinity (NaOH), % (g/L)	21 (52.5)
Cooking liquor-to-wood ratio	4:1
Max. temperature, °C	170
Time to temp., min	100
Time at temp., min	5, 15, 40

III. Cooking conditions for micropulping

Source of variation	DF[a]	MS[b]	Expected mean squares (coefficients for no missing observations)
Sites	1	MSST	$\sigma^2 + 3\sigma^2_u + 9\sigma^2_{ps} + 26\sigma^2_{sst} + 77\sigma^2_{rs} + 230\sigma^2_{st}$
Reps within sites	4	MSR	$\sigma^2 + 3\sigma^2_u + 81\sigma^2_{rs}$
Species	8	MSS	$\sigma^2 + 3\sigma^2_u + 9\sigma^2_{ps} + 24\sigma^2_{sst} + 18\sigma^2_p + 47\sigma^2_s$
Seed sources within species	18	MSP	$\sigma^2 + 3\sigma^2_u + 9\sigma^2_{ps} + 18\sigma^2_p$
Species by site	8	MSSI	$\sigma^2 + 3\sigma^2_u + 9\sigma^2_{ps} + 26\sigma^2_{sst}$
Provenance by site	18	MSPI	$\sigma^2 + 3\sigma^2_u + 9\sigma^2_{ps}$
Trees within plots	104	MSU	$\sigma^2 + 3\sigma^2_u$
Trees between plots	324	MSE	σ^2

[a]Degrees of freedom with no missing observations
[b]Mean squares

IV. Summary of analysis of variance and expected mean squares used to determine significance and components of variance for growth, wood, and pulp properties between two sites

Source	DF	MEAN SQUARES Diameter at breast height, cm	Height to 7-cm top diameter, m	Usable volume, m³
Sites	1	175.03[a]	241.84[b]	13.50×10^{-2} [c]
Reps within sites	4	1.492[d]	22.04	0.45×10^{-2} [d]
Species	8	301.19[a]	146.88[a]	15.76×10^{-2} [a]
Seed source within species	18	12.75[d]	12.00[d]	0.89×10^{-2} [d]
Species by site	8	111.03[a]	59.01[a]	4.06×10^{-2} [a]
Seed source by site	18	17.51[d]	11.35[d]	0.78×10^{-2} [d]
Trees within plots	104	13.28	7.19	0.56×10^{-2}
Trees between plots	307	18.51	5.94	0.48×10^{-2}

[a]$P<0.001$
[b]$P<0.05$
[c]$P<0.01$
[d]Not significant

V. Summary of analyses of variance for growth properties of trees in the Shafton and Helvetia species trials

pressure of about 8 bar; this raised the temperature to 170°C over a period of 100 min. Time at 170°C was varied with each batch of six vessels so that the three cooks of 5, 15, and 40 min, respectively, were completed for each tree.

At the end of the cooking period, the pressure in the digester was released, and the remaining hot water was replaced with cold water to stop the process. Pulp and black liquor from each canister were poured through a 14-mesh screen onto a 150-mesh screen below and washed thoroughly with water under high pressure. Pulp remaining on the 14-mesh screen (classified as reject pulp) was dried and weighed. Pulp on the 140-mesh screen (screened pulp) was squeezed dry, fluffed by hand, and weighed. The moisture content of the pulp was measured from the weight loss of two 20-g samples dried overnight in an oven at 105°C. Screened pulp yield percentage was the o.d. weight of pulp related to the original o.d. mass of the wood chips.

Kappa number, active alkali, and brightness for each pulp aliquot was calculated according to TAPPI Test Methods T 236 cm-85, T 625 cm-85, and T 452 om-92, respectively.

STATISTICAL ANALYSIS

The effects of the different sites were assessed using the following model *(6)*:

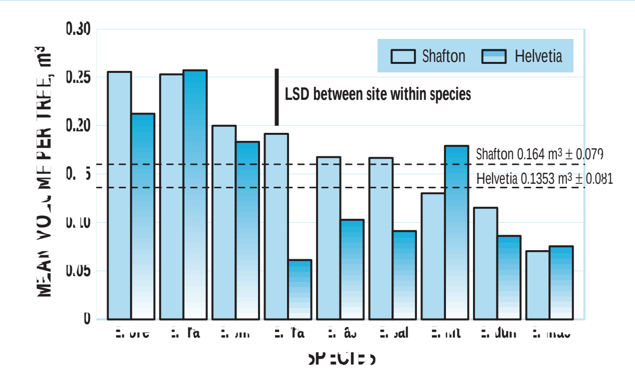
$$Y_{ijklmn} = \mu + s_i + s_j + r_{lj} + p_{im} + p_{imn} + e_{ijklmn} \qquad (2)$$

where

Y_{ijklmn} = the effect of the *k*th tree of the *m*th provenance of the *i*th species in the *n*th plot of the *l*th replication at the *j*th site
μ = a general effect
s_i = the effect of the *i*th species
s_j = the effect of the *j*th site
r_{lj} = the effect of the *l*th replication at the *j*th site
p_{im} = the effect of the *m*th provenance of the *i*th species
p_{imn} = the effect of the *n*th plot of the *m*th provenance of the *i*th species
e_{ijklmn} = the uncontrolled environmental and genetic deviations due to trees.

