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Survival and long-term growth of eucalypts on semi-arid sites in a Mediterranean climate, South Africa

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Four experiments were established on the semi-arid west coast plain of South Africa during the 1990s. The trails tested the survival and growth of several eucalypt species and hybrids, some of which were established in a climate that is drier than their natural distribution range. The aridity indices (AI; defined as mean annual precipitation [MAP]/mean annual potential evapotranspiration) ranged from 0.21 to 0.36 and MAP from 228 to 423 mm. The driest trial site (AI = 0.21 and MAP = 228) had high levels of mortality. However, a number of species (in particular, *Eucalyptus gomphocephala*, *E. camaldulensis* and *E. tereticornis*, as well as individual hybrids of the latter two species with *E. grandis*) survived and grew well at the remaining sites. *Eucalyptus cladocalyx* survived well and attained competitive growth rates only on the wettest site in the group (AI = 0.36). The dominant height of the top-performing genotypes at age 5 ranged between 9 and 10 m on the two wetter sites. This corresponded to mean annual increment values in excess of 10 m^3 ha^{-1} a^{-1}, which is comparable to volume obtained at more favourable aridity indices in the summer rainfall zone of South Africa and exceeds the growth rates obtained in several other arid zone studies globally. The *E. grandis* × *E. camaldulensis* hybrid ranked among the top performers in two trials, but its susceptibility to recently introduced pests and relatively poor wood quality makes it a less attractive choice for planting. The high density and durability of timber, acceptable growth rate (given the low rainfall conditions), and low pest and disease incidence make *E. gomphocephala* and *E. cladocalyx* the species of choice for planting in the drier and relatively wetter sections of the semi-arid zone, respectively.

Keywords: agroforestry, dryland forestry, *Eucalyptus*, Western Cape coastal plain

Introduction

South Africa is a country that relies on plantation forestry for the sustainable supply of timber to several downstream industries: construction and building, pulp and paper, furniture, pole treatment plants and composite board manufacturing. Planted forests also make substantial contributions to timber used on farms, for example utility timber, fencing, and biomass for firewood and energy. With only 0.5% of the country's surface area being covered in closed-canopy indigenous forests, coupled with limited utilisation potential due to the moderately slow growth rates of even the faster-growing indigenous species in southern Africa (de Cauwer et al. 2017; Gush 2017), the government decided to start a plantation forestry industry at the end of the eighteenth century. The forest industry grew rapidly up to a point where some excess logs were exported by the end of the nineteenth century. The oversupply situation was, however, short lived and already by 2005 an increasing shortage of timber was predicted for the future (DWAF 2005). This shortage of timber became more of a concern in the Western Cape after the announcement by government that the forestry industry in the province will be reduced substantially by means of an exit strategy over a period extending up until 2020, whereby traditional plantation areas would be suspended from production in favour of conservation land uses (VECON 2006). There is currently a drive to find alternative, renewable energy sources to reduce South Africa's reliance on fossil fuel burning for energy (DME 2003). In addition, the Working for Water Programme (Binns et al. 2001) is busy eradicating large areas of invasive trees (mainly Australian acacias), a resource that has been extensively used as firewood in peri-urban areas of the Western Cape province (du Toit et al. 2010a). There is thus also a newly developing need for an alternative (non-invasive) form of woody biomass in the province, for use in peri-urban areas (du Toit et al. 2010a). The reduction in suitable forestry land has resulted in the need to explore the potential to establish plantations or woodlots on non-traditional forestry sites, to meet future woody biomass needs (Seifert et al. 2016; Gush 2017). An initiative to investigate the feasibility of potential afforestation of low rainfall areas (<450 mm) along the West Coast region of the Western Cape was started in the early 1990s (van Wyk et al. 2001). The project was dubbed DIRAP

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(Dryland Industrial and Rural Afforestation Programme), and its original objectives were:

(1) the selection of appropriate tree species and provenances that have potential for afforestation on low rainfall sites with sandy soils
(2) the reproduction of selected material through vegetative propagation
(3) determining the most appropriate establishment and silvicultural strategies
(4) developing an efficient, less intensive management system to meet various community forestry objectives.

Pinus species are generally not recommended in South Africa in areas with a rainfall of less than about 600–650 mm a^{-1} and the only pine species that could be considered for woodlots in the semi-arid climate region is *Pinus halepensis*, with a minimum rainfall requirement in its native habitat of 380 mm a^{-1} (Poynton 1979a). *Eucalyptus* is a more versatile genus in terms of the minimum requirement for annual rainfall and on that basis a number of *Eucalyptus* species, provenances and interspecific hybrids, all previously untested under the West Coast climatic conditions, were selected for investigation to meet the objectives of the dryland industrial and rural afforestation project. Another factor in favour of eucalypts is the ability to coppice (Little and du Toit 2003; Little and Gardner 2003), their superior biomass growth (Phiri et al. 2015) and the fact that several drought-tolerant eucalypt species have wood properties that lend themselves to a variety of uses (Wessels et al. 2016; Lundqvist et al. 2017). Eucalypts in the Western Cape can potentially be grown and utilised for bioenergy crops, poles, decking, general utility timber on farms or even sawn timber (van Wyk et al. 2001; Botman 2010; du Toit et al. 2010a; Phiri et al. 2015; Wessels et al. 2016; Lundqvist et al. 2017). In addition, eucalypts provide shelter to livestock, can act as windbreaks, limit soil salinity problems in denuded bottomlands, sequester carbon, and make a vital contribution to honey bee forage and pollination services (van Wyk et al. 2001; de Lange et al. 2013; Harper et al. 2017).

We used long-term mean annual precipitation (MAP; 1950–1999) as well as aridity indices (AI) to characterise the climatic gradient (1) on which our trials have been established and (2) to categorise trials reported in the literature, where possible. AI is defined as MAP/ET_p, where ET_p = mean annual potential evapotranspiration determined by the Penman–Monteith method (Allen et al. 1998). Site–species matching studies for *Eucalyptus* in dry areas in South Africa are limited. However, two trial series that fall mainly into the dry subhumid and the top end of the semi-arid range of coastal Zululand ($0.35 < AI < 0.65$) deserve mention. The first series (Gardner et al. 2001) showed that *E. longirostrata*, *E. tereticornis*, *Corymbia henryi* and *C. citriodora* were viable alternatives to *E. grandis* hybrid clones in dry zones, being superior in terms of survival, disease resistance, growth rate and pulpwood quality on the hottest, driest trial site in the series (MAP = 756 mm; AI = 0.55). The second trial series, designed to test a number of alternative *Eucalyptus* species for drought and disease resistance, included a location near Mkuze on the northern coastal plains of Zululand with a MAP of 676 mm and an AI of 0.48, where *E. longirostrata*, *C. henryi*, *C. citriodora* and *E. agrophloia* were the top performers (Gardner et al. 2009).

However, there are few long-term growth results emanating from formal experiments for the tribe Eucalypteae in semi-arid zones of the country, which is the motivation to publish this paper. For reliable growth predictions of new taxa, it is essential that growth data should be obtained from suitably designed and managed trial sites, because stand productivity can be greatly improved with early, intensive silvicultural practices and stand nutrition, especially in poor, sandy soils (du Toit et al. 2001, 2010b; Gonçalves et al. 2017), which is common in our study area in the Cape West Coast.

The main objectives of this paper were thus to (1) identify the species, provenances or interspecific hybrids that are best suited for planting in the currently prevailing climatic conditions of the semi-arid Cape West Coast, (2) to ascertain which species would be most tolerant in a changed climate with even lower water availability, and (3) to make recommendations for future tree improvement and hybridisation projects, as well as silvicultural experiments.

Material and methods

Location and climate of trial sites

The four trials reported on in this paper were established during 1991 and 1996, respectively as part of two research projects. The individual trials were originally planted as provenance trials, site–species matching trials or demonstration plots, which means trial design and layout were not uniform throughout. However, by viewing all the results together, a comprehensive picture of species/hybrid growth and survival can be formed for the drier range of the semi-arid climate zone on the Cape West Coast. The locations of the trial sites are shown in Figure 1, against a backdrop of the AI. The names of the AI classes (e.g. arid, semi-arid and subhumid) are aligned to international norms. However, the semi-arid class (which has a wide range) was split into relatively wetter (Semi-arid +) and relatively drier (Semi-arid −) subclasses for greater precision (Figure 1). We also give the duration of the moisture growing season (MGS) on each trial site according to the FAO (1978) definition, as modified by Schulze (1997), namely the number of Julian days when long-term mean precipitation > (0.3 × mean potential evapotranspiration). A summary of the climate and basic trial information is presented in Table 1, where trials are ranked in order from the highest to the lowest AI and MAP (SAWS 2013).

