Adaptability of four-year old *Eucalyptus* Species and Clones in Kenya

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Abstract

Eucalyptus is the third most commonly grown tree genus in Kenya, after pine and cypress. The most common species are *E. grandis, E. saligna*, and *E. camaldulensis*. These species are fast-growing, adapted to many agro-ecological zones and have numerous uses. Due to their importance, breeding strategies have been developed to improve productivity. One of the major concerns is assessing their adaptability across sites. Fifteen Eucalyptus grandis x Eucalyptus camaldulensis (GCs) and three Eucalyptus grandis x Eucalyptus urophyla (GUs) hybrid clones were introduced to Kenya from Mondi Forest, South Africa (SA). These clones and local land-races of *E. grandis* (EG), *E. camaldulensis* (EC), *E. saligna* (ES), *E. tereticornis* (ET) and *E. urophyla* (EU) were used to establish trials on four high and three low altitude sites in Kenya. The trials were established in complete randomized block design replicated two to four times. Assessments were done on height, diameter at breast height (DBH), stemform and branching habit at four years. The objective of this paper was to determine adaptability of the four-year-old eucalyptus species and clones in Kenya. Additive Main effect Multiplicative Interaction (AMMI) was used to determine adaptability and stability of the genotypes across the sites. Orthogonal comparisons on the growth were done using ANOVA and generalized linear modeling procedures. Results showed that performance of clones and local land-races was not consistent over all sites. There was a high significant ($p < 0.01$) difference in height, DBH, stemform and branching habit within and between sites. In high altitude sites, GC15 had highest height and DBH of 18.2 m and 14.0cm, respectively, in Machakos. In low altitude sites, GC581 and GC167 had highest height of 14.2 and 14.3 m, respectively. Overall, none of the genotypes was stable across high altitude sites. On the other hand, GC581, GU21 and GC784 were stable across the low altitude sites. The results suggest that, on sites above 2000m, the local land-races, EG and ES, would perform better than clones. It is recommended that GC581, GU21 and GC784 could be used for further wide scale in Kenya across the low altitude sites.

Key words: Eucalyptus, hybrids, local landraces, Kenya

Résumé

L'eucalyptus occupe la troisième place parmi les genres ligneux les plus rencontrés au Kenya, après le pin et le cyprès. Les espèces les plus répandues d'eucalyptus sont *Eucalyptus grandis, E. saligna* et *E. camaldulensis*. Ces espèces sont à croissance rapide, adaptées à plusieurs zones agro-écologiques et s'apprêtent à différentes utilisations. Vue l'importance de leur sélection, beaucoup de stratégies ont été mises en place pour améliorer leur productivité. L'une des préoccupations fondamentales est l'évaluation de leur adaptabilité sur différents sites. Quinze hybrides de *E. grandis* x *E. camaldulensis* (GC) et trois autres de *E. grandis* x *E. urophyla* (GU) ont été introduits au Kenya de la forêt Mondi en Afrique du Sud. Ces clones et autres variétés locales de *E. grandis* (EG) *E. camaldulensis* (EC), *E. saligna* (ES), *E. tereticornis* (ET) et *E. urophyla* (EU) ont servi lors de la mise en place des essais sur des sites de haute et moyenne altitudes au Kenya. Les essais étaient plantés dans un dispositif avec des blocs complètement aléatoires; avec deux à quatre répétitions. Les évaluations ont porté sur les facteurs hauteur, diamètre à la hauteur de la poitrine (DHP), forme de la tige, et formation des branches chez les arbres âgés de quatre ans. Cette étude visait la détermination de l'adaptabilité de ces quatre espèces et clones d'eucalyptus à quatre ans d'âge. L'interaction de l'effet additif et multiplicatif du facteur principal a été utilisée lors des analyses pour déterminer l'adaptabilité et la stabilité des génotypes dans les différents sites. Des comparaisons orthogonales sur la croissance ont été faites à l'aide de l'ANOVA et des procédures généralisées de modélisation linéaire. Les résultats ont prouvé que la performance des clones et des variétés locales n'était pas consistante à travers tous les sites. Il y avait des différences significatives ($p<0,01$) pour la hauteur, le DHP, la forme de la tige et la formation des branches. Dans des sites de hautes altitudes GC 15 avait la hauteur et le DHP les plus élevés d'une valeur de 18,2 m et de 14,0 cm respectivement, à Machakos. Dans les basses altitudes, GC581 et GC167 avaient des hauteurs les plus élevées d'une valeur de 14,2 m et 14,3 m, respectivement. D'une manière générale, aucun des génotypes n'était stable dans les sites de haute altitude. D'autre part, GC581, GU21 et GC784 étaient stables dans les sites de basse altitude. Ces résultats suggèrent que dans les sites au dessus de 2000 m, les variétés locales EG et ES auraient les meilleures performances que les clones. On recommande l'utilisation à grande échelle de GC 581, GU21 et GC784 au Kenya dans des sites de basses altitudes.