The analysis of variance with expected mean squares given in terms of the components of variance is shown in **Table IV.**

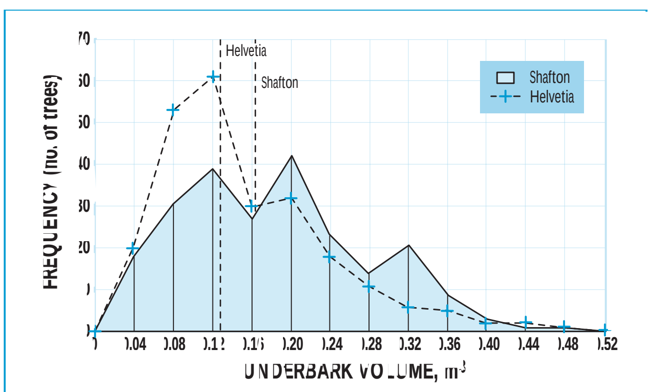
The coefficients for the components of variance were complicated by missing observations and were



1. Mean tree underbark volumes of nine species at Shafton and Helvetia trials

Component	Diameter, cm	Height, m	Volume, m³
Sites	1.4	6.5	4.4
Reps within sites	0.3	1.8	0.5
Species	20.0	18.1	27.3
Seed source within species	0	0.4	0.8
Species by site	14.3	14.6	14.5
Seed source by site	2.4	3.8	2.6
Trees within plots	2.4	3.7	2.0
Trees between plots	50.0	51.1	50.6
Total variance	20.26	11.61	0.00955
Mean	16.83	12.59	14.99×10^{-2}
Coeff. of variation (trees)	19.7	19.4	46.0

VI. Components of variance for growth properties at Shafton and Helvetia trial sites combined expressed as a percentage of the total variance



2. Frequency distributions of underbark volume of trees in Shafton and Helvetia species trials

estimated using the residual error maximum likelihood (REML) subroutine provided with the statistical package GENSTAT. Significance of the site components of variance (σ^2_{ps}, σ^2_{sst}, and σ^2_{st}) was evaluated using an F test of sites (MSST) and replications within sites (MSR) mean squares. MSR and trees-within-plots mean squares (MSU) were used to test significance of replication within sites' components of variance (σ^2_{rs}).

Significance of the species components of variance (σ^2_{sst} and σ^2_{s}) was tested using species (MSS) and provenance (MSP) mean squares. MSP and provenance-by-site mean squares (MSPI) were used to test for the provenance within species components (σ^2_{p}). Mean squares for species by site (MSSI) and MSPI were used to test for the components of variance due to species-by-site interaction (σ^2_{sst}). MSPI and MSU were used to test for significance of the provenances within species-by-site interaction (σ^2_{ps}).

The components of variance were estimated using REML by solution of the expected mean squares.

Least significant differences (LSDs) were estimated for species comparisons across sites. Because the number of trees making up each species differed, an LSD for comparing two species with the minimum and maximum number of trees (9 and 36, respectively) was used. This was slightly larger than the other two LSDs (comparing maximum by maximum or minimum by minimum number of trees).

RESULTS AND DISCUSSION

Growth

A summary of the analyses of variance for growth properties between sites is shown in **Table V.** There were significant differences between sites for diameter ($P<0.001$), height ($P<0.05$), and volume ($P<0.01$). Growth was better at Shafton (mean tree volume of 0.1645 vs. 0.1353 m³ at Helvetia). Species differed between sites ($P<0.001$), and there was a significant site-by-species interaction for all growth properties ($P<0.001$). There was no significant difference between seed sources within species across sites and no significant interaction between seed sources and sites. There was considerable advantage, therefore, in matching species to sites but little in matching seed sources.

The components of variance for growth properties between sites are shown in **Table VI.** Most of the variation was between trees for all three growth properties, followed by species and the species-by-site interaction. Little of the variation occurred between sites, seed sources, or replications.

Mean tree volumes of species and trees at Shafton and Helvetia are shown in **Figs. 1–2.** *E. oreades, E. fraxinoides,* and *E. smithii* were best at both sites. *E. grandis* grew better at Shafton, and *E. nitens* grew better at Helvetia; this contributed strongly to the significant site-by-species interaction. In contrast, *E. fraxinoides, E. smithii,* and *E. macarthurii* had similar growth rates at both sites. Seed sources of *E. saligna*, *E. grandis*, and *E. fastigata* all had poorer growth at Helvetia than Shafton, while all four sources of *E. nitens* grew better at Helvetia (Fig. 2). Individual tree volumes ranged from 0.04 to 0.48 m^3 at both sites, with distributions skewed toward lower values. Superior site quality at Shafton was demonstrated by the greater number of larger trees (0.16–0.36 m^3), while more trees at Helvetia had low volumes (0.04–0.16 m^3).

Source	DF	MEAN SQUARES Cellulose, %	Lignin, %	Pentosans, %
Sites	1	124.040[a]	424.634[b]	648.437[b]
Reps within sites	4	18.50[c]	5.091[a]	1.89[a]
Species	8	207.50[b]	142.482[b]	107.570[b]
Seed source within species	18	12.05[a]	7.564[a]	3.382[a]
Species by site	8	12.75[a]	31.176[b]	1.765[a]
Seed sources by site	18	6.78[a]	3.747[a]	1.860[a]
Trees within plots	1043	3.952	4.859	1.585
Trees between plots	07	2.254	2.501	1.162

[a]Not significant
[b]P<0.001
[c]P<0.01

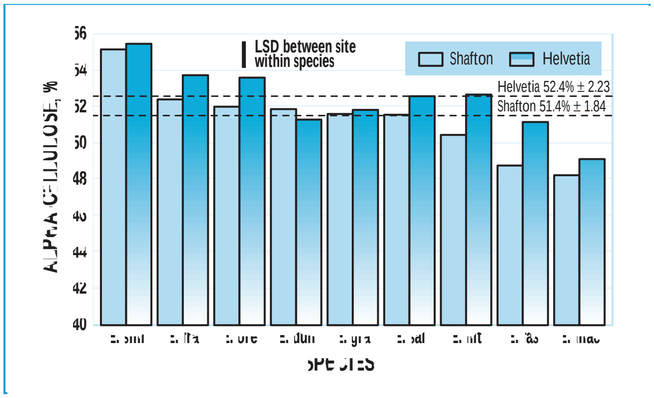
VII. Summary of analyses of variance for wood chemical properties of trees at the Shafton and Helvetia species trials