Site description, trial design and treatments

The MAP of the four experimental sites varies from 228 to 423 mm. The mean annual temperature of this area ranges between approximately 16.4 and 17.6 °C. The summers are characterised by windy and dry conditions with high maximum daily temperatures. February is the hottest month with an average maximum daily temperature of 34 °C (ARC 2013). Figure 2 shows monthly climate patterns for the wettest and driest sites, respectively.

The terrain on all four sites is fairly flat (old sand dunes) with <2% slope in all cases. The natural vegetation in the region is classified as West Coast Renosterveld (Mucina and

Rutherford 2006). The trial sites (especially Pampoenvlei and Flaminkvlei) are often subjected to cool mist events due to the proximity to the ocean. Vast areas of the West Coast Plain have deep sandy soils with a water table in deeper soil horizons. Soil water abstraction from wellfields for municipal and farm use is practiced in several locations of the West Coast Plain (Ratcliffe 2007). At Pampoenvlei this water table was intensively studied and was found as close as 2–3 m below the surface in the wet season (van Wyk et al. 2001); at Waterboerskraal the water table can also be found at depths of <3 m from the surface. The Chemfos site is quite different from the previous two: it is located on an old sand dune overlying a hard-setting fragipan at approximately 1.5–2.1 m depth. The Flaminkvlei site has a sandy soil that is more than 3 m deep, but the subsoil is calcareous below 2.5 m depth.

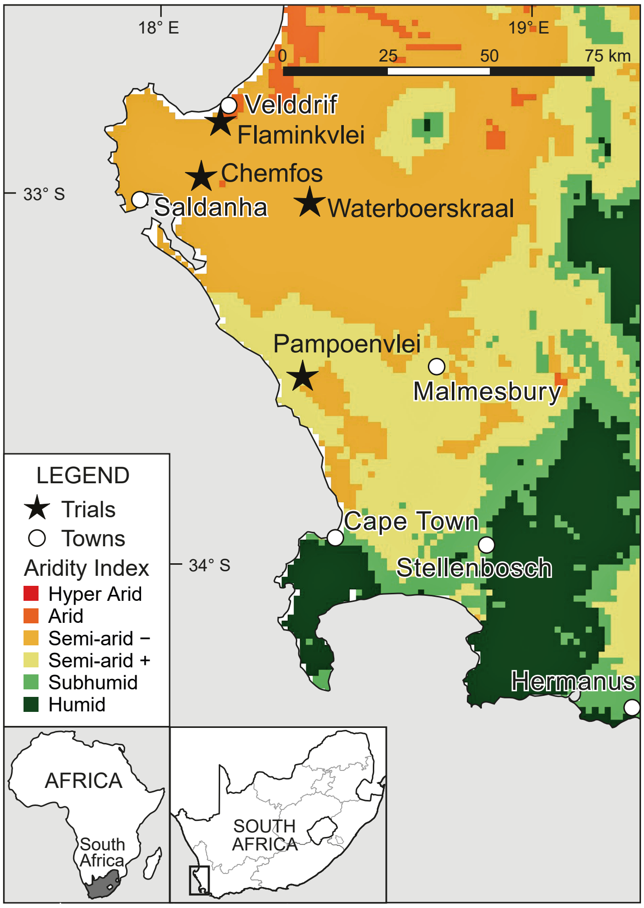


Figure 1: Aridity index map for the Boland and West Coast region showing the location of eucalypt field experiments on a gradient of increasing aridity. The Semi-arid class was split into relatively wetter 'Semi arid +' (AI > 0.35) and relatively drier 'Semi arid –' (AI < 0.35) subclasses for greater precision

The topsoil properties (0–15 cm depth) of the three trial sites that were established with a proper statistical design are shown in Table 2. The trials are all located on the West Coast Plain on sandy, dystrophic soils with low organic matter contents. With decreasing AI in Table 2, there is an increase in exchangeable sodium (Na), as well as a decrease in resistivity, indicating increases in salinity and sodicity with increasingly arid climatic conditions. The topsoil pH of the Flaminkvlei site (3.7 km from the coast, adjacent to the Berg River mouth at low elevation) is also much higher than the other two sites (Table 2).

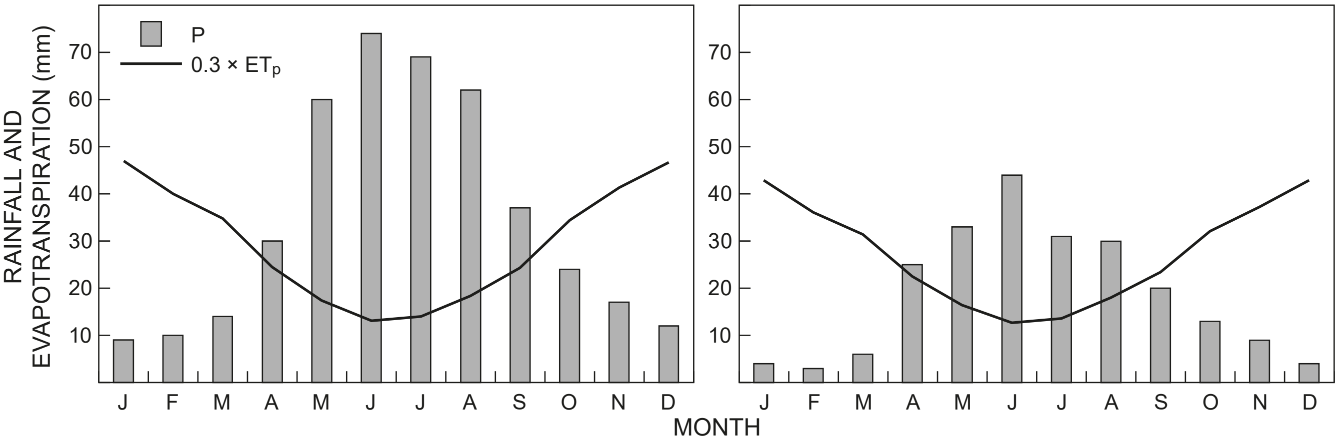
Several provenances of pure species as well as interspecific hybrids were tested in the four trials. The pure species were genetically unimproved and their seedlot numbers/provenances are given in Tables 3–5. The hybrids in the trials were some of the early commercially deployed eucalypt hybrids that were available in South Africa at the time. In the text that follows, hybrids of *E. camaldulensis*, *E. tereticornis* and *E. urophylla* with *E. grandis* as mother will be referred to as *E. g* × *c*, *E. g* × *t* and *E. g* × *u*, respectively. The seedlings were raised in two nurseries: the Forestry nursery at the University of Stellenbosch and Kluitjieskraal nursery at Wolseley. An espacement of 2 m × 5 m was used on all the above-mentioned trials except Chemfos where an espacement of 3 m × 4 m was implemented (Table 1). The wide initial spacing in all these trials was motivated by the importance to reduce competition for soil water on these dry sites, as also illustrated in more recent experiments by Gonçalves et al. (2017) and Hakamada et al. (2017). The sites were prepared by ploughing and rotavating the rows. During planting, 3 g pre-hydrated hydrogel was applied in the bottom of the

Table 1: Location, trial information, long-term average climatic data as well as actual rainfall estimates for the duration of the experiments from nearby weather stations. ET_p = mean annual potential evapotranspiration, MAP = mean annual precipitation

Trail site	Pampoenvlei	Waterboerskraal	Chemfos	Flaminkvlei
Establishment date (year)	1991	1997	1991	1997
Initial spacing (stems ha^{-1})	1 000	1 000	833	1 000
Survival of top five taxa (%)	90	76	75	48
Age at last measurement (years)	22	16	22	16
Rainfall during trial (mm)[a]	453	357	318	191
Gridded long-term avarage data (1950–1999) for exact trial location				
Mean annual precipitation (mm)	423	316	256	228
Aridity index (MAP/ET_p)	0.36	0.25	0.24	0.21
Altitude (m)	115	67	51	9
Mean annual temperature (°C)	17	17.6	16.4	16.6
Moisture growing season length (d)[b]	141	117	119	88

[a] Rainfall for the duration of the trial was taken from a single rainfall station close to each trial site

[b] Duration of the moisture growing season is days where MAP > (0.3 × ET_p)



	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
P	9	10	14	30	60	74	69	62	37	24	17	12	4	3	6	25	33	44	31	30	20	13	9	4
0.3 × ET_p	47	40	35	24	17	13	14	18	24	34	41	47	43	36	31	23	16	13	14	18	23	32	37	43

Figure 2: Long-term average monthly precipitation (P) and 0.3 × ET_p for the wettest site Pampoenvlei (a; aridity index 0.36) and the driest site Flaminkvlei (b; aridity index 0.21), averaged over the period 1950 to 1999. The moisture growing season is defined as the period where P > 0.3 × ET_p

Table 2: Soil properties (0–15 cm depth) for the Pampoenvlei, Waterboerskraal and Flaminkvlei trial sites. n.d. = not determined

Soil property	Pampoenvlei	Waterboerskraal	Flaminkvlei
Soil profile depth (m)	>4	>3	>3
Topsoil texture class	Sand	Sand	Sand
pH (KCl)	4.8	3.9	6.1
Organic carbon (%)	n.d.	0.18	0.19
Resistivity (Ohm)	9 250	5 003	2 253
Extractable acidity ($cmol_c$ kg^{-1})	0.48	0.38	0.38
Bray II P (mg kg^{-1})	4	2	12
Exchangeable Ca ($cmol_c$ kg^{-1})	1.53	0.14	1.22
Exchangeable Mg ($cmol_c$ kg^{-1})	0.27	0.16	0.49
Exchangeable K ($cmol_c$ kg^{-1})	0.02	0.05	0.14
Exchangeable Na ($cmol_c$ kg^{-1})	0.01	0.07	0.16

planting pit. Fertiliser was applied at a rate of 100 g of 3:1:1(25) per tree at Pampoenvlei and Chemfos (Ellis and van Laar 1999). Thus, the following rates of nutrient elements were applied per plant: 15 g nitrogen, 5 g phosphorus and 5 g potassium. At Waterboerskraal and Flaminkvlei the rate was 200 g of 3:2:1(25) per tree and each tree received 2 L water after planting. Other than site preparation, fertilisation at planting and initial weed control, the trials did not receive any silviculture treatment after establishment.

