

Wood and fibre productivity potential of promising new eucalypt species for coastal Zululand, South Africa

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Summary

In South Africa pressure is increasing to improve the quantity and quality of eucalypt wood being produced from the existing forestry land base, and to identify species that would enable profitable forestry on land currently considered marginal. In a series of site × species interaction trials established on the Zululand coastal plain during 1992, alternative eucalypt species were compared with a number of commercial eucalypt species and clones at three sites. At rotation age of 7 y, the wood and fibre productivity of the five most promising new species, namely *Corymbia henryi*, *C. citriodora* ssp. *citriodora*, *Eucalyptus longirostrata*, *E. pilularis* and *E. tereticornis*, was assessed at two of the sites.

On the basis of merchantable wood production, *E. longirostrata* Monto provenance showed excellent potential for high productivity (wet) sites on the Zululand coastal plain, and *C. citriodora* ssp. *citriodora* and *C. henryi* excellent potential for marginal (moderately dry) sites. On the basis of fibre production, *E. longirostrata* Monto and *C. henryi* showed excellent potential for high productivity sites, and *C. citriodora* ssp. *citriodora* and *C. henryi* excellent potential for marginal sites.

Eucalyptus longirostrata could be a good partner for *E. grandis* and *E. urophylla* for the production of hybrids better adapted to the range of environmental conditions in coastal Zululand than either of the latter two species. In such hybrid combinations, the high basic wood density of *E. longirostrata* could be of advantage to the local hardwood woodchip export industry.

Keywords: plantations; adaptation; species trials; site-species matching; productivity; wood properties; pulping; *Eucalyptus*; *Corymbia*; South Africa

Introduction

Wood is one of man's most important resources, and its significance is increasing (Brown and Hillis 1984). Pulp is an important end use of wood, accounting for 522 million m³ or 15% of total world wood consumption in 2004 (FAO 2005). In the 1950s, 95% of paper was made from wood fibre, and 90% of that fibre was obtained from coniferous trees. Forty years later

— although world paper consumption has increased five-fold — wood fibre still accounts for 90% of total fibre input. Non-coniferous species, however, now contribute 30%, with an increasing fraction of this made up of eucalypts grown mainly in the subtropics and tropics (Brown *et al.* 1997). Timber from eucalypt plantations has progressively replaced supplies from natural tropical hardwood forests in a variety of solid-wood markets and applications over the past decade (Flynn 2003). The main reasons for this shift are the decreased risk of diverse sources of supply and increased demand for products derived from 'sustainably managed' forests by major international retailing chains (Dunne 2000; Flynn 2003). To meet the increasing global demand for wood, worldwide plantation hardwood timber outputs will need to be increased. This may be done either by increasing the amount of timber obtained from the existing land base, or by planting additional land (Brown and Hillis 1984; Kimmins 1994).

In South Africa, present and future land use policies are likely to restrict the conversion of non-forested land to timber plantations. Factors that may contribute to increased timber yield from the existing land base include the use of site-species matching (Gardner 2001; Miranda and Pereria 2002), tree breeding and clonal propagation of pure species or hybrids (Denison and Kietzka 1993a; Duncan *et al.* 2000; Pierce and Verryn 2000) and improved silvicultural techniques (Du Toit *et al.* 2001; Smith *et al.* 2001; Little *et al.* 2002). Research involving the matching of a wide range of eucalypt species to site conditions within the different geographic regions in South Africa has been carried out since the early 1950s (Gardner 2000). Of these regions, Zululand (lying between 27° and 29°S latitude) is one of the most important plantation forestry areas in South Africa, contributing 20% of the country's hardwood pulpwood (DWA 2005). Large-scale planting of eucalypts on the Zululand coastal plain began during the early 1920s and was based almost entirely on *Eucalyptus grandis* seedlings (Poynton 1979; Harrison 1993). To counter the incidence of disease associated with *E. grandis* combined with the desire to extend the areas planted to drier regions, forestry had by 1980 become almost entirely based on clones of either *E. grandis* or hybrids of *E. grandis* with *E. urophylla*, *E. camaldulensis* or *E. tereticornis* (Denison and Kietzka 1993b; Gardner 2001). Despite meeting industry objectives (reduced incidence of disease and increased drought

tolerance and growth), the aforementioned species and hybrids were not adequately adapted to the large areas of marginal environments available (Gardner 2001).

To explore potential alternative eucalypt species for the region, three site \times species interaction trials were established on the coastal plain during 1992. At rotation age, 7 y after planting, the trees were assessed for various growth attributes at all three sites, and the best-performing species and controls across all sites were sampled at two sites, Terranera and False Bay, and tested for pulping properties. The results of these assessments, reported by Gardner (2001), revealed that *Corymbia henryi* (Hill and Johnson 1995), *C. citriodora* ssp. *citriodora* (McDonald and Bean 2000), *E. longirostrata* (Chippendale 1988) (formerly *E. punctata* var. *longirostrata*), *E. pilularis* and *E. tereticornis* had the best overall growth potential of all 'new' species tested. Further investigations were then carried out at Terranera and False Bay to determine the potential wood and fibre productivity of each of the latter species in coastal Zululand conditions. The results of the latter investigations are presented and discussed in this paper.

Material and methods

Study sites

Mean annual precipitation (MAP) is the most important bioclimatic variable determining productivity of forest tree plantations in sub-tropical, coastal Zululand (Gardner 2001), where MAP decreases rapidly with increasing distance from the coast and also from south to north (Schulze 1997). The predominant soil parent materials in the area, Quaternary aeolianite and alluvium, have given rise to soils with generally sandy textures (Herbert and Musto 1993). The soils most typical on the coastal plain are arenic lixisols and arenic kandiusults (FAO–UNESCO 1974).

The initial three trials were sited along a linear transect of the commercial forestry belt (Gardner 2001), from the wettest and most productive site at Terranera (MAP 1197 mm) in the south,

to the driest and least productive site at False Bay (MAP 764 mm) in the north (Table 1). Apart from False Bay having a much lower MAP than Terranera, the higher evaporation at False Bay exacerbates moisture stress at this site. As pulping data were available only for Terranera and False Bay (Gardner 2001), wood and fibre productivity was investigated only in these two trials.

Trial design and treatments

At each site, an experiment consisting of 15 eucalypt species and clones (treatments) was laid out in a randomised complete-block design. Some of the species and inter-specific hybrids (clones) were represented by more than one seedlot or clone (Gardner 2001). Each experiment consisted of three replicates of 30 treatments. Treatment plots consisted of 30 trees (5 rows \times 6 trees in each row) with the inner net plot of 12 trees being measured (3 rows \times 4 trees in each row). For the variates 'stem straightness', 'mean infection index', 'merchantable volume', 'wood yield' and 'fibre productivity', all measured trees were used. Details of the origins of the seedlots and clones included in the investigations of wood and fibre productivity are presented in Table 2. The Australian provenances (seedlots) were chosen for possible suitability to trial site conditions and availability of seed. The control treatments were local, improved seedlots of *E. grandis* and *E. urophylla*, the best local-performing natural-stand provenance of *E. camaldulensis* (Petford) (Darrow 1983; Eldridge *et al.* 1993) and local top-performing hybrid clones of *E. grandis* \times *E. camaldulensis* and *E. grandis* \times *E. urophylla* (Denison and Kietzka 1993a; Eldridge *et al.* 1993).

Measurements and assessments

Tree growth attributes

Survival was monitored through the duration of the experiment, and stem straightness, incidence of disease, height (*ht*) and diameter at breast height (*dbh*) were assessed or measured at rotation end (7 y of age).