WOOD CHEMICAL COMPOSITION

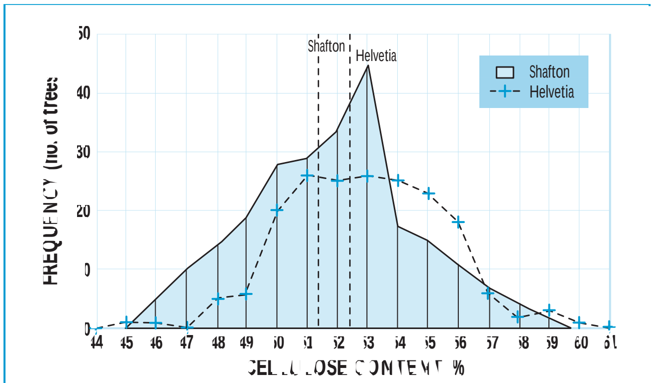
Table VII gives a summary of analyses of variance for wood chemical properties. Both lignin and pentosans varied significantly between sites (P<0.001), but there was no significant difference for alpha-cellulose. In trials of *Populus* hybrids grown on two sites in Pennsylvania, alpha-cellulose and extractives content varied significantly, but there was no significant difference in lignin content *(7)*. Similarly, significant differences were measured between four sites for alpha-cellulose, pentosans, and extractives of *E. globulus* in Portugal, but no significant difference was found for lignin.

All three wood chemical properties varied between species (P<0.001), but there was no significant difference between seed sources. There was a significant species-by-site interaction for lignin. Cellulose varied between replications (P<0.001), showing evidence of some microenvironmental influence.

Alpha-cellulose contents at Shafton and Helvetia of species and trees are shown in **Figs. 3–4.** There was a difference of only 1% in mean alpha-cellulose content at the two sites. *E. smithii* was best at both sites, with at least 2% more alpha-cellulose than any other species, while *E. macarthurii* was poorest, with 7% less than the *E. smithii*. *E. fraxinoides*, *E. oreades*, and *E. macarthurii* had 1% more cellulose at Helvetia, while *E. fastigata* and *E. nitens* had 2% more. *E. smithii*, *E. grandis*, and *E. dunnii* all had similar contents at both sites. The four seed sources of *E. smithii* had the highest alpha-cellulose at both sites. The sources of *E. Smithii*, *E. grandis*, and *E. nitens* varied more at Helvetia than at Shafton, while the opposite occurred with sources of *E. fraxinoides* and *E. fastigata*. *E. dunnii* sources, on the other hand, showed very little variation. The range in alpha-cellulose at the two sites was similar (45%–60%), but there were more trees at Shafton with low values [46%–51% (Fig. 4)].

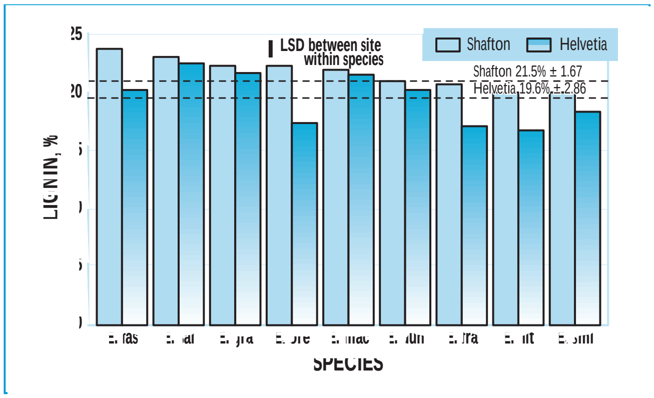


3. Mean alpha-cellulose content in wood from nine species at Shafton and Helvetia

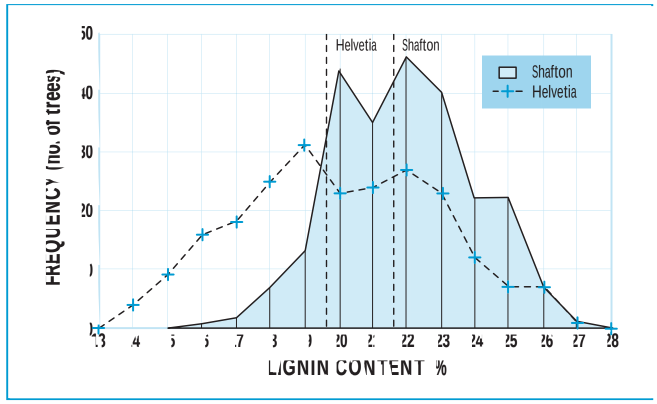


4. Frequency distributions of alpha-cellulose content of trees in the Shafton and Helvetia species trials

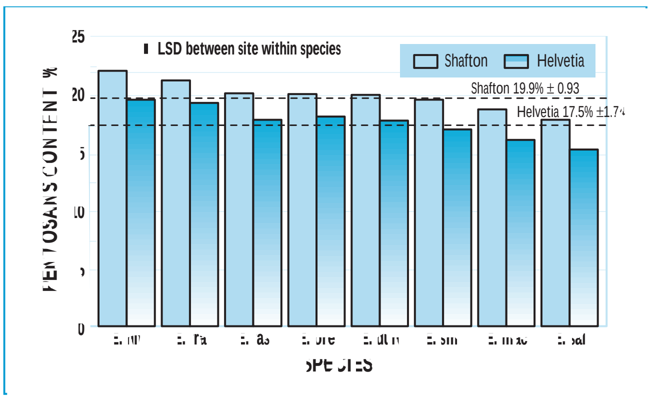
Lignin contents of species and trees are illustrated in **Fig. 5.** *E. fastigata* had the highest lignin content at Shafton followed by *E. saligna* and *E. grandis*, but at Helvetia, *E. saligna* had the highest followed by *E. grandis*