A total of 50 seedlots were tested in the Pampoenvlei trial (Table 3), which consisted of 13 pure species from 33 provenances and five interspecific hybrids from 17 provenances. The trial design was a completely randomised block experiment with five replicates in three different blocks. Each plot consisted of a row of five trees. Only the five replicates in Block 3 are reported in this document because of destructive sampling and thinning at an earlier age in Blocks 1 and 2.

The Chemfos trial has 39 seedlots (Table 4), which consisted of 11 pure species from 16 provenances and six interspecific hybrids from 23 provenances. It was basically planted as a group of demonstration plots, but the number of replications for each genotype varied, depending on availability of planting material. Fifteen of the Pampoenvlei seedlots were duplicated in the Chemfos trial, and the seed material was sourced from breeding programmes for dry climates of Morocco, Israel, Australia and South Africa (van Wyk et al. 2001). Square plots of 16 trees (4 × 4) were used.

The trial design at Waterboerskraal and Flaminkvlei consisted of eight replicates in randomised blocks. Each plot consisted of a row of five trees. At Waterboerskraal, 35 seedlots of 19 *Eucalyptus* species were planted and at Flaminkvlei, 25 seedlots of 11 *Eucalyptus* species were planted (Table 5). Five species, which were in use in the Western Cape at the time of planting, were included as Kluitjieskraal seedlot controls. The species for Waterboerskraal and Flaminkvlei were sourced from the drier areas in Western and Southern Australia, but the rainfall on the trials in South Africa is much lower than the lower limits of the species in their native habitats.

Measurements and growth performance estimates

Tree volume calculation

Trials were measured regularly in the years following establishment, but due to staff changes and limited project funding, measurements were missed for a number of years. The authors started to remeasure the two groups of trials at 20–22 and 14–16 years, respectively, and the final measurements are reported here. The diameter at breast height (DBH) of all trees was measured with diameter tapes and the stand age at the final measurement is shown in Table 1. The individual tree cross-sectional area was calculated from the DBH measurements (including the DBH

Table 3: Species and provenances planted at Pampoenvlei

Treatment no.	Species	Seedlot type[a]	Seedlot no.	Provenance[b]
1	*E. grandis* × *E. tereticornis*	HF	58*4	South Africa
2	*E. grandis* × *E. tereticornis*	HF	19*3	South Africa
3	*E. grandis* × *E. camaldulensis*	HF	38*11	South Africa
4	*E. grandis* × *E. camaldulensis*	HF	75*11	South Africa
5	*E. grandis* × *E. camaldulensis*	HF	4*11	South Africa
6	*E. grandis* × *E. camaldulensis*	HF	50*4	South Africa
7	*E. grandis* × (*E. grandis* × *E. tereticornis*)	HF	50(38*24328)	
8	*E. grandis* × (*E. grandis* × *E. tereticornis*)	HF	77(38*24328)	
9	*E. grandis* × (*E. grandis* × *E. tereticornis*)	HF	76(45*24328)	
10	*E. grandis* × (*E. grandis* × *E. tereticornis*)	HF	75(15*24328)	
11	*E. camaldulensis*	P		Murchinson River WA
12	*E. camaldulensis*	P		Cape River QLD
13	*E. camaldulensis*	P		Flinders River QLD
14	*E. camaldulensis*	P		Castlereagh River NSW
15	*E. camaldulensis*	P		Gilbert River QLD
16	*E. camaldulensis*	P		Gibb River
17	*E. camaldulensis*	P		Leonard River
18	*E. camaldulensis*	P		Palmer River QLD
19	*E. camaldulensis*	P		Albacutya VIC
20	*E. camaldulensis*	P		Petford QLD
21	*E. camaldulensis*	P		Israel 1988
22	*E. camaldulensis*	P		Morocco
23	*E. viminalis* × *E. camaldulensis*	HF	80065	Morocco
24	*E. viminalis* × *E. camaldulensis*	HF	80066	Morocco
25	*E. viminalis* × *E. camaldulensis*	HF	80067	Morocco
26	*E. grandis*	SM	791105	Morocco
27	*E. grandis*	SM	791117	Morocco
28	*E. grandis*	SM	791118	Morocco
29	*E. grandis*	SM	791068	Morocco
30	*E. grandis* × *E. globulus*	HF	791115	Morocco
31	*E. grandis* × *E. camaldulensis*	HF	80071	Morocco
32	*E. grandis* × *E. camaldulensis*	HF	80072	Morocco
33	*E. gomphocephala*	SM	80073	Morocco
34	*E. gomphocephala*	SM		Israel 1988
35	*E. globulus*	SM	791104	Morocco
36	*E. globulus*	SM	791114	Morocco
37	*E. astringens*	SM	791072	Morocco
38	*E. brockwayi*	SM		Israel 1988, CS(10)
39	*E. brockwayi*	SM	791070	Morocco
40	*E. tereticornis*	SM	80075	Morocco
41	*E. viminalis* × *E. camaldulensis*	HF	80065	Morocco
42	*E. bosistoana*	SM	791116	Morocco
43	*E. botryoides*	SM	80068	Morocco
44	*E. loxophleba*	SM	791071	
45	*E. cladocalyx*	SM		Israel 1988, PEG(10*)
46	*E. sargentii*	SM		Israel 1988
47	*E. dundasii*	SM		Israel 1988, CS(5)
48	*E. camaldulensis*	SM		Broken Hill, Israel
49	*E. camaldulensis*	SM		Hula Valley, Israel
50	*E. astringens*	SM	791068	Morocco

[a] Seedlot type refers to the nature of the seedlot: HF = hybrid family, P = provenance, SM = seed mixture
[b] WA = Western Australia, QLD = Queensland, NSW = New South Wales, VIC = Victoria

measurements of all stems on multi-stemmed trees). The percentage survival was calculated by registering only one count if the tree was multi-stemmed, then summing the tallies and dividing by the number of trees initially planted per treatment. The cross-sectional areas of stems were summed per plot and divided by the plot area to express the plot basal area per unit area of land (i.e. in m^2 ha^{-1}). The basal area per treatment was used to rank the performance of different taxa and to select the top 50% performers.

Heights were only measured for the top 50% performing species and seedlots with a Vertex hypsometer. The measured heights and DBH pairs were used to establish a regression for the relationship between DBH and height. Separate DBH–height regression functions were