Mots clés: Eucalyptus, hybrides, races locales, Kenya

Introduction

Forests in Kenya cover 2% of the total land area, and this falls far below the recommended 10% at international standards. Despite this, there is continued decline of forests mainly due to high demand for forest products, which calls for strategies to increase supply and subsequently reduce the rate of loss. One of the strategies is the introduction of fast-growing tree species, such as Eucalypts. Although Eucalypts originate from Australia, they are among the main plantation species in many countries due to their adaptability to many agro-ecological zones, fast growth and numerous uses (Chikamai *et al.*, 2006; Mbuya *et al.*, 1994). Brazil is the leading country in Eucalyptus plantations with 5 million ha. (McNabb, 1994), followed by China with 460,000 ha. (Jiayu and Siming, 1996). In comparison, the total Eucalyptus plantation area in Kenya is 7615 ha. (Chagala-Odera *et al.*, 2003) comprising of *E. grandis* (EG) *E. saligna (ES), E. camaldulensis (EC)* and *E. tereticornis (ET)*.

Genetic improvement of *Eucalyptus* species has been done in many countries such as South Africa (Owen and Van Der Zel, 2000), Brazil (Alzate *et al.*, 2005; Lang, 2004), China (Jiayu and Siming, 1996), and Kenya in order to improve productivity. This has resulted in high genetic gains in respective countries with Brazil having the highest productivity of 75 m^3/ha/yr (McNabb, 1994). In Kenya, the initial productivity of the most widely grown species, *E. grandis*, was between 20m^3/ha/yr (Oballa and Giathi, 1996) and 30m^3/ha/yr (Duke, 1983), but through breeding, this has doubled to 70m^3/ha/yr (Oballa and Giathi, 1996) for some regions. The current breeding program intends to increase production to 100 m^3/ha/yr.

One of the strategies for improving productivity is through hybridization. Studies have been undertaken in several countries on growth performance of hybrids including *Eucalyptus* spp. (Verryn, 2000; Wei and Boralho, 1998), Poplar (Yu and Pertti, 2003) and maize (Giauffret *et al.*, 2000), and results used to successfully establish plantations on a wide range of sites. The other strategy is by identifying the most adaptable genotypes within sites and over a wide range of environments. Stability of a genotype is realized if it performs consistently well across environments and over time (Osoro *et al.*, 2006; Goncalves *et al.*, 2003).

Performance of a genotype is affected by the environment and the interaction. High environmental influence on a genotype is indicated by high variation in performance of a specific genotype across sites. On the other hand, Genotype X Environment Interaction (GEI) is one of the major complications in breeding due to the choice of environments and complexity of forest trees (Ceccarelli, 2000). Genotype X Environment Interaction has been reported for Eucalypts (Verryn, 2000; Wei and Boralho, 1998), *Pinus silvestris* (Haapanen, 1996), Poplar hybrids (Yu and Pertti, 2003), *Psuedotsuga menziesii* (Campbell, 1992); maize (Giauffret *et al.*, 2000); and *Pinus patula*, (Kanzler *et al.*, 2003). In Kenya, there is little information on the GEI for *Eucalyptus* spp. except for preliminary studies, which indicated varied performance of Eucalyptus hybrids and local land-races (Mugwe and Tuwei, 2004; Muchiri *et al.*, 2005; Oeba *et al.*, 2005), hence the need to undertake further studies.

Eucalyptus grandis X *camaldulensis* (GC) and *Eucalyptus grandis* X *urophylla* (GU) hybrid clones were introduced from Mondi Forests, South Africa (SA) and used to establish trials in four high and three low altitude sites in Kenya. Local land-races of *E. grandis, E. saligna, E. camaldulensis and E. tereticornis* were used as controls. The aim of the trials was to determine the growth performance of these clones in comparison with the local land-races over a wide range of sites.

The objective of this paper was to determine the adaptability of four-year old *Eucalyptus* spp. and hybrid clones in Kenya in Timboroa, Embu, Machakos, Hombe, Gede, Sokoke and Msambweni.

Materials and Methods

Plant Material

Fifteen GC and three GU hybrid clones were obtained from Mondi Forests, SA. These materials were raised in hedges in the nursery in Karura. Cuttings were collected from the hedges, propagated and used to establish trials on seven high and low altitude sites. Seeds of local land-races namely, *E. grandis* (EG), *E. saligna* (ES), *E. camaldulensis (EC) and E. tereticornis* (ET) were collected, seedlings raised in the nursery and used as controls. The clones and local land-races used in establishing trials are given in Table 1, and details of the sites in Table 2.