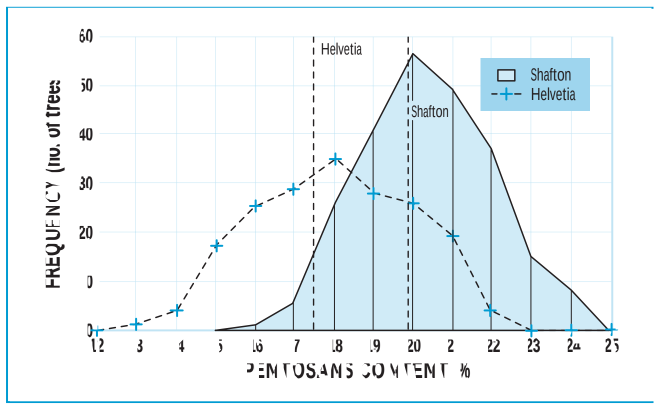
5. *Mean lignin content in wood from nine species at Shafton and Helvetia*



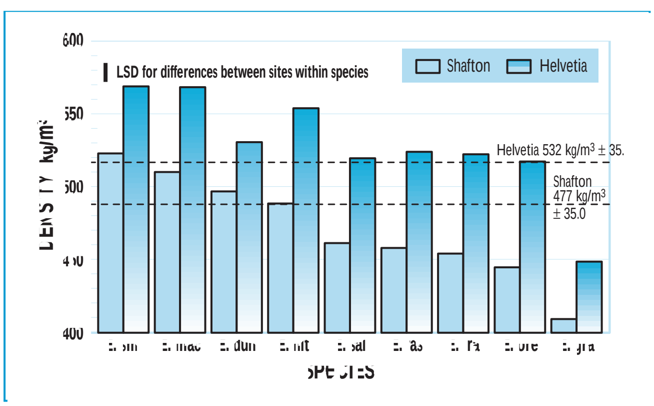
6. *Frequency distributions of lignin content in wood from trees at Shafton and Helvetia*



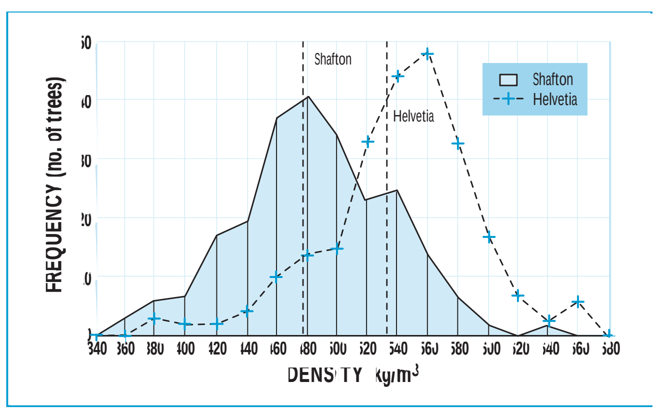
7. *Mean pentosans content of nine species at Shafton and Helvetia*



8. *Frequency distributions of pentosans content of trees at Shafton and Helvetia*



9. *Mean wood density of eucalypt species at Shafton and Helvetia*



10. *Frequency distributions of wood density of trees at Shafton and Helvetia*

and *E. macarthurii*. *E. smithii* and *E. nitens* had the lowest lignin at Shafton and Helvetia, respectively. All species had a lower lignin content at Helvetia.

There was little variation in lignin content of sources within species, and all but two sources (one each of *E. saligna* and *E. macarthurii*) had higher lignin at Shafton. Trees at Helvetia had a minimum lignin content of 13%, while those at Shafton only went as low as 15% (**Fig. 6**). There were also more trees at Helvetia with lignin contents between 14% and 18%, while at Shafton, there were a greater number of trees with contents between 21% and 25%.

Pentosans content of species, their seed sources, and trees at the two sites are shown in **Fig. 7.** Site

Source	DF	MEAN SQUARES Density, kg/m³	Extracted density, kg/m³
Sites	1	369,774[a]	135,711[a]
Reps within sites	4	3,250[b]	664[b]
Species	8	68,270[a]	53,841[a]
Seed source within species	18	2,871[b]	2,400[b]
Species by site	8	2,193[b]	1,614[b]
Seed source by site	18	1,588[b]	1,428[b]
Trees within plots	104	126,539	1,260
Trees between plots	307	454,879	1,330

[a]P<0.001
[b]Not significant

VIII. Analysis of variance of wood density and extracted wood density at Shafton and Helvetia

Component	Wood density, kg/m³	Extracted wood density, kg/m³
Sites	36.2	20.3
Reps within sites	0	0
Species	27.2	31.6
Seed source within species	1.7	2.0
Species by site	0.6	0.6
Seed source by site	0.9	0.5
Trees within plots	0	0
Trees between plots	33.4	45.0
Total variance	4276	2910
Mean across sites	505	460
CV between sites (trees)	7.7	8.1

IX. Components of variance (CV) at Shafton and Helvetia for wood density and extracted wood density

had a strong influence as pentosans content was less for all species at the colder site. Ranking was the same at both sites, and *E. nitens* and *E. saligna* had the highest and lowest contents, respectively. Performance of the sources was similar at the two sites, with the same ones ranked the highest and lowest at both sites (Fig. 10). All the sources, however, had a higher content at Shafton. There was a large difference in the frequency distributions for pentosan content of trees at the two sites (**Fig. 8**). Trees at Shafton ranged from 15% to 25%, while those at Helvetia only had contents of 13%–23%. This suggested that, if pentosans are desirable for some products, it may be impossible to obtain high values on some sites.