Table 4: Species and provenances planted in the Chemfos experiment

Treatment no.	Species	Seedlot type[a]	Seedlot no.	Provenance
1	*E. cladocalyx*	SM		Israel 1988, CS(5)
2	*E. globulus*	SM	791104	Morocco
3	*E. diversicolor*			
4	*E. dundasii*			
5	*E. globulus*	SM	791067	South Africa
6	*E. globulus*	SM	791114	Morocco
7	*E. gomphocephala*	SM		Israel 1988
8	*E. grandis*	SM	791105	Morocco
9	*E. grandis*	SM	791117	Morocco
10	*E. grandis*	SM	791118	Morocco
11	*E. grandis* × *E. camaldulensis*	HF	38*11	South Africa
12	*E. grandis* × *(E. grandis* × *E. tereticornis)*	HF	22(15*2432)	South Africa
13	*E. grandis* × *(E. grandis* × *E. tereticornis)*	HF	4(50*24319)	South Africa
14	*E. grandis* × *(E. grandis* × *E. tereticornis)*	HF	50(15*2432)	South Africa
15	*E. grandis* × *(E. grandis* × *E. tereticornis)*	HF	75(15*24328)	South Africa
16	*E. grandis* × *(E. grandis* × *E. tereticornis)*	HF	76(45*2431)	South Africa
17	*E. grandis* × *E. camaldulensis*	HF	016/008SA	South Africa
18	*E. grandis* × *E. camaldulensis*	HF	101/11SA	South Africa
19	*E. camaldulensis*		791074	Morocco
20	*E. grandis* × *E. camaldulensis*	HF	38*7SA	South Africa
21	*E. grandis* × *E. camaldulensis*	HF	4*11	South Africa
22	*E. grandis* × *E. camaldulensis*	HF	75*11	South Africa
23	*E. grandis* × *E. camaldulensis*	HF	80071	Morocco
24	*E. grandis* × *E. globulus*	HF	791115	Morocco
25	*E. grandis* × *E. nitens*	HF	194/201SA	South Africa
26	*E. grandis* × *E. nitens*	HF	360/149SA	South Africa
27	*E. grandis* × *E. tereticornis*	HF	38*3	South Africa
28	*E. grandis* × *E. tereticornis*	HF	4*8	South Africa
29	*E. grandis* × *E. tereticornis*	HF	50*4	South Africa
30	*E. grandis* × *E. urophylla*	HF	001/009	South Africa
31	*E. grandis* × *E. urophylla*	HF	45*3-3	South Africa
32	*E. grandis* × *E. urophylla*	HF	50*20-1	South Africa
33	*E. grandis* × *E. urophylla*	HF	50*3-3	South Africa
34	*E. grandis* × *E. urophylla*	HF	58*2-1	South Africa
35	*E. occidentalis*			
36	*E. sargentii*	SM		Israel 1988
37	*E. tereticornis*	SM	80075	Morocco
38	*P. radiata*	SM	1189	South Africa
39	*P. radiata*	SM	1531	South Africa

[a] Seedlot type refers to the nature of the seedlot: HF = hybrid family, P = provenance, SM = seed mixture

used for each of the top performing taxa at each trial site. The estimated (regression) heights of trees, as well as their DBH, was used to estimate tree volume for most species, using the Schumacher and Hall functions listed in Bredenkamp (2012). The volume function for *E. gomphocephala* was derived from a tree volume study for this species that utilised the sample trees from the Pampoenvlei site (Phiri 2013; Phiri et al. 2015).

Assessment of the growth performance

Individual tree volume data were summed per plot and scaled up to be expressed as stem wood volume per hectare. A word of caution is required: three of the experiments have row plots with relatively good survival among the top performers, but in some cases surrounded by plots with a number of dead or supressed individuals. Where top performers are situated next to dead/suppressed trees, their volume production potential will inevitably be over-estimated. We acknowledge this shortcoming, but argue that the neighbouring trees in each of the five to eight replications differ, and that the *relative* performance of trees are the most important information to be provided by these trials. We also provide the mean volume growth performance of the five best taxa tested, which is, arguably, a more realistic expectation for volume growth on a given site than the volume growth of the single best performing taxon (that may have competed against inferior genotypes in *some* of the replications).

Statistical analysis

The volume growth of all promising species could not be estimated accurately, as volume functions do not exist for all taxa under investigation. Furthermore, several taxa recorded very low survival and can thus essentially be considered as off-site plantings for the sites in question. For these reasons, statistical analysis was performed only on

Table 5: Species and provenances planted at Waterboerskraal and Flaminkvlei

Treatment number		Species	Seedlot no.[a]	Provenance
Waterboerskraal	Flaminkvlei			
1		*E. bakeri*	17505	8 km east of Karara, QLD
2	1	*E. camaldulensis*	12272	Minilya River, WA
3	2	*E. camaldulensis*	13180	North of Greenough, WA
4	3	*E. camaldulensis*	15025	Lake Hindmarsh, northwest VIC
5	4	*E. camaldulensis*	15035	Lake Coorong, VIC
6	5	*E. camaldulensis*	15440	George River, WA
7	6	*E. camaldulensis*	15441	De Grey River, WA
8	7	*E. camaldulensis* var. *obtusa*	18944	80 km northwest of North Hampton, WA
9	8	*E. cladocalyx*	19349	Marble Range, SA
10	9	*E. coolabah* var. *rhodoclada*	15430	Murchison River, WA
11		*E. eryhrocorys*	19447	35 km northwest of Eneabba, WA
12	10	*E. gomphocephala*	16581	Limekiln Ludlow, WA
13	11	*E. gomphocephala*	17637	Yalgorup SF, WA
14	12	*E. leucoxylon* subsp. *leucoxylon*	16527	28 km south of Naracoorte, SA
15	13	*E. microtheca*	12528	Hardy River southwest of Tom Price, WA
16		*E. microtheca*	12532	Minilya River, WA
17	14	*E. microtheca*	12533	Northeast of Carnavon, WA
18	15	*E. microtheca*	12534	Kennedy Range, WA
19		*E. microtheca*	12535	Lyons River (IBPGR), WA
20	16	*E. microtheca*	12536	Gascoyne River, WA
21	17	*E. microtheca*	12537	Yarra Yarra Creek, WA
22	18	*E. microtheca*	15070	Hamersleys/Pilbara (4), WA
23	19	*E. rudis*	19100	Dongara to Enneaba, WA
24		*E. salmonophloia*	17987	Karonie-Coonana, WA
25		*E. tereticornis*	15924	South of Loch Sport, VIC
26	20	*E. transcontinentalis*	12840	13 km north of Coolgardie, WA
27	21	*E. camaldulensis*		Kluitjieskraal
28	22	*E. citriodora*		Kluitjieskraal
29	23	*E. cladocalyx*		Kluitjieskraal
30	24	*E. melliodora*		Kluitjieskraal
31	25	*E. paniculata*		Kluitjieskraal
32		*E. kochii* subsp. *plenissima*	15431	74 km south of Billabbalong, WA
33		*E. salmonophloia*	10110	24 km south of Coolgardie, WA
34		*E. mannensis*	11807	Shark Bay, Denham Track, WA
35		*E. polybractea*	17433	Whipstick Forest, VIC

[a] All seed from selected trees with no further tree breeding
[b] WA = Western Australia, SA = South Australia, QLD = Queensland, VIC = Victoria

the basal area growth of the top performing taxa, using a simple analysis of variance test with a *post-hoc* test (*F*-test), as implemented in Statistica 13 software (StatSoft, Inc., Tulsa, OK, USA).

Results

Survival

The percentage survival of all taxa in the four trials are presented in Figures 3 to 6, with a summary in Table 6. The overall survival was relatively poor, with the lowest survival being recorded at sites with the lowest aridity indices. This clearly illustrates the fact that many of the genotypes were exposed to a level of aridity that was too intense to attain acceptable survival rates. At Flaminkvlei, even the 75th percentile for survival among taxa was 42%, indicating that the site is probably too arid for planting most of the taxa that were tested. The most resilient species across the four experiments included *E. gomphocephala*, *E. camaldulensis* and *E. tereticornis*, as well as individual hybrids of the latter two species with *E. grandis,* namely *E. g* × *t* and *E. g* × *c* (Figures 3–6). The top performing species *E. gomphocephala* and *E. cladocalyx* appeared to have minimal diseases, but some incidence of *Gonipterus scutellatus* (eucalypt snout beetle) damage was observed on the leaves of sample trees that had been felled.

Height growth

The average of the dominant heights for the top five taxa at age 22 years were 20.4 m and 18.8 m for Pampoenvlei and Chemfos, respectively. The corresponding values at age 16 years were 22.0 m and 15.2 m for the Waterboerskraal and Flaminkvlei sites, respectively. Genotypes that achieved the best height growth were *E. cladocalyx* at Pampoenvlei, Waterboerskraal and Flaminkvlei, and *E. g* × *c* at Chemfos.

Basal area and volume growth

Results of the basal area of all genotypes tested in the trials are presented in Figures 3–6. Volume estimates for the top performers are shown in Figures 7 and 8; these estimates should be viewed with caution, for reasons described in the materials and methods section.