Table 1. Site descriptions and planting details for trials at Terranera and False Bay in Zululand, South Africa

Site conditions	Trial name	
	Terranera	False Bay
Climatic description	Warm, wet	Hot, dry
Latitude and longitude	28°42'04"S, 32°08'04"E	28°00'22"S; 32°19'51"E
Altitude (m asl)	25	75
Rainfall distribution pattern	Summer maximum	Summer maximum
Mean annual precipitation (mm) ^a	1197	764
Mean annual temperature (°C) ^b	21.7	21.9
Mean annual A-pan evaporation (mm) ^b	1479	1544
Soils: Taxonomy ^c	Arenosol	Arenosol
Depth (m)	>1.2	>1.2
Planting date	24 June 1992	14 May 1992
Spacing at planting (m)	2.7 \times 2.7	3 \times 2.5

^a Eight-year mean for the period 1992–1999

^b Schulze (1997)

^c FAO–UNESCO (1974)

Table 2. Origins of the seedlots and hybrid clones evaluated for wood and fibre productivity in trials at Terranera and False Bay in Zululand, South Africa

Nature of treatment and treatment name	Seedlot/clone no.	Origin				
		Locality	No. of seed parents	Latitude	Longitude	Altitude (m asl)
Seedlots						
<i>E. camaldulensis</i> ^W	16720‡	Petford area, Qld	101	17°24'	145°2'	590
<i>E. grandis</i> ^W	EG_1*	Zululand (SO)	80	—	—	—
<i>E. longirostrata</i> ^{W,F}	15602‡	27 km SE of Gympie, Qld	2	26°18'	152°49'	380
<i>E. longirostrata</i> ^{W,F}	15637‡	NW of Monto, Qld	27	24°49'	150°57'	500
<i>E. pilularis</i> ^{W,F}	13537‡	10 km W of Beerburum, Qld	5	26°57'	152°52'	40
<i>E. tereticornis</i> ^{W,F}	13319‡	N of Woolgolga, NSW	6	29°55'	153°12'	30
<i>E. urophylla</i> ^W	EU_1*	Zululand (SO)	116	—	—	—
<i>C. citriodora</i> ssp. <i>citriodora</i> ^{W,F}	18062‡	Expedition Range, Qld	2	24°37'	149°2'	400
<i>C. henryi</i> ^{W,F}	13572‡	S of Grafton, NSW	10	29°45'	152°58'	85
Hybrid clones						
<i>E. grandis</i> × <i>E. camaldulensis</i> ^{W,F}	GC_2**	Zululand	—	—	—	—
<i>E. grandis</i> × <i>E. urophylla</i> ^{W,F}	GU_2**	Zululand	—	—	—	—

‡ Imported, unimproved seedlot obtained from CSIRO, Australia

* South African commercial seedlot

**South African commercial hybrid clone

^W Species or clone selected for merchantable wood volume determination

^F Species or clone selected for pulping property determination (note: *E. pilularis* sampled at Terranera only)

Using a four-point scoring system, stem straightness was assessed as follows:

- 1 = poor stem straightness with less than 25% of the bole straight and the remainder undulating or spiraling
- 2 = poor to fair stem straightness where some portion of the bole is straight, but the degree of undulation, kinking or spiraling in the stems makes the tree unsatisfactory on the whole
- 3 = good stem straightness where besides some minor defects the bole is otherwise straight
- 4 = excellent, where the entire bole is straight with only one or two very minor defects.

Trees were not generally downgraded for forking. However, a tree that scored 4 (excellent) was downgraded to score 3 (good) if any forking occurred above breast height. These scores were combined, and the plot means used for analysis.

Each measured tree was rated for visual symptoms of four major stem diseases encountered in Zululand, *Botryosphaeria dothidea*, *Coniothyrium* (various spp.), *Chrysosporthe austroafricana* (previously described as *Cryphonectria cubensis*) (Gryzenhout *et al.* 2004) and *Endothia gyrosa* (0 = free of symptoms; 1 = slightly infected; 2 = moderately infected; 3 = severely infected). The combination of these scores on a treatment plot basis provided a 'mean infection index' (MII) to give an overall indication of susceptibility to disease. MII was calculated by averaging the four scores for individual disease infection for each seedlot or clone.

Stem volume

Of the 15 species and clones that were planted at each site, only those 11 that exhibited good growth across all three sites during

the final assessments at 7 y were selected for accurate determination of stem volume. From each treatment plot, six trees, free from defects, were randomly selected. This equated to 18 trees per treatment at each site. For each of these trees, height to a minimum over-bark stem diameter of 0.07 m ($H_{0.07}$) was determined, and under-bark diameter measured at each 1-m interval from tree base to the point of $H_{0.07}$. For each 1-m stem section, the under-bark volume (V_{sec}) was calculated using the formula for a truncated cone. The sum of these was used to determine merchantable under-bark volume (V_m) per tree. \log_{10} transformations of V_m , dbh and ht were used for determining separate Schumacher and Hall (1933) volume models on an individual species basis for each site. Using these derived data and stocking for relevant treatment plots, total 'merchantable wood volume' (V_{mha}) per species or clone per site was then calculated.

Wood and pulping properties

As the elected pulping laboratory could accommodate only a limited number of wood samples at the time, the wood and pulping property tests were confined to the six 'new' species most promising across all three sites and two selected commercial clones based on 4-y measurements (Gardner 2001). Thus, of the 11 taxa assessed for merchantable wood volume, only eight were assessed for wood and pulping properties (Table 2). For the latter investigations, two trees, free of defects and closest to the mean plot diameter at breast height, were selected from each treatment plot (six trees per taxon per site). When felled, two discs 20 mm thick were cut at 1-m intervals along the length of the tree bole from the base to $H_{0.07}$.

One set of discs was used to assess whole-tree density (TAPPI test method T258 om-89) and extractable content of the wood

(TAPPI test method T204 om-88). The product of the merchantable wood volume per hectare ($\text{m}^3 \text{ha}^{-1}$) and the wood density (kg m^{-3}) divided by 1000 gives an indication of the wood yield per hectare (t ha^{-1}). Unbleached kraft-pulp tests were carried out at the Mondi Business Paper pulp-mill laboratory, Richard's Bay, South Africa. The cooking and analytical process is briefly described as follows:

To determine the extractable content, individual wedges from each disc were chipped and Wiley milled in order to obtain a sample of air-dried sawdust to pass through a 0.40-mm screen (TAPPI test method T257 cm-85). The ground wood from the wedges was combined to form a representative whole-tree bulk sample, and the ethanol-benzene (T204 om-88) and hot water (T207 om-88) extractable contents were then determined for each sample.

The second set of discs from each tree was used for pulping tests. The discs were bulked for each taxon for each site (16 taxa samples), and chipped by a guillotine-style laboratory chipper to produce chips of a uniform size. Samples were pulped in an 'Aurora' electrically heated, batch type, re-circulating liquor digester using the Kraft process. The cooking conditions used in this study were similar to those used in the batch digesters at the Richards Bay mill pre-2005. The cooking conditions when applied to the normal mix of woodchips at Richards Bay would result in a pulp the kappa number of which was approximately 20.