Source	DF	MEAN SQUARES Pulp yield, %	Alkali cons., %	Brightness, %	Kappa no.
Sites	1	213.752[a]	1009.243[b]	1280.405[b]	290.751[b]
Reps within sites	4	10.312[b]	34.189[c]	43.900[d]	13.060[b]
Species	8	1371.000[d]	293.300[d]	353.580[d]	101.232[d]
Seed source within species	18	119.000[b]	19.560[c]	7.700[c]	3.983[c]
Species by site	8	13.102[d]	49.180[d]	16.660[a]	8.889[b]
Seed source by site	18	2.306[c]	20.130[c]	11.260[c]	2.728[c]
Trees within plots	104	2.830[c]	13.780[c]	7.570[c]	2.887[c]
Trees between plots	307	1.896	9.460	5.300	2.036

[a]P<0.05
[b]P<0.01
[c]Not significant
[d]P<0.001

X. Summary of analyses of variance of pulp properties for wood from trees grown at Shafton and Helvetia

WOOD DENSITY

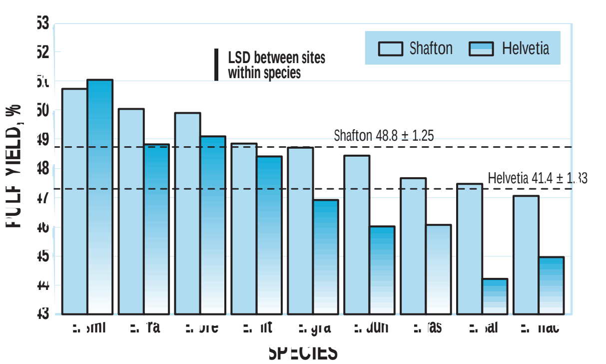
Mean squares from the analyses of variance of wood density are given in **Table VIII.** There were significant differences in density and extracted wood density between the Shafton and Helvetia sites (P<0.001). Species differed for both properties (P<0.001), but there were no significant differences between their seed sources.

Components of variance for wood density and extracted wood density are given in **Table IX.** The greatest proportion of the variation occurred between sites, species, and trees. There was relatively little variation between seed sources or from interactions with sites.

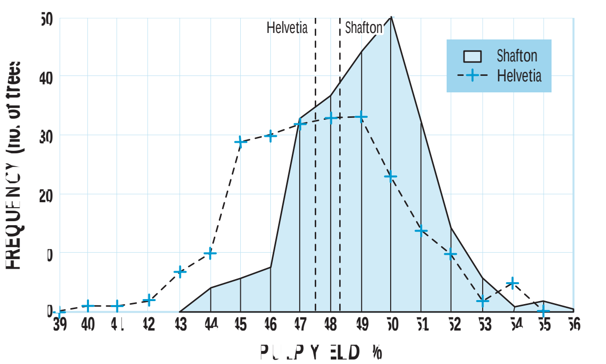
Wood density of species and trees at Shafton and Helvetia are shown in **Figs. 9–10.** There were large differences between both species and sites. *E. smithii* had the highest density at both sites, followed by *E. macarthurii; E. oreades* and *E. grandis* had the lowest. All species had higher densities at Helvetia, the colder site. This was probably due to a higher level of extractives. Seed sources within species also all had higher densities at Helvetia. Sources of *E. smithii, E. nitens,* and *E. fastigata* varied more than those of *E. saligna* and *E. grandis.* There were more trees with higher densities at Helvetia than Shafton, suggesting that the environment had a strong influence on individual trees as well as species and seed sources (Fig. 10).

PULP PROPERTIES

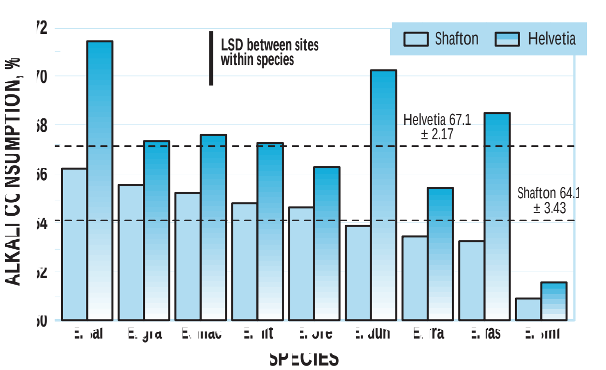
Analyses of variance for the pulp properties of trees sampled at



11. Mean pulp yield of wood from nine species grown at Shafton and Helvetia



12. Frequency distribution of pulp yield of trees at Shafton and Helvetia



13. Alkali consumption of wood from species grown at Shafton and Helvetia

Component	Pulp yield, %	Alkali cons., %	Brightness, %	Kappa no.
Sites	14.1	19.9	29.2	22.7
Reps within sites	0.4	0.4	1.3	0.7
Species	41.6	19.0	32.9	28.6
Seed source	3.8	0.2	0	1.4
Site-by-species interaction	6.1	5.3	0.8	4.0
Seed source by site	0	3.1	2.5	0
Trees within plots	5.0	7.4	4.3	5.5
Trees between plots	28.9	44.7	28.9	37.0
Total variance	6.532	21.066	18.349	5.482
Mean between sites	48.05	65.60	26.89	15.67
Coeff. of variation (trees)	2.9	4.7	8.6	9.1