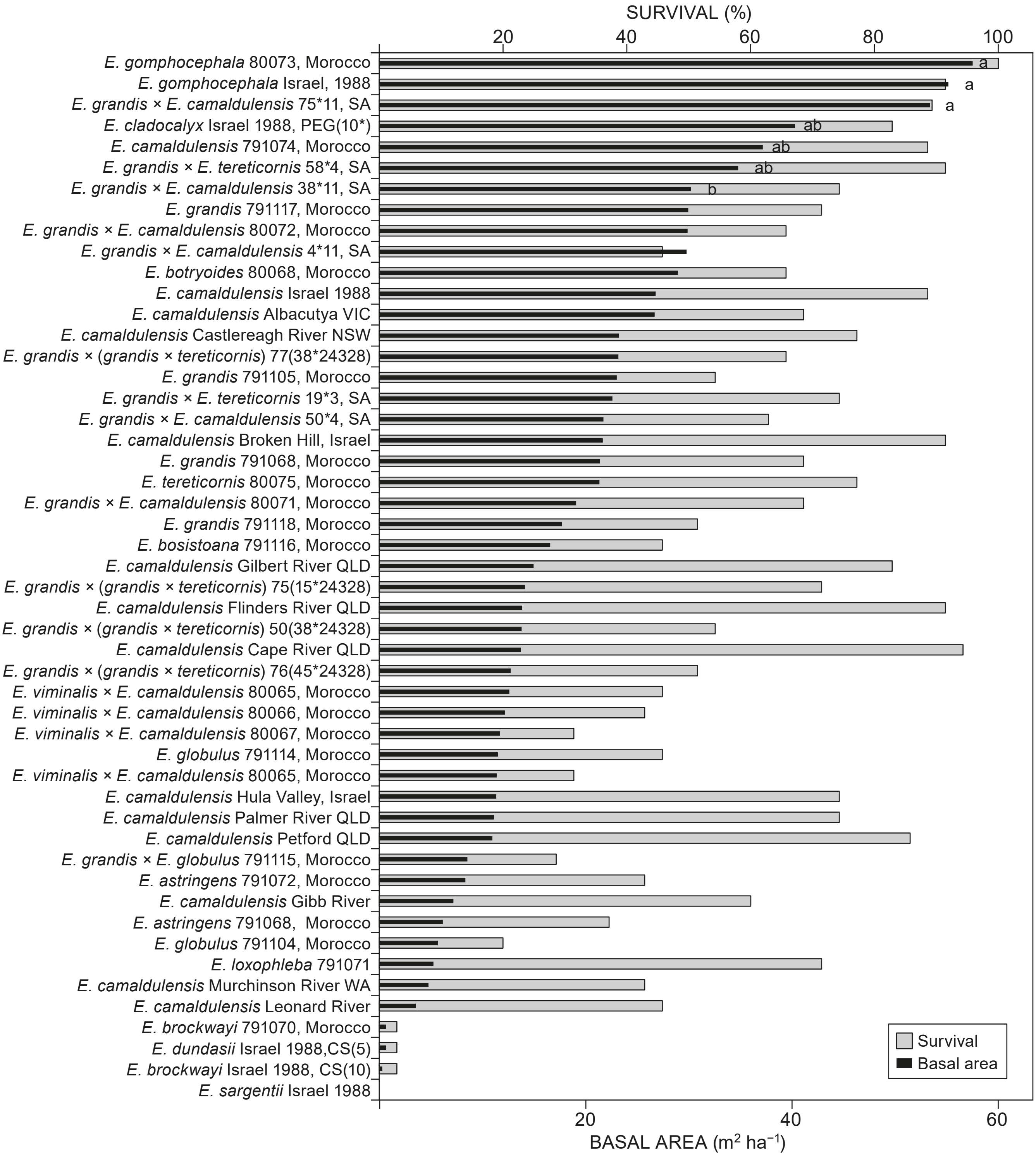


Figure 3: Basal area and survival at age 21 for the Pampoenvlei trial (aridity index 0.36). Basal area means with the same letter are not significantly different ($p < 0.05$)

The top performers in all trials where statistical analysis could be performed was *E. gomphocephala* (Figures 3, 5 and 6). The volume and basal area growth of *E. cladocalyx* (Kluitjieskraal and Israeli seedlots) also deserves mention: it was statistically not significantly different from the *E. gomphocephala* genotypes at Pampoenvlei and Waterboerskraal, but was significantly poorer on the driest site at Flaminkvlei (AI = 0.21; MAP = 228 mm). The only other species that attracted attention on the driest sites were *E. camaldulensis* and *E. tereticornis*; however, the basal area of these species was substantially smaller than that of *E. gomphocephala*. On the Pampoenvlei site

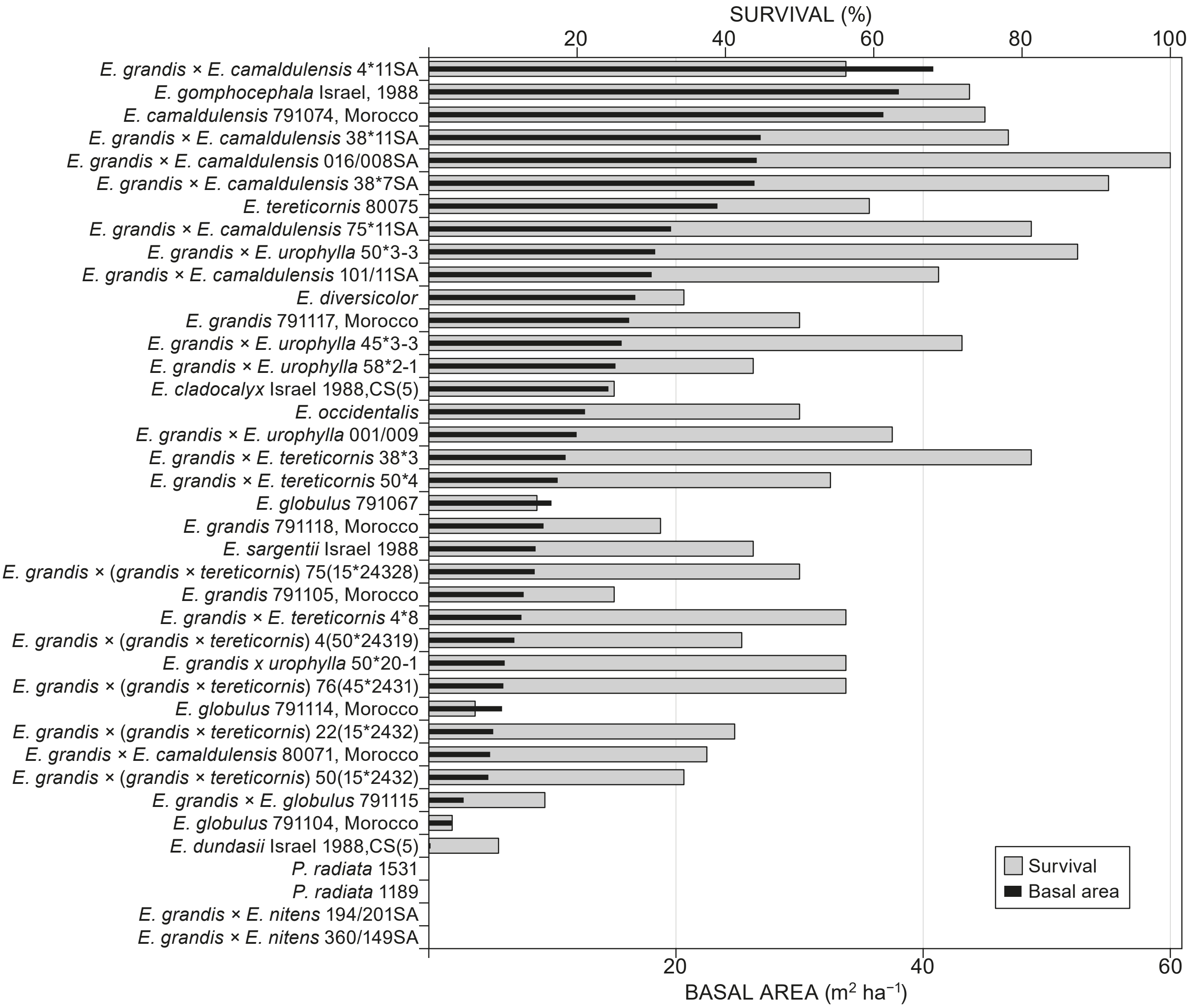


Figure 4: Basal area and survival at age 21 for the Chemfos trial (aridity index 0.24)

(AI = 0.36; MAP = 423 mm), *E. camaldulensis* as pure species (Moroccan seedlot), as well as the South African hybrids of *E. g* × *c* and *E. g* × *t* attained marginally acceptable survival and growth rates that were not significantly poorer than the top performers (Figure 3).

Average volume per hectare for the top five genotypes was 360 and 237 m³ ha^{-1} at Pampoenvlei and Chemfos (both at age 22 years) (Table 6), whereas the corresponding volume estimates (but measured at 16 years) attained 317 and 116 m³ ha^{-1} at Waterboerskraal and Flaminkvlei, respectively (Table 6). The corresponding MAI values (in the same order as the preceding sentence) were 16.3, 10.8, 19.8 and 7.3 m³ ha^{-1} a^{-1}, respectively, bearing in mind that they are based on estimates from different age classes across the trials. This data set emphasises the point that the Flaminkvlei site is at the limit of the tolerance level of even the hardiest species tested. Genotypes that achieved the best volume per hectare were *E. gomphocephala* at Pampoenvlei, Waterboerskraal and Flaminkvlei, and *E. g* × *c* at Chemfos.