Pulping conditions were as follows:

- Active alkali charge (% Na_2O) of oven-dry wood – 15%
- Sulphidity of the cooking liquor – 25%
- Liquor : wood ratio – 4.6 ml : 1 g
- Pulping cycle:
 - Ambient to 170°C – 90 minutes
 - Cooking time at 170°C – H-factor 900 (± 50 minutes)
- Degassing was carried out at 90°C and at 110°C to remove gasses not condensable in water at such a rate that no liquor was lost from the digester
- Cooling to atmospheric pressure at end of cook – 15 minutes

A spent (black) liquor sample was taken through a coil condenser at the end of the cook, prior to cooling, and then analysed for residual alkali content (TAPPI test method T625 om-85). The kappa number of cooked pulp was determined using TAPPI test method T236 cm-85. The kappa number is the volume (ml) of 0.1N potassium permanganate solution consumed by one gram of moisture-free pulp. The results are corrected to 50% consumption of the permanganate added. Immediately after removal from the digester, the pulp samples were de-fibreised using a blunt-bladed disintegrator. The disintegrated pulp was screened through a Packer screen fitted with a 0.8-mm slotted screen to remove the shives and uncooked material. The pulp fibres that passed through the slots were used to calculate the screened pulp yield (SPY), while the retained material was used to calculate the percentage rejects. SPY, therefore, represented mass of pulp produced per mass of oven-dry wood charged to the digester, expressed as a percentage. This indicates the amount of pulp produced relative to the amount of wood pulped.

Specific consumption (volume of wood consumed to produce one tonne of pulp) was calculated from SPY and basic density.

Specific consumption is important as it directly affects the economics of pulping, and its effect is magnified where the raw wood is shipped for processing overseas.

Using the data for merchantable wood volume ($\text{m}^3 \text{ha}^{-1}$) and SPY (%), wood yield (t ha^{-1}) and fibre production (t pulp ha^{-1}) were calculated for each species and clone.

Statistical analyses

Prior to analysis, Bartlett's test (Snedecor and Cochran 1980) was used to test the assumption of homogeneity of variance, necessary to permit a valid analysis of variance. The variate 'mean infection index' (MII) was transformed ($(\sqrt{x+1})$), Gomez and Gomez 1984) prior to analysis. The analysis of variance (based on plot means) appropriate for a randomised complete block design was used to test for treatment effects (F -test) using Genstat® for Windows™ (Lane and Payne 1996). Only if the F -value was significant were treatment differences further investigated using least significant differences. These were calculated as the product of the standard error of the difference of the means and the tabulated t -value (Steel and Torrie 1981) for relevant degrees of freedom.

Results and discussion

Stem straightness

In both trials, the hybrid clones ranked highly with respect to stem straightness (Table 3). This was anticipated, as both the clones and their parent trees were the products of breeding programs where stem straightness was an important selection criterion.

Of all seedling treatments, *C. citriodora* ssp. *citriodora* and *C. henryi* were the most consistent across sites in producing straight stems. The stem straightness of *E. longirostrata* (Monto) was strongly influenced by site, as the species scored above the trial average at Terranera (3.3) but below the trial average at False Bay (2.5). The hybrid parent control species *E. camaldulensis* and *E. urophylla* were consistently poor at both sites. Since stem straightness is moderately heritable, one would expect that this trait in any of the above species or provenances could be improved through breeding (Zobel and Talbert 1984; Verryn 2000). Lee *et al.* (2005a) reported improved stem straightness in *C. torelliana* \times *C. citriodora* ssp. *variegata* hybrids over and above that in either parent.

Disease

The mean infection index provides an indication of the overall susceptibility of the species to the four stem diseases most prevalent in Zululand. A high incidence of disease is undesirable as it may lower site productivity through either a reduction in growth or increased mortality (Denison and Kietzka 1993a). In South Africa, bark is manually removed from the stem in-field (Herbert and Robertson 1991), and the presence of disease hinders this process (Nicol 1992). The most disease-prone treatment was the local *E. grandis* commercial seedlot, which had by far the highest MII scores of all treatments at both Terranera (1.25) and False Bay (1.26) (Table 3). Although only *E. grandis* had MII

Table 3. Summary of the analyses of variance and data for end-of-rotation (7 y of age) measurements in trials at Terranera and False Bay in Zululand, South Africa

Analysis	Source of variation	df	Stem straightness (score, 1–4 (best))		Mean infection index (MII) (score, 0–3 (poorest))		Merchantable volume (m ³ ha ⁻¹)	
			Terranera	False Bay	Terranera	False Bay	Terranera	False Bay
			Mean squares					
	Replicate	2	0.013	0.299	0.0024	0.0012	35	481
	Species	10	0.303**	0.834**	0.0148**	0.0136**	24204**	9063**
	Residual	20	0.032	0.074	0.0013	0.0024	3202	760

Summary of data		Treatment means ‡					
Treatment							
<i>E. camaldulensis</i>		2.51 ^d	2.13 ^f	1.042 ^a	1.057 ^a	109 ^e	88 ^{ef}
<i>E. grandis</i>		3.52 ^{abc}	2.64 ^{cde}	1.253 ^b	1.262 ^b	235 ^{bc}	104 ^{def}
<i>E. longirostrata</i> (Gympie)		3.12 ^c	2.81 ^{cd}	1.040 ^a	1.019 ^a	171 ^{cde}	129 ^{cde}
<i>E. longirostrata</i> (Monto)		3.33 ^{bc}	2.46 ^{def}	1.031 ^a	1.034 ^a	223 ^{bc}	141 ^{cd}
<i>E. pilularis</i>		3.29 ^{bc}	2.77 ^{cde}	1.026 ^a	1.070 ^a	206 ^{cd}	85 ^f
<i>E. tereticornis</i>		3.33 ^{bc}	2.35 ^e	1.080 ^a	1.064 ^a	173 ^{cde}	141 ^{cd}
<i>E. urophylla</i>		3.14 ^c	2.14 ^f	1.024 ^a	1.024 ^a	202 ^{cde}	85 ^f
<i>C. citriodora</i> ssp. <i>citriodora</i>		3.39 ^{abc}	3.31 ^{ab}	1.044 ^a	1.050 ^a	114 ^{de}	187 ^{ab}
<i>C. henryi</i>		3.36 ^{bc}	2.99 ^{bc}	1.007 ^a	1.038 ^a	184 ^{cde}	166 ^{bc}
<i>E. grandis</i> × <i>E. camaldulensis</i>		3.67 ^a	3.59 ^a	1.000 ^a	1.096 ^a	320 ^b	214 ^a
<i>E. grandis</i> × <i>E. urophylla</i>		3.66 ^a	3.58 ^a	1.014 ^a	1.079 ^a	422 ^a	228 ^a
Mean		3.30	2.80	1.051	1.072	214	142
sed ⁺		0.15	0.22	0.030	0.040	46	20
Coefficient of variation (units)		5.4	9.7	3.5	4.5	26	17

** Significant at $P < 0.01$ ‡ Within each column, values followed by the same letter are not significantly different ($P < 0.05$) according to Student's t -test

+ Standard error of the treatment differences

scores significantly different from the other treatments at each site, this species and *E. tereticornis* at Terranera and the *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* commercial clones at False Bay all had MII scores above the trial mean, suggesting a possibility of above-average disease susceptibility of these treatments. *Eucalyptus camaldulensis*, *E. urophylla*, *E. longirostrata* (both Gympie and Monto provenances), *C. citriodora* ssp. *citriodora* and *C. henryi* all had MII scores below the trial mean at both sites, suggesting some possible resistance to the particular stem diseases assessed. The high disease infection scores in the *E. grandis* commercial seedlot at both Terranera and False Bay suggest that the potential for breeding for resistance to the stem diseases prevalent in Zululand is limited in the particular *E. grandis* local landrace (Eldridge *et al.* 1993). By contrast, the unimproved Gympie and Monto seedlots of *E. longirostrata* showed low disease infection scores at both Terranera (1.04 and 1.03) and False Bay (1.02 and 1.03), suggesting that resistance to the particular diseases is present in the particular natural populations of this species.