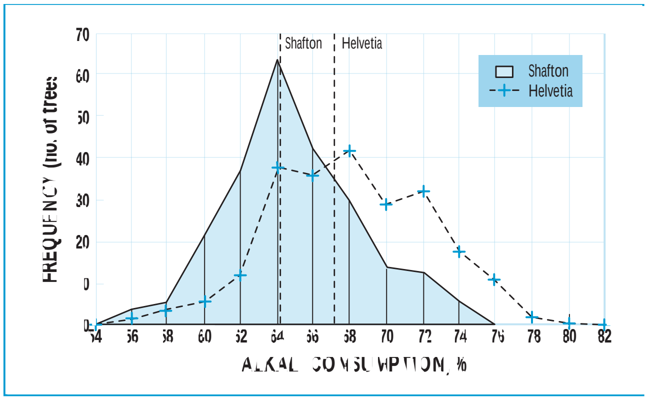
XI. Components of variance for pulp properties at Shafton and Helvetia trial sites combined expressed as a percentage of total variance

Shafton and Helvetia are given in **Table X.** Differences between species and sites for pulp yield, alkali consumption, brightness, and kappa number were significant. Both environmental and genetic effects were influential. Pulp yield varied between seed sources within species (P<0.01), and there was a significant site-by-species interaction for all four pulp properties.

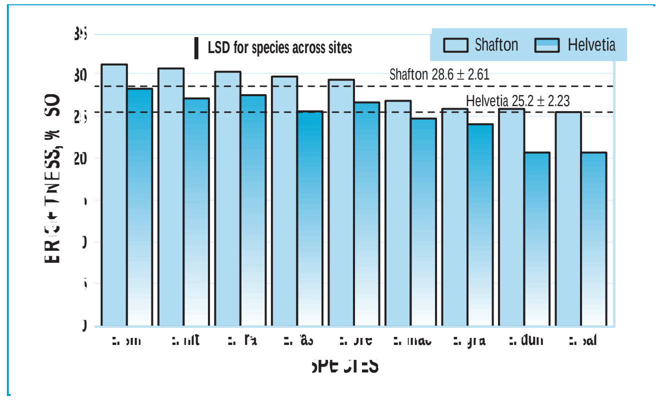
The interaction for pulp yield (illustrated in **Fig. 11**) was, however, caused by only two species (*E. oreades* and *E. saligna*). In a study of 24 seed sources of *E. camaldulensis* grown on two sites with different growth rates in Italy, a significant difference was found for pulp yield between the sites, but there was no significant site-by-provenance interaction *(8)*. Pulp yield, brightness, and kappa number varied between replications within sites, reinforcing the indicated sensitivity to environment. Unlike growth factors, variation in pulp properties between trees within and between plots was not significant.

Components of variance for pulp properties between sites are shown in **Table XI.** Most of the variation in pulp yield was between species and sites, indicating that improvement would best be effected through influence at these levels. Although statistically significant, there was comparatively little variation in pulp yield resulting from the site-by-species interaction, and variation between seed sources and trees was also surprisingly small. Variation between sites for the other three pulp properties was also an important component relative to species and trees, suggesting that the environment had a greater effect on these properties than it had on pulp yield.

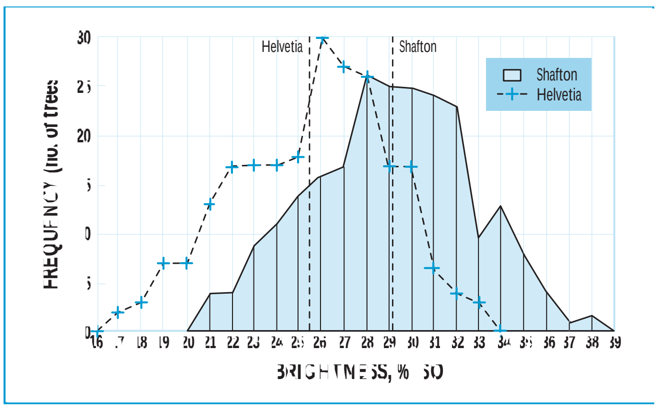
Mean pulp yields for the nine species at Shafton and Helvetia are shown in Fig. 11. Trees growing at the warmer Shafton site produced, on average, 1.3% more pulp. For a crop yielding 200 tons/ha, this would equate to 2.6 tons/ha. *E. smithii* was best at both sites and produced slightly more pulp at Helvetia than at Shafton. *E. macarthurii* and *E. saligna* were poorest at Shafton and Helvetia, respectively. Most species had higher yields at



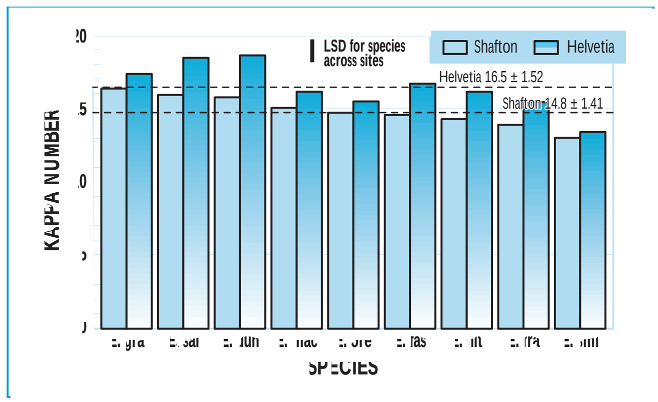
14. Frequency distribution of alkali consumption of trees at Shafton and Helvetia



15. Brightness of pulp of nine species grown at Shafton and Helvetia



16. Frequency distribution of pulp brightness of trees at Shafton and Helvetia



17. Kappa number after 40-min cooking of nine species at Shafton and Helvetia

Shafton, but differences between species were greater than between sites (as indicated by the analysis of variance).