Discussion

Survival

The poor survival at Flaminkvlei may be a result of the combined effects of poor silviculture, the very low rainfall on the site, the short duration of the moisture growing season, and less favourable soil conditions (Tables 1 and 2). Both the exchangeable Na and electrical conductance was significantly higher in the Flaminkvlei soil sample, but neither of these numbers indicate dangerously high levels of Na or general salinity in the topsoil. However, Ellis and van Laar (1999) found dangerously high levels of Na in the leaves of trees at the wettest site in this trial group (Pampoenvlei). It has been ascribed to salt spray from the ocean, but it is also highly likely that deep soil horizons harbour higher

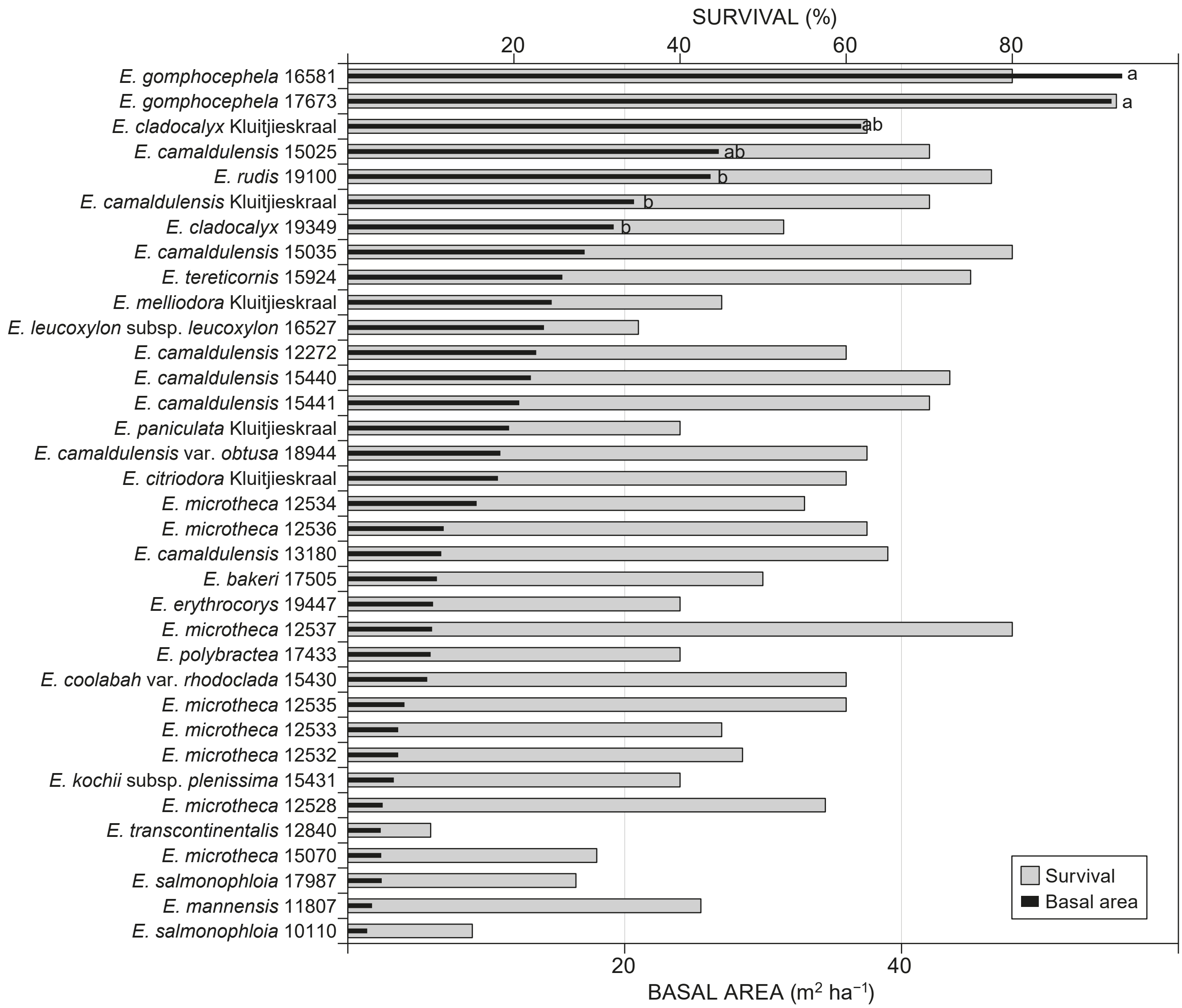


Figure 5: Basal area and survival at age 16 for the Waterboerskraal trial (aridity index 0.25). Basal area means with the same letter are not significantly different ($p < 0.05$)

levels of salinity on these sites, and that this contributed to elevated Na in the foliage. This effect will be amplified in the Flaminkvlei site with its higher levels of Na and lower resistance, indicating the presence of salts in the soil solution. Furthermore, the low organic matter levels and less favourable levels of salinity and sodicity, and the alkaline conditions in the calcareous subsoil, makes the Flaminkvlei site even less suitable for most fast-growing eucalypt species (highly productive sites in high rainfall areas are usually excessively leached, acidic, with low salt levels and low levels of exchangeable Na). We will thus concentrate our discussion on those sites where acceptable survival rates were obtained (with AI between 0.24 and 0.36). The survival results (excluding the Flaminkvlei trial) showed that some of the tested taxa are not suited to the semi-arid climate conditions; however, the taxa with the best survival rates did show some adaptation to sites that are considered to be more arid than their natural environments.

Two of the *Eucalyptus* species, which were traditionally planted in the Western Cape, *E. camaldulensis* and *E. gomphocephala*, showed generally good survival and growth across most sites. In contrast, *E. cladocalyx* grew well at Pampoenvlei (wettest site) but suffered high mortality in the other trials. This finding was echoed by Botman (2010) who showed that *E. cladocalyx* can outperform *E. gomphocephala* in the dry subhumid region of the Western Cape (Coetzenburg trial, AI = 0.64), but was inferior to *E. gomphocephala* in the semi-arid zone (Darling trial, AI = 0.36). The Chemfos trial and the Darling experiment described by Botman (2010) differs from the Pampoenvlei and Waterboerskraal sites on some important characteristics: the latter group is located on lower terrain positions in the landscape (mid- and footslopes) and has a ground water table within 3 m of the surface. It appears that *E. cladocalyx* will only be productive in the wetter section of the semi-arid zone ('Semi-arid + ' in