The results of the stem disease assessments highlight two important points. First, the high level of susceptibility to stem diseases in the local, commercial *E. grandis* seedling material; secondly, that gains in disease resistance may be possible through inter-specific hybridisation (e.g. the *E. grandis* × *E. camaldulensis* hybrid clone at Terranera) and possibly via hybrids of *E. longirostrata* with *E. urophylla*. Potts and Dungey (2004)

emphasise that the hybridisation of two eucalypt species does not necessarily result in the F₁ hybrid having greater disease resistance than either parent. To the contrary, the degree of resistance in the F₁ is usually intermediate to varying degrees or similar to that of the more susceptible parent.

Survival

The main factors influencing survival were sandblast during the first year after planting, and wind-throw, drought and stem diseases during subsequent years (Gardner 2001). Survival up to 10 months after planting was good, with the mean survival for Terranera and False Bay being 93% and 91% respectively (Table 4). Most species recorded 80% or greater survival at both sites, although *E. pilularis* at Terranera, and *E. urophylla* and *C. citriodora* ssp. *citriodora* at False Bay were exceptions, all recording 78% survival at the respective sites. By 48 months, species originating from humid climates, such as *E. urophylla* and *E. pilularis*, suffered increased mortality resulting from the 1992–1994 drought in the region (Darrow 1997). By rotation end, the mean survival figures for Terranera and False Bay were 87% and 81% respectively. *Eucalyptus grandis*, *E. pilularis*, *E. urophylla* and *C. citriodora* ssp. *citriodora* all recorded survival below the trial mean at both sites. *Eucalyptus pilularis* showed the poorest and second-poorest survival of all treatments at Terranera (64%) and False Bay (64%), respectively. At

Terranera the survival of *E. grandis* was satisfactory (83%), but when subjected to the more severe conditions at False Bay the species had the poorest survival (50%) of all 11 treatments. The high survival of *E. camaldulensis* and the *E. grandis* × *E. camaldulensis* commercial hybrid clone at Terranera (100% and 100% respectively) and False Bay (97% and 97% respectively) confirmed that *E. camaldulensis* is well adapted to environmental conditions in coastal Zululand (Darrow 1983; Eldridge *et al.* 1993). The results suggest that, of all alternative species tested, *C. henryi* and *E. longirostrata* (Monto) have the greatest ability to survive under the wide range of environmental conditions of the coastal Zululand commercial forestry belt.

Merchantable volume

Merchantable volume ($\text{m}^3 \text{ha}^{-1}$) as calculated here is a good indicator of the potential productivity of a species or site, as it incorporates both stocking and the volume of the tree that can be used by wood processors. The Terranera site was more productive than False Bay, producing 50% more merchantable wood volume (Table 3). The commercial hybrid clones of *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* outperformed all seedlots at either site, the latter producing the greatest merchantable volume at both Terranera and False Bay ($422 \text{ m}^3 \text{ha}^{-1}$ and $228 \text{ m}^3 \text{ha}^{-1}$, respectively).

At Terranera, the *E. grandis* control ($235 \text{ m}^3 \text{ha}^{-1}$) and the unimproved *E. longirostrata* Monto seedlot ($223 \text{ m}^3 \text{ha}^{-1}$) were

the only seedlots to produce merchantable wood volumes above the trial mean ($214 \text{ m}^3 \text{ha}^{-1}$). *Corymbia henryi* was unable to capitalise on the favourable growing conditions at this site, producing only $184 \text{ m}^3 \text{ha}^{-1}$. The *E. camaldulensis* control ($108 \text{ m}^3 \text{ha}^{-1}$) produced the lowest merchantable volume of all species at Terranera. At False Bay, *C. citriodora* ssp. *citriodora* ($187 \text{ m}^3 \text{ha}^{-1}$) and *C. henryi* ($166 \text{ m}^3 \text{ha}^{-1}$) were the only seedlots to produce merchantable volumes above the trial mean ($142 \text{ m}^3 \text{ha}^{-1}$), outperforming the *E. grandis* control ($104 \text{ m}^3 \text{ha}^{-1}$). At the same site, *C. citriodora* ssp. *citriodora* ($187 \text{ m}^3 \text{ha}^{-1}$), *C. henryi* ($166 \text{ m}^3 \text{ha}^{-1}$), *E. longirostrata* Monto ($141 \text{ m}^3 \text{ha}^{-1}$) and *E. tereticornis* ($141 \text{ m}^3 \text{ha}^{-1}$) outperformed the two control species *E. camaldulensis* ($88 \text{ m}^3 \text{ha}^{-1}$) and *E. urophylla* ($85 \text{ m}^3 \text{ha}^{-1}$). *Corymbia citriodora* ssp. *citriodora* appeared better adapted to the drier conditions at False Bay where the seedlot was the most productive of the new species, compared to being the second-lowest yielder at Terranera. In contrast, *E. pilularis* appeared better adapted to the wetter conditions at Terranera where the seedlot was third-most productive species ($206 \text{ m}^3 \text{ha}^{-1}$) compared to being lowest-yielding seedlot at False Bay ($85 \text{ m}^3 \text{ha}^{-1}$).

The results highlighted the following: first, of all 'new' species evaluated, *E. longirostrata* (Monto), *C. citriodora* ssp. *citriodora* and *C. henryi* showed the most promise for merchantable wood production on the coastal plain; secondly, although *E. longirostrata* appears better adapted to highly productive (wet) sites, the species

Table 4. Summary of the analyses of variance and data for tree survival at the end of the first and fourth growing seasons and at the end of the rotation (7 y of age) in trials at Terranera and False Bay in Zululand, South Africa

Analysis	Source of variation	df	Terranera			False Bay		
			10 months	48 months	84 months	10 months	48 months	84 months
			Mean squares					
Replicate	2		59	82	59	44	59	280
Species	10		215*	357**	332*	250*	365*	732*
Residual	20		75	59	84	95	138	196

Treatment	Treatment means (%) [‡]						
	10 months	48 months	84 months	10 months	48 months	84 months	10 months
<i>E. camaldulensis</i>	100 ^a	100 ^a	100 ^a	100 ^a	100 ^a	100 ^a	97.2 ^a
<i>E. grandis</i>	91.7 ^{ab}	91.7 ^{ab}	83.3 ^{bc}	80.6 ^{bc}	72.2 ^c	50.0 ^d	
<i>E. longirostrata</i> (Gympie)	100 ^a	100 ^a	88.9 ^{abc}	97.2 ^{ab}	97.2 ^{ab}	75.0 ^{abc}	
<i>E. longirostrata</i> (Monto)	100 ^a	100 ^a	94.4 ^{ab}	100 ^a	97.2 ^{ab}	91.7 ^{ab}	
<i>E. pilularis</i>	77.8 ^b	66.7 ^c	63.9 ^d	83.3 ^{bc}	77.8 ^b	63.9 ^c	
<i>E. tereticornis</i>	97.2 ^a	94.4 ^a	88.9 ^{abc}	97.2 ^{ab}	91.7 ^{ab}	91.7 ^a	
<i>E. urophylla</i>	86.1 ^{ab}	80.6 ^b	77.8 ^{cd}	77.8 ^c	72.2 ^c	69.4 ^{bc}	
<i>C. citriodora</i> ssp. <i>citriodora</i>	88.9 ^{ab}	88.9 ^{ab}	83.3 ^{bc}	77.8 ^c	77.8 ^b	75.0 ^{abc}	
<i>C. henryi</i>	100 ^a	97.2 ^a	91.7 ^{abc}	97.2 ^{ab}	97.2 ^{ab}	91.7 ^{ab}	
<i>E. grandis</i> × <i>E. camaldulensis</i>	100 ^a	100 ^a	100 ^a	97.2 ^{ab}	97.2 ^{ab}	97.2 ^a	
<i>E. grandis</i> × <i>E. urophylla</i>	80.6 ^b	80.6 ^b	80.6 ^{bc}	91.7 ^{abc}	91.7 ^{ab}	91.7 ^{ab}	
Mean	92.9	90.9	86.6	90.9	88.4	81.3	
sed ⁺	7.08	6.27	7.50	7.96	9.58	11.45	
Coefficient of variation (units)	9.3	8.4	10.6	10.7	13.3	17.2	