With the exception of *E. dunnii* and *E. macarthurii*, the same seed source of each species was best for pulp yield at both Shafton and Helvetia. Most seed sources gave lower yields at Helvetia.

Frequency distributions of trees for pulp yield at the two sites are shown in **Fig. 12.** The range in pulp yields at Shafton and Helvetia was similar, with some trees producing yields up to 55%.

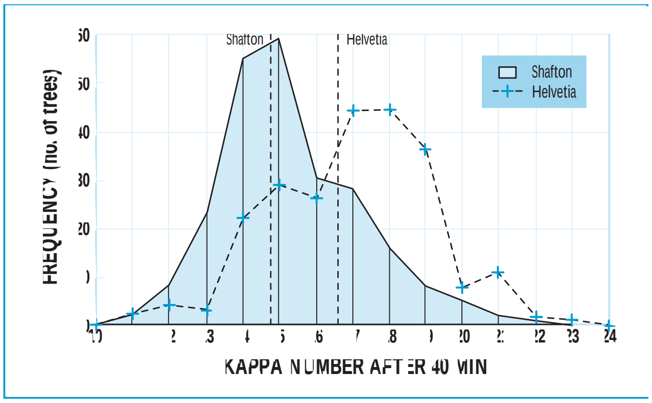
There were more trees with low yields (44%–46%) at Helvetia and high yields at Shafton (49%–51%). As the range of genotypes was similar at both sites, this was further indication of the influence of environment on pulp yield. This environmental influence may also be reflected by a difference in pentosans content.

Alkali consumption for species and trees at Shafton and Helvetia are shown in **Figs. 13–14.** *E. smithii* used the least alkali at both sites, and *E. saligna* used the most.

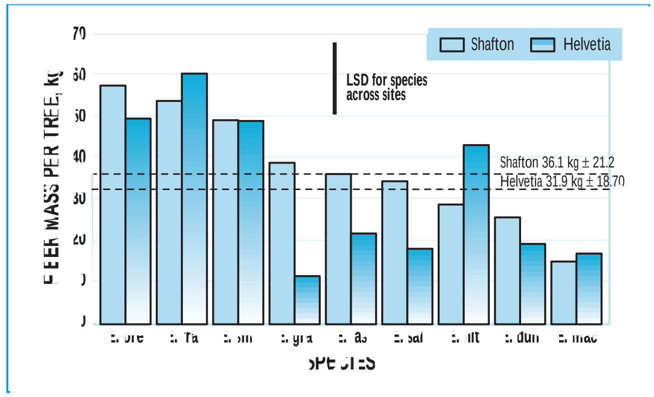
All species had a higher consumption of alkali at the colder site, Helvetia. Only seed sources of *E. smithii*, *E. fraxinoides*, and *E. macarthurii* consumed less alkali at Helvetia, and for each of these species, the source with the lowest alkali consumption at Helvetia had the highest at Shafton and vice versa. Trees at Helvetia (Fig. 14) had a high alkali consumption, with a few consuming more than 80%. Variation in alkali consumption of trees was greater at Helvetia.

Pulp brightness of unbleached handsheets is often considered unimportant, but as differences in handsheet color were easily visible between species and sites, brightness is included here as it may be important for the bleaching process. Pulp brightness for species and trees at Shafton and Helvetia are shown in **Figs. 15–16.** Brightness was higher at Shafton (28.6% at Shafton vs. 25.2% at Helvetia), indicating a strong environmental effect.

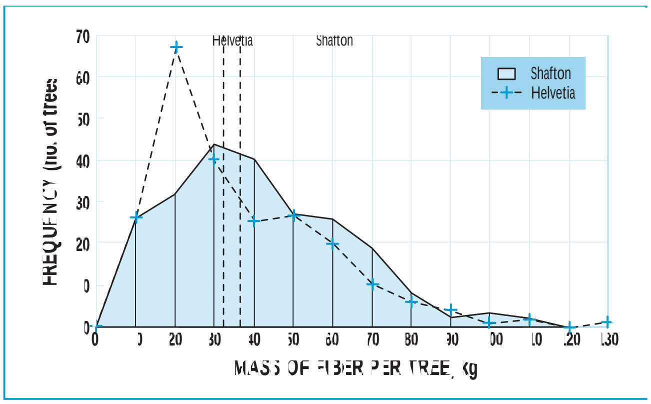
Species ranking was similar at the two sites; *E. smithii* had the highest brightness at both sites, and *E. saligna* had the lowest. With the exception of one seed source of *E. macarthurii*, all sources had a higher brightness at Shafton. There was no similarity in the ranking of the seed sources within species between the two sites. Pulp brightness per tree was 16%–34% and 20%–39% at Helvetia and Shafton,



18. Frequency distributions of kappa number after 40-min cooking of trees at Shafton and Helvetia



19. Fiber mass per tree of nine eucalypt species at Shafton and Helvetia



20. Frequency distribution of fiber mass per tree at Shafton and Helvetia

Source	DF	Fiber mass per tree, kg
Sites	1	2690.1[a]
Reps within sites	4	494.0[a]
Species	8	8632.2[b]
Seed sources	18	548.7[a]
Site-by-species interaction	8	1967.3[b]
Site by seed source	18	241.0[a]
Trees within plots	1043	332.3[a]
Trees between plots	07	261.3

[a]Not significant
[b]P<0.001

XII. Analysis of variance of fiber mass per tree at Shafton and Helvetia

respectively (Fig. 16). This suggested that high brightness values were less likely to be found in trees from the slower-growing sites.