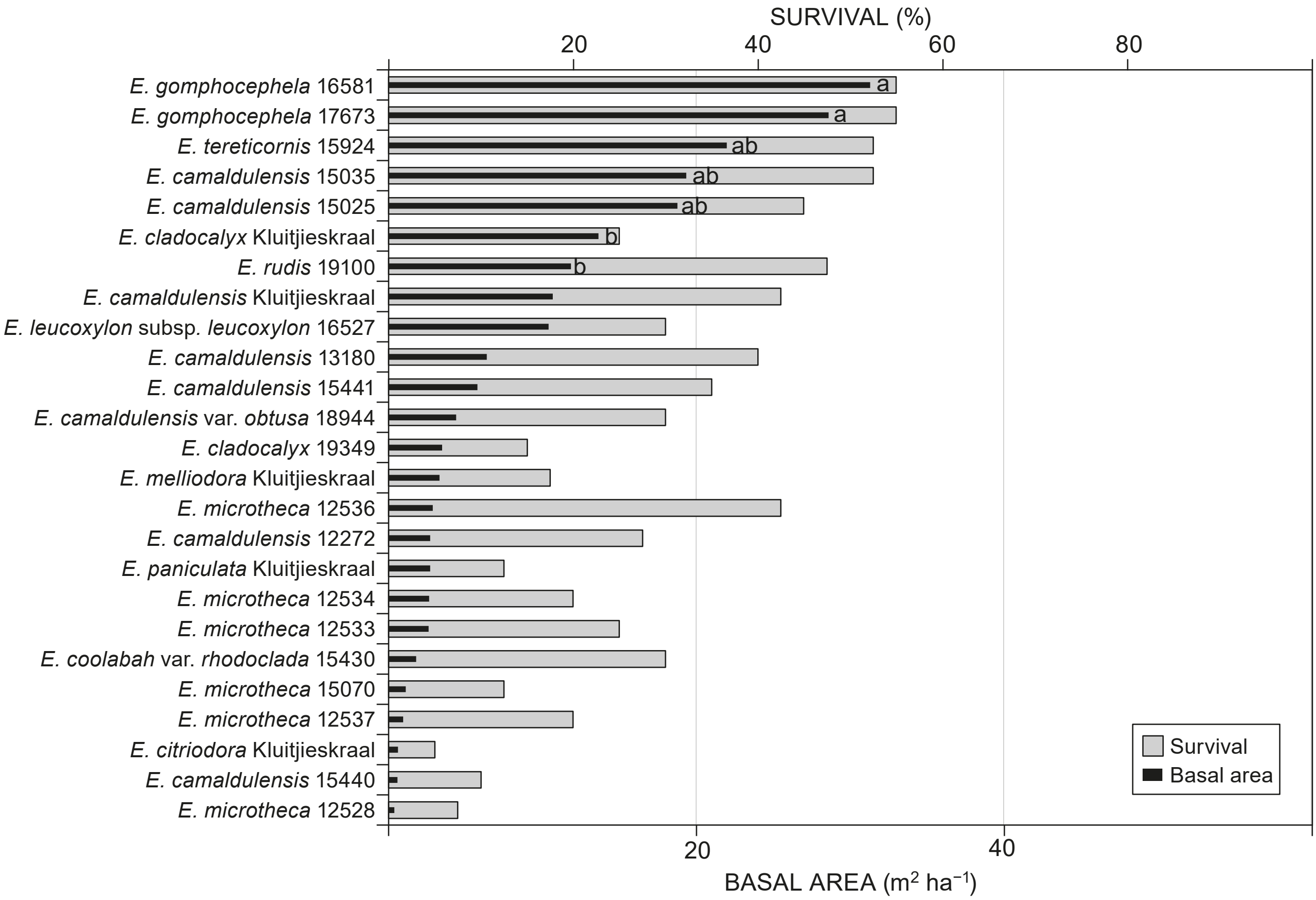


Figure 6: Basal area and survival at age 16 for the Flaminkvlei trial (aridity index 0.22). Basal area means with the same letter are not significantly different ($p < 0.05$)

Figure 1), especially if it is planted on low-lying sites with access to groundwater.

A small number of the alternative taxa tested had survival rates greater than 80% in some of the trials, namely *E. tereticornis*, *E. microtheca* (seedlot number 12537) and *E. rudis* as well as individual hybrids of *E. g* × *c*, *E. g* × *t* and *E. g* × *u* (Figures 3–6). *Eucalyptus camaldulensis* and *E. tereticornis* both have a wide natural distribution across Australia, with MAP varying between 250 and 625 mm a^{-1} for the former, and between 600 and 2 500 mm a^{-1} for the latter (Poynton 1979b; Florabank 2016). The *E. g* × *c* as a hybrid often combines several favourable traits of the parents. Notably, *E. g* × *c* hybrids are usually fast-growing, much straighter than the *E. camaldulensis* parents, and they have smaller boles and lower leaf areas than the *E. grandis* parents on comparable sites, which is useful under arid conditions (van Wyk et al. 2001; Esprey et al. 2004; Dovey et al. 2006, 2011). However, in the summer rainfall zone of South Africa, *E. camaldulensis*, *E. grandis* and most *E. g* × *c* hybrids have been found to be particularly susceptible to two insect pests that were introduced to South Africa long after the Western Cape trials were planted: *Thaumastocoris peregrinus* (bronze bug) and *Leptocybe invasa* (gall wasp) (Thu et al. 2009; Nadel et al. 2010). Both pests were not widespread in the Western Cape for most of the duration of the experiments, which means that survival and productivity of *E. g* × *c* may be much less in future plantings, given the current presence of these pests and the high level of susceptibility of *E. g* × *c.*

Eucalyptus gomphocephala and *E. cladocalyx* have natural distributions in Western Australia (near Perth) and South Australia, respectively (Poynton 1979b; Boland et al. 2006; Botman 2010). Although both distributions fall within Mediterranean climates, the rainfall where *E. gomphocephala* occurs in Western Australia (MAP range 760–1 020 mm) is fairly concentrated over the winter months. The distribution of *E. cladocalyx* is spread over MAPs ranging from 380 to 630 mm, but the duration of the rainfall season is longer than that of the *E. gomphocephala* distribution zone of Western Australia. This may be the reason why *E. gomphocephala* is particularly resistant to prolonged summer drought conditions, and performs well in the drier end of the range of semi-arid zone in South Africa.

It is possible that the survival of the best performing taxa in the trials can be further improved with balanced nutrition and with some form of ground cover to conserve the soil moisture during the hot dry summers, combined with more intensive vegetation management on competing plants, especially during the first two years after planting (du Toit et al. 2010b).

Table 6: Summary of tree growth in all four trials. DBH = diameter at breast height; H_{dom} = height of dominants, i.e. mean height of 80th percentile trees ranked by DBH; MAI = mean annual increment

Trial site and measurement age (y)	DBH (cm)	Multi-stems (%)	Survival (%)	Basal area (m² ha⁻¹)	H_{dom} (m)	Volume (m³ ha⁻¹)	MAI (m³ ha⁻¹ a⁻¹)
Trial average							
Pampoenvlei (22)	19	27	60	19			
Chemfos (22)	19	17	45	13			
Waterboerskraal (16)	13	19	55	13			
Flaminkvlei (16)	13	21	30	8			
Average for top five taxa							
Pampoenvlei (22)	24.3	16.3	90	50.3	20.4	360	16.3
Chemfos (22)	24.6	12.5	76	35.6	18.8	238	10.8
Waterboerskraal (16)	22.5	17.3	75	39.1	22.0	317	19.8
Flaminkvlei (16)	20.7	23.3	48	23.0	15.2	116	7.3

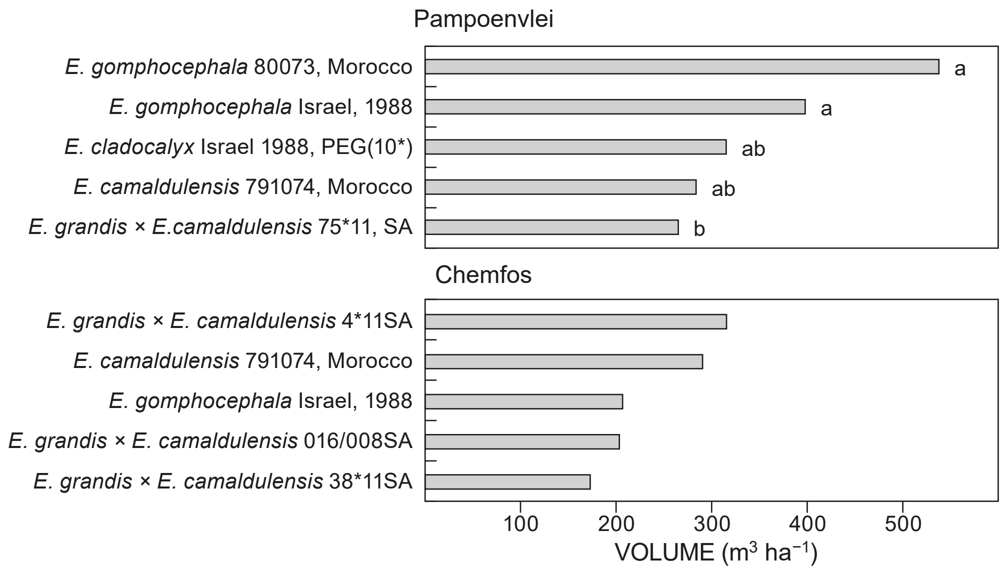


Figure 7: Estimated volume growth of the top performing taxa at age 22 at Pampoenvlei and Chemfos. Bars with the same letter are not significantly different ($P < 0.05$). No statistical analysis was performed for the Chemfos trial due to an unbalanced design

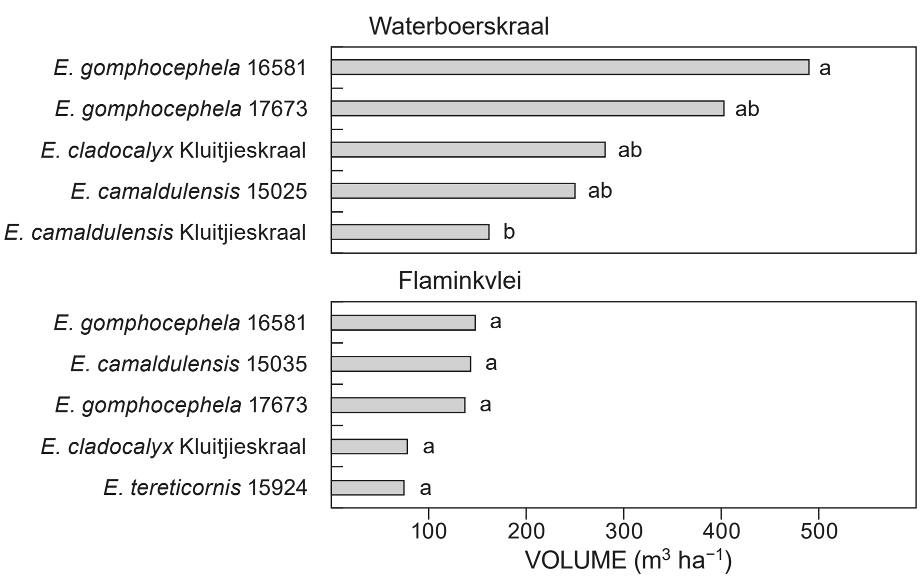


Figure 8: Estimated volume growth of the top performing taxa at age 16 at Waterboerskraal and Flaminkvlei. Within each trial, means with the same letter are not significantly different ($P < 0.05$)