* Significant at $P < 0.05$

** Significant at $P < 0.01$

[‡] Within each column, values followed by the same letter are not significantly different ($P < 0.05$) according to Student's *t*-test

⁺ Standard error of the treatment differences

also appears to have good potential for use as a hybrid parent in inter-specific combinations with low-density phenotypes of *E. grandis* and *E. urophylla* for marginal (dry) sites; thirdly, *C. citriodora* ssp. *citriodora* (Expedition Range), unlike its close relative *C. henryi* (Grafton), appears better adapted to marginal rather than highly productive growing conditions in Zululand. In the case of *C. henryi*, lack of drought tolerance may not be provenance-specific, as in a later (1996-established) trial series in a hotter and drier sector of Zululand, the *C. henryi* Myrtle Creek provenance showed only moderate drought-tolerance and was outperformed by both the Monto and Chinchilla provenances of *E. longirostrata* on the basis of survival and growth (Gardner 2004, 2006).

Wood and pulping properties

Site appeared to substantially influence wood and pulping properties, with species and clones showing lower wood densities and higher pulp yields at the wet site, Terranera, than at the far drier site, False Bay (Table 5). Similar effects of site on pulping properties have been observed for *E. grandis* and *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* clones grown in Zululand (Retief *et al.* 1997; Stanger 2004).

Species ranks for basic wood density were rather consistent between sites. Although basic wood density in *E. longirostrata* appeared strongly influenced by provenance, in general, *C. citriodora* ssp. *citriodora*, *C. henryi* and *E. longirostrata* were consistently at the upper end of the basic density range, whereas the *E. grandis* × *E. urophylla* clone and the *E. tereticornis* seedlot were consistently at the lower end of the range for either site (Table 5).

The Mondi Business Paper mill where the wood samples were processed requires a SPY of $\geq 51.5\%$, a kappa number of ≤ 22 , and a pulpability factor of ≥ 2.34 (the latter factor is derived by dividing SPY by kappa number, giving a good indication of pulpwood quality without having to do multiple cooks and interpolate to the desired kappa number of 20). Ideal basic wood density for local kraft pulping is 480–520 kg m⁻³, while a higher density of 520–650 kg m⁻³ is preferred for woodchips exported for kraft pulping.

At Terranera, only the *E. grandis* × *camaldulensis* clone (500 kg m⁻³) fell within the ideal 'basic wood density' range for local kraft pulping. The densities of *E. pilularis* (476 kg m⁻³) and *E. grandis* × *E. urophylla* clone (411 kg m⁻³) were both lower than the ideal range, whilst those of *E. longirostrata* Monto (574 kg m⁻³), *E. longirostrata* Gympie (637 kg m⁻³), *C. henryi* (581 kg m⁻³) and *C. citriodora* ssp. *citriodora* (637 kg m⁻³) were above the optimum range. The latter four taxa had basic densities within the ideal range for woodchip exports.

At False Bay, only the *E. grandis* × *urophylla* clone (502 kg m⁻³) fell within the optimum basic density range for local kraft pulping. *Eucalyptus longirostrata* Monto (632 kg m⁻³), *E. tereticornis* (549 kg m⁻³) and the *E. grandis* × *camaldulensis* clone (596 kg m⁻³) were within the optimum density range for export woodchips.

Although high-density wood offers some important advantages over low-density wood, such as improved digester productivity, paper quality can be negatively affected when wood density becomes excessive (Downes *et al.* 1997). The basic densities of the three promising 'new' species, *E. longirostrata*, *C. henryi*

Table 5. Summary of the kraft pulping results for selected eucalypt species and hybrid clones at 7 y of age in trials at Terranera and False Bay in Zululand, South Africa

Location and treatment	Basic density (kg m ⁻³ wood)	Screened pulp yield (SPY) (%)	Kappa no.	Pulpability factor (SPY kappa ⁻¹)	Specific consumption (m ³ wood t pulp ⁻¹)
Terranera					
<i>E. longirostrata</i> (Gympie)	637	51.0	24.0	2.12	3.08
<i>E. longirostrata</i> (Monto)	574	52.9	21.4	2.47	3.29
<i>E. pilularis</i> ‡	476	52.0	20.8	2.50	4.04
<i>E. tereticornis</i>	465	50.3	24.5	2.06	4.28
<i>C. citriodora</i> ssp. <i>citriodora</i>	637	54.3	29.4	1.85	2.89
<i>C. henryi</i>	581	55.9	19.5	2.87	3.08
<i>E. grandis</i> × <i>E. camaldulensis</i>	500	51.4	22.5	2.29	3.89
<i>E. grandis</i> × <i>E. urophylla</i>	411	53.0	21.3	2.49	4.59
False Bay					
<i>E. longirostrata</i> (Gympie)	667	47.2	32.5	1.45	3.18
<i>E. longirostrata</i> (Monto)	632	48.2	31.3	1.54	3.28
<i>E. tereticornis</i>	549	47.3	34.6	1.37	3.85
<i>C. citriodora</i> ssp. <i>citriodora</i>	672	53.3	21.1	2.52	2.79
<i>C. henryi</i>	658	53.5	22.4	2.39	2.84
<i>E. grandis</i> × <i>E. camaldulensis</i>	596	49.7	28.7	1.73	3.38
<i>E. grandis</i> × <i>E. urophylla</i>	502	45.2	38.3	1.18	4.41

‡ *E. pilularis* was sampled at Terranera only

and *C. citriodora* ssp. *citriodora*, were all above the local ideal range for kraft pulping at both trial sites. Wood density is a highly heritable trait in *Eucalyptus* (Malan 1988; Eldridge *et al.* 1993). Therefore density in any of the aforementioned species should be amenable to change, if required, through breeding including hybridisation (Verryn 2000).

In the case of *E. longirostrata*, local experience has shown that the species easily hybridises (controlled crosses) with low-density species such as *E. grandis* or *E. urophylla* (S. Verryn, CSIR, pers. comm. 2005). Therefore, in addition to within-species selection, inter-specific hybridisation would probably be useful for lowering wood density in *E. longirostrata* should this be required. In the case of *C. henryi* or *C. citriodora* ssp. *citriodora*, neither species is known to hybridise with others outside the genus *Corymbia* (Hill and Johnson 1995); breeding for wood properties, and indeed other traits, would probably be on an intra-generic basis. Successful controlled crossing of species within the *Corymbia* such as *C. citriodora* ssp. *citriodora*, *C. citriodora* ssp. *variegata* and *C. torelliana*, with the aim of improving a range of traits such growth rate; disease, frost and drought resistance; and root-strike in cuttings, has been reported by Lee *et al.* (2005a,b).