Kappa numbers after the 40-min cook for species, their seed sources, and trees are shown in **Figs. 17–18.** Differences in rate of delignification have significance when species or sources are mixed in the same digester. *E. smithii* had the lowest kappa number at both sites, showing that it had the fastest rate of delignification. Otherwise, species ranking differed at the two sites; *E. grandis* had the highest kappa number at Shafton followed by *E. saligna* and *E. dunnii,* while at Helvetia, *E. dunnii* had the highest followed by *E. saligna* and *E. grandis.* Generally, there was little difference between kappa numbers of seed sources within species. Apart from one seed source of *E. smithii,* all sources had higher kappa numbers at Helvetia. The range in kappa numbers of trees at the two sites was similar, but there were more trees with higher values at Helvetia (Fig. 18).

Fiber mass per tree (in units of kg) was calculated as the product of density (kg/m^3), tree volume (m^3), and pulp yield (%). The mean squares from the analysis of variance of fiber mass per tree are given in **Table XII.** There were no significant differences between sites or between seed sources, but species themselves differed significantly (P<0.001). There was a highly significant species-by-site interaction; this was probably attributed to *E. grandis,* which grew better at Shafton, and *E. nitens,* which did better at Helvetia. The combined growth of the two species was equal at both sites.

Components of variance (CV) for fiber mass per tree are given in **Table XIII.** Fiber mass varied the most between trees followed by species and, as indicated by the analysis of variance, there was relatively little variation between sites. The variation due to the interaction between sites and species for fiber yield was sufficiently large to justify the testing of species across sites. Variation in fiber mass between trees from the two sites was large (CV = 47.6) and was related to the high variation in volume production.

Fiber yields per tree for species and trees are shown in **Figs. 19–20.** *E. fraxinoides, E. oreades,* and *E. smithii* were best at both sites; *E. dunnii* and *E. macarthurii* were the poorest. The change in ranking of *E. grandis* and *E. nitens* at Shafton and Helvetia was linked to that observed for volume growth. More fiber was produced at Shafton (36.1 kg) than at Helvetia (31.9 kg). Seed sources of *E. smithii*, *E. grandis*, and *E. macarthurii* varied more than sources of the other species.

All sources of *E. saligna*, *E. grandis*, and *E. fastigata* gave greater fiber mass per tree at Shafton, while *E. nitens* and *E. fraxinoides* produced more at Helvetia, showing the former species to be better adapted for growth on the warmer site. Frequency distributions of trees for fiber mass at the two sites were similar with the same range. Both distributions were skewed toward low fiber mass, although more trees gave low fiber mass (10–25 kg) at Helvetia. However, at both sites, there were trees with fiber mass as high as 110–120 kg; this showed that by selecting the correct species and silvicultural practices, fiber production per tree need not be limited by climatic constraints such as cold winter temperatures.

CONCLUSIONS

Irrespective of site, species differed significantly for all wood, growth, and pulp properties ($P<0.001$). Irrespective of species, sites differed significantly for all growth, wood, and pulp properties except for cellulose content and fiber mass. Pentosans content and wood density were the wood properties most strongly affected by site. There were significant site-by-species interactions for volume, lignin content, and all the pulp properties. This suggested that site–species matching could improve productivity and wood quality at both sites. At the species level, *E. fraxinoides*, *E. smithii*, and *E. oreades* were the most productive species, with fast growth, high pulp yield, and brightness but low alkali consumption and kappa number. *E. saligna* was one of the poorest species, with low pulp yield, high alkali consumption, and slow delignification.

Most of the variation in the commercially important properties (pulp yield, fiber mass per tree, and alkali consumption) occurred between trees, and the greatest gains from tree breeding are likely to be realized through selection at this level. Seed source within species did not vary greatly, but only a limited number of sources were studied for each species (1–4). Variation in fiber mass per tree at the species and tree level was sufficiently large to justify the resources required for tree improvement. The difference of 50 kg of fiber per tree between the best and the poorest species is a good illustration of the considerable improvement in productivity that may be achieved. TJ

Component	Fiber mass per tree, kg
Sites	0.7
Reps within sites	0.6
Species	28.6
Seed source	3.3
Site-by-species interaction	12.3
Seed source by site	0
Trees within plots (plot error)	4.0
Trees between plots	50.5
Total variance	524.6
Mean across sites	34.0
CV between sites (trees)	47.6

XIII. Components of variance (CV) at Shafton and Helvetia for fiber mass per tree

Clarke is program manager, Eucalypts, Shaw is research general manager, and Jones is a research officer at Sappi Forests Research, P.O. Box 473, Howick, South Africa. Wessels is a research officer at Sappi Research and Development, P.O. Box 3252, Enstra, Springs, South Africa.

Received for review Dec. 4, 1996.
Revised Sept. 23, 1997.
Accepted Oct. 11, 1997.

LITERATURE CITED

1. Hamilton, G. J., *Forest Mensuration Handbook,* Forestry Commission Booklet No. 39, Her Majesty's Stationary Office, London, 1975, p. 275.
2. Garbutt, D. C. F., *Paper S. Africa* 9(4): 27(1989).
3. Liyama, K. and Wallis, A. F. A., *Appita J.* 41(6): 442(1988).
4. Easty, D. B., Berben, S.A., DeThomas, F.A., *et al., Tappi J.* 74(10): 257(1990).
5. Wright, J.A., Birkett, M. D., and Gambino, M. J. T., *Tappi J.* 74(8): 165(1990).
6. Gomez, K.A. and Gomez, A.A., *Statistical Procedures for Agricultural Research,* Wiley & Sons, New York, 1984, p. 332.
7. Blankenhorn, P. R., Bowersox, T. W., Kuklewski, K. M., *et al., Wood Fiber Sci.* 17(3): 351(1985).
8. Sesbou, A. and Nepveu, G., *Annales des Sciences Forestieres* 47(3): 201(1990).