Height growth and site index estimates

The dominant height growth of the best performing taxa allows us to assess the productivity potential of the site, relative to known height growth trajectories, using the site index concept. Coetzee (1999) and his successors (Smith et al. 2005) developed trajectories for top height development of *E. grandis* on sites with SI_5 ranging from 11 to 28 m in KwaZulu-Natal. The average height growth of the top five taxa in our least arid site (Pampoenvlei) was 8.12 m at 5 years and 9.45 m at age 6 years (van Wyk et al. 2001). The height growth was also measured at 14 years of age in the Waterboerskraal experiment, which allows us to interpolate to the estimated top height at base age 5, using the data of Smith et al. (2005). For this site we estimate a dominant height at 5 years of age equal to approximately 9–10 m. Unfortunately, the height growth on all Western Cape trials was not measured for some years, so there are no data to accurately gauge dominant height for Flaminkvlei and Chemfos at age 5 years. However, we can estimate that the SI_5 would probably be in the range of 4–8 m for Flaminkvlei and Chemfos, based on the performance of the trials with slightly higher aridity indices.

Basal area and volume growth

As mentioned before, the basal area was used as the main criterion to rank genotypes and to select top performers. The reason for the inclusion of the basal area of all the multi-stems in the calculation of the basal area is that it allows a more accurate representation of the growth potential of the species on the site, irrespective of poor tree form. Tree form can be improved to some degree by closer spacing and corrective pruning, and obviously through genetic tree improvement. The basal area calculation identified *E. gomphocephala* and *E. grandis* × *E. camaldulensis* as the most productive taxa across all of the four trials. It is worth mentioning that if multiple stems are ignored and genotypes are ranked on the DBH of the one biggest stem only, then the top performers shift to *E. gomphocephala* at Pampoenvlei, *E. grandis* × *E. camaldulensis* at Chemfos and *E. cladocalyx* at Waterboerskraal and Flaminkvlei. *Eucalyptus cladocalyx* had no multiple stems on the last two sites.

The average MAI of the top performers at Waterboerskraal and Pampoenvlei was 19.8 and 16.3 m^3 ha^{-1} a^{-1}, respectively. This is potentially an overestimate (for the reason given in the materials and methods section), and also corroborated by the utilisable MAI growth of the poorest site in the *E. grandis* spacing trial series ($SI_5 = 11.4$; 925 stems ha^{-1}), which yielded approximately 14 m^3 ha^{-1} a^{-1} (Smith et al. 2005). We would thus have expected an MAI of approximately 12 m^3 ha^{-1} a^{-1} (based on site index curves) if the trial had been fully stocked with a single genotype. The Chemfos demonstration plots suffer from the fact that all of the top genotypes were not tested, and that the plots were not randomised, but the positive side of this trial is that square plots were employed where trees competed against their own kind. The slightly lower MAI at Chemfos (with similar AI and MGS as Waterboerskraal) may therefore be a more realistic estimate of potential productivity on the drier end of the spectrum that was tested (in the absence of an accessible water table and on comparatively shallower soils), namely 10.8 m^3 ha^{-1} a^{-1}. The easily accessible water table at both Pampoenvlei and Waterboerskraal would have allowed the trees to have access to additional water that is not reflected in the rainfall values. This increased availability of soil water contributed to the comparatively high growth rates, considering the low MAP on both sites. The very low MAI at Flaminkvlei is partly due to the high mortality, extremely short moisture growing season, slightly saline soil, and the fact that the trees did not occupy the site fully.

The growth result obtained on the West Coast Plain can be contrasted against dryland trials that were carried out in the dry, subtropical zone of KwaZulu-Natal, where we calculated the aridity indices of the driest sites in each of two trial series to be 0.55 (Nyalazi) and 0.45 (Mkuze), respectively, using the method cited in Schulze (1997). At Nyalazi, volume growth at 7 years of age ranged between 180 and 210 m^3 ha^{-1} for the best performers mentioned above, and wood density between 630 and 670 kg m^{-3} (Gardner et al. 2001). This represents an MAI of 26–30 m^3 ha^{-1} a^{-1}. At the Mkuze trial site on an structured soil, the *E. grandis* × *E. camaldulensis* hybrid clone produced the highest merchantable wood volume at 10 years of age (104 m^3 ha^{-1}) with *E. argopholia* and *E. longirostrata* (Chinchilla) producing the second and third highest at 96 and 67 m^3 ha^{-1}, respectively (Gardner et al. 2009). This represents and MAI range of approximately 7–10 m^3 ha^{-1} a^{-1} for the best performers. The rest of the growth and yield results from dryland trials with *Eucalyptus* and *Corymbia* in Zululand were all better than the results found in the Western Cape. This is to be expected as the majority of the Zululand trials fell in the dry subhumid zone but the West Coast Plain sites all fell in the drier portion of the semi-arid zone (Figure 1, Table 1). Furthermore, the rainfall in the Western Cape occurs during the winter season when temperatures are suboptimal for growth.

In a *Eucalyptus* species and spacing trial on a site with an average annual rainfall of 886 mm in the KwaZulu-Natal Midlands, the average MAI for all planting densities peaked at less than 1 for the worst species to 12 m^3 ha^{-1} a^{-1} for the best species at age 9, after a severe drought at age 8 (Crous et al. 2013).

In *Eucalypts for Planting* (FAO 1981), a summary was made of volume growth of *Eucalyptus* on dry sites in several countries with dry climates. The summary revealed growth of 2–8 m^3 ha^{-1} a^{-1} in Portugal, the driest site having MAP of 417 mm. Volume growth of 4.7 m^3 ha^{-1} a^{-1} was obtained for *E. camaldulensis* on the more severe climatic classes of Morocco (241–496 mm MAP). In Israel 2 m^3 ha^{-1} a^{-1} was reported on the driest site classes (c. 200 mm MAP) and between 20 and 30 m^3 ha^{-1} a^{-1} on sites with rainfall of 542–569 mm and deep soils (FAO 1981).

In a study in Gippsland, Australia, 140 seedlots of 36 species were compared over 12 sites. The tree volume achieved on the driest site (Stradbroke), with a rainfall of 600 mm, ranged from 0 to 250 m^2 ha^{-1} at 11 years, with an average MAI below 9 m^3 ha^{-1} a^{-1} (Duncan et al. 2000).

When comparing the growth performance of the West Coast dryland trials (barring Flaminkvlei) with results obtained on the drylands of Zululand and other Australian and Mediterranean climates, it is quite remarkable (even using the more conservative MAI estimate obtained for

Chemfos), considering that the West Coast trials have aridity indices of 0.36 and lower, with MAPs between 423 and 256 mm. The seasonality of the rainfall (when evapotranspiration is also lower) must surely contribute to allow a substantial portion of the annual growth to occur during winter and spring. It also follows that *E. gomphocephala* must have the ability to minimise transpiration during the hot and dry summer months. Lastly, the effect of water tables in the deeper subsoil horizons on stand productivity needs to be researched more thoroughly for the West Coast Plain soils.

Conclusions and recommendations

The species with the best volume growth on the semi-arid sites under investigation was *E. gomphocephala.* This species deserves further selection and breeding, and research should also focus on silvicultural techniques such as slightly closer spacing combined with early thinning (and where necessary, corrective pruning) to obtain better stem form. The planting of *E. cladocalyx* is only an option in the wetter portion of the semi-arid zone (see 'Semi-arid +' in Figure 1), especially in lower-lying landscape positions where it will have access to additional water. This species has excellent form and good wood properties that can be used for multiple products (Wessels et al. 2016; Lundqvist et al. 2017), and also deserves further breeding, as the Kluitjieskraal seedlot is made up of open-pollinated seeds – there is thus much room for improvement.

The *E. g* × *c* hybrid also achieved acceptable growth rates under the test conditions and produced trees with excellent stem form, but its general susceptibility to *Leptocybe* and *Thaumastucoris* pests, coupled to inferior wood properties (Wessels et al. 2016; Lundqvist et al. 2017), makes this hybrid a less favourable choice. Of all the remaining species that were tested for the first time on our four trial sites, the 'new' species that showed most potential were *E. rudis* on Waterboerskraal and *E. tereticornis* on Flaminkvlei.

If climate change predictions are correct, the semi-arid zone of the Western Cape might experience more erratic rainfall patterns and generally drier conditions in future. Under these circumstances, even sites in the wetter portion of what is now classified as the semi-arid zone should be earmarked for planting with *E. gomphocephala*, as it has shown itself to be very tolerant of summer drought under our trial conditions, and appears to be fairly disease free to date.

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