On the basis of 'SPY', at Terranera *C. henryi* (55.9%), *C. citriodora* ssp. *citriodora* (54.3%), *E. longirostrata* (Monto) (52.9%), *E. pilularis* (52.0%) and the *E. grandis* × *E. urophylla* commercial hybrid clone were within the required range of $\geq 51.5\%$. At the same site, *E. tereticornis* produced the lowest SPY of all species and clones (50.3%). At False Bay, only *C. henryi* (53.5%) and *C. citriodora* ssp. *citriodora* (53.3%) fell within the desired range, with the commercial *E. grandis* × *E. urophylla* clone producing the lowest SPY of all species and clones (45.2%). Because the Terranera and False Bay sites represent the two extremes of growing conditions in coastal Zululand, and *C. henryi* and *C. citriodora* ssp. *citriodora* performed well at both sites on the basis of SPY, the two species appear to be the best adapted of all species evaluated to the range of forestry environmental conditions in the region. The same flexibility is unlikely in the case of *E. pilularis* — pulp-tested at Terranera only (SPY 52.0%) — as the species showed a high level of drought-sensitivity and poor survival and growth at False Bay (Gardner 2001). Regarding the commercial clones, at Terranera both the *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* clone were within the required SPY range (51.4 and 53.0% respectively), whilst at False Bay neither performed adequately (49.7 and 45.2% respectively). The reversal of ranking in SPY between the *E. grandis* × *E. camaldulensis* and *E. grandis* × *E. urophylla* commercial hybrid clones at the two different sites (Table 5) suggests specificity of site requirement of either clone. In the case of the *E. grandis* × *E. urophylla* clone, the apparent lack of flexibility of the clone was further supported by the fact that it was top-ranking treatment for merchantable wood volume at both Terranera and False Bay (Table 3), yet at False Bay the SPY and other pulping properties of the clone were markedly inferior to those of all other species and clones tested.

On the basis of 'pulpability factor', at the wet site Terranera, *C. henryi* (2.87), *E. pilularis* (2.50), *E. longirostrata* (Monto) (2.47) and the *E. grandis* × *E. urophylla* commercial clone (2.49)

were within the required range of ≥ 2.34 . At the dry False Bay site, only *C. citriodora* ssp. *citriodora* (2.52) and *C. henryi* (2.39) fell within the required range. *Corymbia henryi*, therefore, was the only species or clone to perform consistently well across sites on the basis of 'pulpability'.

'Specific consumption', the volume of wood (in cubic metres) required to produce one tonne of pulp, has important economic implications for both pulp-processing and woodchip exporting industries. In the case of the former, low specific consumption increases digester productivity, whilst in the latter, low specific consumption reduces shipping costs. At Terranera, *C. citriodora* ssp. *citriodora* (2.89 m³ t⁻¹), followed by *E. longirostrata* (Gympie) (3.08 m³ t⁻¹), *C. henryi* (3.08 m³ t⁻¹) and *E. longirostrata* (Monto) (3.39 m³ t⁻¹) provided the greatest yields (Table 5). The *E. grandis* × *E. urophylla* commercial clone provided the lowest yield at 4.59 m³ t⁻¹. At False Bay, *C. citriodora* ssp. *citriodora* (2.79 m³ t⁻¹) was again best performer, followed by *C. henryi* (2.84 m³ t⁻¹), *E. longirostrata* (Gympie) (3.18 m³ t⁻¹) and *E. longirostrata* (Monto) (3.28 m³ t⁻¹). The *E. grandis* × *E. urophylla* commercial clone (4.41 m³ t⁻¹) provided the lowest yield of all species and clones at this site.

On the basis of specific consumption across both sites, *C. citriodora* ssp. *citriodora*, *C. henryi* and *E. longirostrata* could be rated highly when compared to the two commercial controls, the *E. grandis* × *E. urophylla* and *E. grandis* × *E. camaldulensis* clones.

Fibre productivity

On the basis of fibre productivity (tonnes screened pulp per hectare) (Table 6), at Terranera *E. longirostrata* (Monto) (65.0 t ha⁻¹) was the highest-yielding unimproved species (followed by *C. henryi* at 57.8 t ha⁻¹), significantly outperforming the two lowest-yielding species *E. tereticornis* (39.1 t ha⁻¹) and *C. citriodora* ssp. *citriodora* (37.1 t ha⁻¹). The *E. grandis* × *E. urophylla* commercial clone was the most productive treatment at this site at 88.8 t ha⁻¹, significantly outperforming all other species and clones except for the *E. grandis* × *E. camaldulensis* commercial clone (80.2 t ha⁻¹). At False Bay, the unimproved *C. citriodora* ssp. *citriodora* seedlot was the most productive treatment at 65.3 t ha⁻¹, significantly outperforming all other species and clones except for the *E. grandis* × *E. camaldulensis* commercial hybrid clone (59.9 t ha⁻¹) and *C. henryi* (56.5 t ha⁻¹).

The results for fibre productivity demonstrated three important points regarding the potential of the 'new' species for coastal Zululand. First, because *C. henryi* ranked highly at both sites investigated, the species appears to have a high fibre production potential for the range of sites encountered in coastal Zululand. Secondly, *C. henryi*'s close relative *C. citriodora* ssp. *citriodora* appears highly site specific. At the dry False Bay site, this taxon excelled on the basis of fibre productivity, whereas at the significantly wetter Terranera site it was the poorest of all treatments. Thirdly, *E. longirostrata* (Monto) appears to have the greatest fibre productivity potential of all promising 'new' species for high-rainfall (traditionally highly productive) sites on the Zululand coastal plain.

Table 6. Summary of the analyses of variance and data for wood yield and fibre production of selected eucalypt species and clones in trials at 7 y of age at Terranera and False Bay in Zululand, South Africa

	Location		Wood yield (t ha ⁻¹)		Fibre production (t ha ⁻¹)	
	Terranera	False Bay	Terranera	False Bay	Terranera	False Bay
Analysis						
Source of variation	df		Mean squares			
Replicate	2	2	236	408	61	100
Treatment	7	6	3724**	1184*	1024**	429**
Residual	14	12	486	289	140	74
Summary of data						
Treatment	Treatment means ‡					
<i>E. longirostrata</i> (Gympie)			104	79	53 ^{cd}	37 ^c
<i>E. longirostrata</i> (Monto)			123	84	65 ^{bc}	40 ^c
<i>E. pilularis</i>			94	—	49 ^{cd}	—
<i>E. tereticornis</i>			78	73	39 ^d	35 ^c
<i>C. citriodora</i> ssp. <i>citriodora</i>			68	123	37 ^d	65 ^a
<i>C. henryi</i>			103	106	58 ^{cd}	56 ^{ab}
<i>E. grandis</i> × <i>E. camaldulensis</i>			156	120	80 ^{ab}	60 ^{ab}
<i>E. grandis</i> × <i>E. urophylla</i>			168	104	89 ^a	47 ^{bc}
Mean			112	98	59	49
sed [†]			18	14	10	7
Coefficient of variation (units)			20	17	20	18

* Significant at $P < 0.05$ ** Significant at $P < 0.01$ ‡ Within each column, values followed by the same letter are not significantly different ($P < 0.05$) according to Student's t -test

† Standard error of the treatment differences

Conclusion

Eucalyptus longirostrata, *C. henryi* and *C. citriodora* ssp. *citriodora* have excellent potential for commercial forestry on the Zululand coastal plain.

For merchantable wood production, *E. longirostrata* (Monto) showed excellent potential for high productivity (wet) sites and *C. citriodora* ssp. *citriodora* and *C. henryi* similar potential for marginal (moderately dry) sites on the coastal plain. The saw-timber properties of locally-grown *E. longirostrata* have yet to be accurately determined. If these properties are similar to those of the closely-related *E. punctata* and *E. propinqua*, it is likely that timber of the former species will be suitable only for heavy construction, building and treated poles, and not for high quality end-products (Poynton 1979; Brown and Hillis 1984). The results of the Zululand trials tend to confirm earlier reports that timber of *E. longirostrata*, *C. citriodora* ssp. *citriodora* and *C. henryi* is of moderate to high basic density (Poynton 1979; FAO 1980a,b; Lee *et al.* 2006). The excellent saw-timber properties of 'forest tree' species within the *Corymbia*, such as *C. citriodora* ssp. *citriodora*, *C. maculata* and *C. henryi* are well documented (Poynton 1979; Brown and Hillis 1984; Dickinson *et al.* 2004). Because of their relatively high merchantable timber yields at False Bay, *C. citriodora* ssp. *citriodora* and *C. henryi* appear to have good potential for saw-timber production on moderately dry sites in Zululand. Due to the relatively good performance of *E. pilularis* at Terranera, coupled with the species' worldwide reputation for high quality saw-timber production (Poynton 1979; Brown and Hillis 1984), *E. pilularis* should not be discounted as

a potential saw-timber species for high productivity sites in coastal Zululand.

On the basis of fibre production, *E. longirostrata* (Monto) and *C. henryi* showed excellent potential for high productivity sites on the coastal plain, whilst *C. citriodora* ssp. *citriodora* and *C. henryi* showed similar potential for marginal (moderately dry) sites in the same region.

In the site × species interaction trials discussed, the unimproved species were represented by single-provenance bulked-family seedlots that provided narrow samples of the genetic resources of the species (Table 2). Other provenances of the same taxa may perform differently on similar sites. The most reliable inference which can be made from the site × species trial results is that species that performed well warrant further, detailed investigation. Because of the overall promising performances of *E. longirostrata* and *C. henryi* in past and present ICFR site × species trials on the Zululand coastal plain, the ICFR established provenance/progeny trials and breeding seed orchards of these species in the region during 2001. The trials and seed orchards are being managed for rapid first-generation turnover and incorporation of the improved genetic material into commercial eucalypt breeding programmes in the region. Based on recent overseas experience, it would be prudent for South African breeders, at this stage, to consider the establishment of a local base breeding population of *C. torelliana*, for ultimate use in inter-specific hybrid combination with other species within the *Corymbia* such as *C. henryi*. In Australia, levels of resistance to quambalaria shoot blight (*Quambalaria pitereka*) (Simpson 2000)

and percentage root-strike in stem cuttings in *C. citriodora* ssp. *citriodora* and *C. henryi* have been increased substantially via inter-specific hybridisation with *C. torelliana* (Lee *et al.* 2005a), a species possessing far greater *Quambalaria* resistance and rooting potential than the former two (Dickinson *et al.* 2004; Lee *et al.* 2005b). Currently, *Quambalaria pitereka* is not problematic to eucalypt plantation forestry in South Africa, although recent cases of damage to *E. grandis* nursery cuttings and field-grown *E. nitens* seedlings by *Quambalaria eucalypti* have been reported in the same country (FABI 2005).

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References

- Brown, A.G. and Hillis, W.E. (1984) General introduction. In: Hillis, W.E. and Brown, A.G. (eds) *Eucalypts for Wood Production*. Academic Press, Sydney, pp. 2–5.
- Brown, A.G., Nambiar, E.K.S. and Cossalter, C. (1997) Plantations for the tropics: their role, extent and nature. In: Nambiar, E.K.S. and Brown, A.G. (eds) *Management of Soil, Nutrients and Water in Tropical Plantation Forests*. ACIAR, Canberra, pp. 1–23.
- Chippendale, G.M. (1988) *Eucalyptus*. In: George, A.S. (ed.) *Flora of Australia*, vol. 19, AGPS, Canberra, pp. 495–509.
- Darrow, W.K. (1983) Provenance-type trials of *Eucalyptus camaldulensis* and *E. tereticornis* in South Africa and South-West Africa: Eight-year results. *South African Forestry Journal* **124**, 13–22.
- Darrow, W.K. (1997) *Eucalypt Site-Species Trials in Zululand: Results at Four Years of Age*. Institute for Commercial Forestry Research, ICFR Bulletin Series No. 3/1997, Pietermaritzburg, 26 pp.
- Denison, N.P. and Kietzka, J.A. (1993a) The use and importance of hybrid intensive forestry in South Africa. *South African Forestry Journal* **165**, 55–60.
- Denison, N.P. and Kietzka, J.A. (1993b) The development and utilisation of vegetative propagation in Mondi for commercial afforestation programmes. *South African Forestry Journal* **166**, 53–60.
- Dickinson, G.R., Lee, D.J. and Huth, J.R. (2004) Early plantation growth and tolerance to ramularia shoot blight of provenances of three spotted gum taxa on a range of sites in Queensland. *Australian Forestry* **67**, 122–130.
- Downes, G.M., Hudson, I.L., Raymond, C.A., Dean, G.H., Michell, A.J., Schimleck, L.R., Evans, R. and Muneri, A. (1997) *Sampling Plantation Eucalypts for Wood and Fibre Properties*. CSIRO Publishing, Collingwood, Australia, pp. 2–5.
- Duncan, E.A., van Deventer, F., Kietzka, J.E., Lindley, R.C. and Denison, N.P. (2000) The applied subtropical *Eucalyptus* clonal programme in Mondi forests, Zululand coastal region. In: MacLennan, L.A. (ed.) *Forest Genetics for the Next Millennium*. Proceedings of the IUFRO Symposium, 8–13 October 2000, Durban. ICFR, Pietermaritzburg, South Africa, pp. 95–97.
- Dunne, N. (2000). International trends in the timber furniture industry and the implications for South African furniture exporters. CSDS Working Paper No. 25. University of Natal, Durban, pp. 14–24.
- Du Toit, B., Arbuthnot, A., Ocroft, D. and Job, A. (2001) The effects of remedial fertilizer treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand coastal plain. *Southern African Forestry Journal* **192**, 9–18.
- DWAF (2005) *Report on Commercial Timber Resources and Primary Roundwood Processing in South Africa 2003/2004*. Department of Water Affairs and Forestry (DWAF), Pretoria, 239 pp.
- Eldridge, K., Davidson, J., Harwood, C.E. and Van Wyk, G. (1993) *Eucalypt Domestication and Breeding*. Clarendon Press, Oxford, 288 pp.
- FABI (2005) *FABI Fourth Biennial Report*. Forestry and Agricultural Biotechnology Institute, Pretoria, pp. 3–8.
- FAO (1980a) *Pulping and Papermaking Characteristics of Fast-Growing Plantation Wood Species*. Vol. 1. Food and Agriculture Organization of the United Nations, FAO Forestry Paper Series No. 19/1, Rome, 396 pp.
- FAO (1980b) *Pulping and Papermaking Characteristics of Fast-Growing Plantation Wood Species*. Vol. 2. Food and Agriculture Organization of the United Nations, FAO Forestry Paper Series No. 19/2, Rome, 472 pp.
- FAO (2005) *FAOSTAT Database Collections*. <http://faostat.fao.org/>. Last accessed February 2005.
- FAO–UNESCO (1974) *Soil Map of the World*. Vol. 1. UNESCO, Paris.
- Flynn, R. (2003) *Eucalyptus: Having an Impact on the Global Solidwood Industry*. Wood Resources International, Washington, USA. <http://www.wri-ltd.com/marketcommentary.html>.
- Gardner, R.A.W. (2000) *Report on 1997 ICFR/CSIRO Collaborative Seed Collection Trip in Northern New South Wales, Australia, and Subsequent Deployment of the Seedlots in South Africa*. Institute for Commercial Forestry Research, ICFR Bulletin Series No. 15/2000, Pietermaritzburg, 30 pp.
- Gardner, R.A.W. (2001) Alternative eucalypt species for Zululand: Seven year results from site:species interaction trials in the region. *Southern African Forestry Journal* **190**, 79–88.
- Gardner, R.A.W. (2004) Selection of *Eucalyptus* species and provenances for hot, dry conditions in northern, coastal Zululand in South Africa. In: Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M. and Tome, M. (eds) *Eucalyptus in a Changing World*. Proceedings of IUFRO Conference, 11–15 October, Aveiro, Portugal, RAIZ, Aveiro, Portugal, pp. 171–172.
- Gardner, R.A.W. (2006) Investigating drought tolerant eucalypt species and provenances for northern, coastal Zululand. In: Bender, C.M. (ed.) *6th Plant Breeding Symposium of the Southern African Plant Breeders Association*. Proceedings of SAPBA Symposium, 13–15 March, Langebaan. SAPBA, Bloemfontein, South Africa, p. 43.
- Gomez, K.A. and Gomez, A.A. (1984) *Statistical Procedures for Agricultural Research*. John Wiley and Sons, New York, 680 pp.
- Gryzenhout, M., Myburg, H., Van der Merwe, N.A., Wingfield, B.D. and Wingfield, M.J. (2004) *Chrysoporthe*, a new genus to accommodate *Cryphonectria cubensis*. *Studies in Mycology* **50**, 119–142.
- Harrison, E.R. (1993) *The Saligna Story*. Kingspress, Empangeni, South Africa, 31 pp.
- Herbert, M.A. and Musto, J.W. (1993) *The Sandy Forestry Soils on the Zululand Coastal Plain*. Institute for Commercial Forestry Research, ICFR Bulletin Series No. 12/1993, Pietermaritzburg, 11 pp.

- Herbert, M.A. and Robertson, M.A. (1991). Above-ground biomass composition and nutrient content for *Eucalyptus* species in the southeastern Transvaal. In: Schönau, A.P.G. (ed.) *Intensive Forestry: The role of Eucalypts*. Proceedings of the IUFRO Conference, 2–6 September, Durban. SAIF, Pretoria, South Africa, pp. 662–674.
- Hill, K.D. and Johnson, L.A.S. (1995) Systematic studies in the eucalypts.7. A revision of the bloodwoods, genus *Corymbia* (Myrtaceae) *Telopea* **6**, 185–504.
- Kimmins, J.P. (1994) Identifying key processes affecting long-term site productivity. In: Dyck, W.J., Cole, D.W. and Comerford, N.B. (eds) *Impacts of Forest Harvesting on Long-Term Site Productivity*. Chapman and Hall, London, pp. 119–150.
- Lane, P.W. and Payne, R.W. (1996) *Genstat® for Windows™, An Introductory Course*. 2nd edn. Lawes Agricultural Trust, Rothamsted Experimental Station.
- Lee, D.J., Nikles, D.G., Pomroy, P.C., Brawner, J., Wallace H. and Stokoe, R. (2005a) *Corymbia* species and hybrids: a solution to Queensland hardwood plantations? In: Lee, D.J. (ed.) *Corymbia Research Meeting: Underpinning Development of a Profitable Hardwood Plantation Industry in Northern Australia by Research into Corymbia Species and Hybrids*. Proceedings of the Inaugural Meeting of *Corymbia* Researchers and the Plantation Industry, 1–2 June, Gympie. Department of Primary Industries and Fisheries, Brisbane, Australia, pp. 5–7.
- Lee, D.J., DeBuse, V.J., Pomroy, P.C., Robson, K.J. and Nikles, D.G. (2005b) *Developing Genetically Adapted Tree Varieties for Marginal Areas of Northern Australia*. Rural Industries Research and Development Corporation Publication No. 04/186. Kingston, ACT, Australia, pp. 9–53.
- Lee, D.J., Lawson, S., Armstrong, M. and Dickinson, G.R. (2006) *Hardwoods Advice: Plantation Species Profiles: Spotted Gums*. Department of Primary Industries and Fisheries, Queensland Government, Australia.
http://www2.dpi.qld.gov.au/hardwoods_qld/10142.html.
- Little, K.M., Schumann, A.W. and Noble, A.D. (2002) Performance of a *Eucalyptus grandis* × *E. camaldulensis* hybrid clone as influenced by a cowpea cover-crop. *Forest Ecology and Management* **168**, 43–52.
- Malan, F.S. (1988) Genetic variation in some growth and wood properties among 18 full-sib families of South African grown *Eucalyptus grandis*: a preliminary investigation. *South African Forestry Journal* **146**, 38–43.
- McDonald, M.W. and Bean, A.R. (2000) A new combination in *Corymbia* 'section Politaria': *C. citriodora* ssp. *variegata* (Myrtaceae). *Austrobaileya* **5**, 735–736.
- Miranda, I. and Pereria, H. (2002) Variation of pulpwood quality with provenances and site in *Eucalyptus globulus*. *Annals of Forest Science* **59**, 283–291.
- Nicol, N. (1992) *Plantation Pathology: Notes for Identification of Common Pathological Problems in South African Forestry*. Institute for Commercial Forestry Research, ICFR Bulletin Series No. 23/1992, Pietermaritzburg, 15 pp.
- Pierce, B.T. and Verry, S.D. (2000) Five year results from a site by clone interaction series of *Eucalyptus grandis* in the summer rainfall areas of South Africa. In: MacLennan, L.A. (ed.) *Forest Genetics for the Next Millennium*. Proceedings of the IUFRO Conference, 8–13 October, Durban. ICFR, Pietermaritzburg, South Africa, pp. 186–191.
- Potts, B.M. and Dungey, H.S. (2004) Interspecific hybridisation of *Eucalyptus*: key issues for breeders and geneticists. *New Forests* **27**, 115–138.
- Poynton, R.J. (1979) *Tree Planting in Southern Africa. Vol. 2. The Eucalypts*. DEA, Government Printer, Pretoria, 882 pp.
- Retief, R.J., Male, J.R., Malan, F.S., Dyer, S.T., Conradie, D., Turner, P., Havenga, A. and Gama, D. (1997) *First Report on the Effect of Site Quality on the Wood and Pulp Properties of Eucalyptus grandis Clonal Material*. ENV/PI 97045. Division of Water, Environment and Forestry Technology, CSIR, Pretoria, 11 pp.
- Schulze, R.E. (1997) *South African Atlas of Agrohydrology and Climatology*. Report TT 82/96. Water Research Commission, Pretoria, South Africa, 276 pp.
- Schumacher, F.X. and Hall, F.D.S. (1933) Logarithmic expression of timber-tree volume. *Journal of Agricultural Research* **47**, 719–734.
- Simpson, J.A. (2000) *Quambalaria*, a new genus of eucalypt pathogens. *Australasian Mycologist* **19**(2), 57–62.
- Smith, C.W., Little, K.M. and Norris, C.H. (2001) The effect of land preparation at re-establishment on the productivity of fast growing hardwoods in South Africa. *Australian Forestry* **64**, 165–174.
- Snedecor, G.W. and Cochran, W.G. (1980) *Statistical Methods*. 7th edn. The Iowa State College Press, Iowa, 507 pp.
- Stanger, T. (2004) Evaluation of the dissolving pulp properties of fifteen sub tropical hybrid *Eucalyptus* clones. In: Borralho, N.M.G., Pereira, J.S., Marques, C., Coutinho, J., Madeira, M. and Tome, M. (eds) *Eucalyptus in a Changing World*. Proceedings of the IUFRO Conference, 11–15 October, Aveiro. RAIZ, Aveiro, Portugal, pp. 705–706.
- Steel, R.G.D. and Torrie, J.H. (1981) *Principles and Procedures of Statistics: A Biometrical Approach*. 2nd edn. McGraw-Hill International Book Company, Singapore, 633 pp.
- Verry, S.D. (2000) Eucalypt hybrid breeding in South Africa. In: Dungey, H.S., Dieters, M.J. and Nickles, D.G. (eds) *Hybrid Breeding and Genetics of Forest Trees*. Proceedings of the QFRI CRC – SPF Symposium, 9–14 April, Noosa, Queensland. Brisbane. Department of Primary Industries, Queensland, pp. 435–439.
- Zobel, B. and Talbert, J. (1984) *Applied Forest Tree Improvement*. John Wiley & Sons, Inc., USA, 505 pp.