Table 1: Hybrid clones and local land-races used in the trials on high altitude sites (Machakos, Embu, Hombe and Timboroa) and low altitude sites (Gede, Sokoke and Msambweni) in Kenya

Material	Species and clones				
	High Altitude Sites			Low Altitude Sites	
Local land-races	*E. saligna,*	*E. grandis,*	*E. tereticornis,*	*E. camaldulensis,*	*E. urophylla*
GCs	GC3,	GC10,	GC14,	GC15,	GC522,
	GC581,	GC642		GC14,	GC167,
	GC514,	GC540,	GC581,	GC584,	
	GC785,	GC796	GC784,		
GUs	GU7,	GU8,	GU21		

Table 2: Summary of altitude, soil type and mean annual rainfall of the high and low altitude sites

Site	Altitude (metres above sea level)	Type of Soil	MeanAnnual Rainfall (mm)
Machakos	2066	Volcanic ash	1400
Embu	1800	Shallow	1800
Hombe	2300	Volcanic ash	1300
Timboroa	3000	Volcanic ash	1200
Sokoke	325	Arenosols	700
Gede	13	Solonetz	940
Msambweni	10	Arenosols	1175

Experimental design

The seven trials were established in complete randomized block design with three replicates in all high altitude areas. At Sokoke, Gede and Msambweni, there were 2, 3 and 4 replicates, respectively. There were sixteen trees per plot for each trial, but not all hybrid clones and local land-races were established on all sites.

Measurements

Assessment was done at four years for all the sites for diameter at breast height (DBH), height, branching habit and stem-form. The latter two were assessed on a scale of 1-4, with 1 being the worst and 4 the best.

Data analysis

Mean average height and DBH were obtained and compared for various balanced data sets using Analysis of Variance (ANOVA) procedures. Mean Annual Increment (MAI) was also calculated for all genotypes in all the experimental sites.

For data sets that constituted many missing values and violated the assumption of normality, Generalized Linear Model (GLM) was used to determine genotypic differences within sites. Adaptability of various genotypes on different sites was analyzed using Additive Main Effect Multiplicative Interaction (AMMI) model (Gauch, 1992) to generate Interactive Principal Component Analyses (IPCA) 1 and 2 scores. The genotype and environment scores were multiplied to give the PCA model's expected value for a given genotype in that environment. Since IPCA scores usually have different interpretation and meaning of stability, AMMI stability values (ASV) were calculated using the formula by Purchase (1997). These values produce balanced measurements between the two IPCAs. Scores near zero indicate genotypes that are more stable, while those furthest from zero were less stable (Yau, 1995; Purchase, 1997). Branching habit and stem-form scores were analyzed using ordinal regression based on univariate approach. All analyses were done using Genstat 8.11 release statistical package (Genstat, 2005).

Results

High Altitude Areas

Analysis of Variance for height, DBH, stem-form and branching habit showed highly significant ($p<0.01$) differences among clones and local land-races within sites (Table 3). For the local land-races, *E. grandis* had the best growth across the four sites with a mean height of 17.6 m and MAI of 4.7 at Machakos, while *E. camaldulensis*, had the lowest mean height of 5.4 m and MAI of 1.4 in Timboroa (Tables 3 and 4). However, the overall performance for all the local land-races at Timboroa was low. Among the clones, GC15 had the highest mean height of 18.2 m at Machakos, while GC14 had the lowest at 8.3 m in Hombe. GC581 was the best clone across the sites as it ranked first in Timboroa, Embu and Hombe. Results for branching habit and stem form were consistent with those for height and DBH and were lowest in Timboroa.

Table 3: Mean Height (HT in m), DBH in cm), Stemform (SF) and Branching Habit (BH) of the high altitude sites for species and clones.

Geno	Timboroa				Embu				Machakos				Hombe			
type	Ht	DBH	SF	BH	HT	DBH	SF	BH	HT	DBH	SF	BH	HT	DBH	SF	BH
EC	5.4a	5.5a	1.8ab	2.9d	9.1a	7.6a	2.6a	3.1a	7.5a	5.6a	1.8a	2.6b	10.0a	10.6ac	1.7a	2.1
EG	7.7b	9.2b	2.6d	2.8d	10.9b	10.1b	3.0b	3.1a	17.6ef	14.6d	3.2d	3.1c	12.0c	14.4d	2.8d	2.4
ES	9.6d	11.7c	2.2c	1.9a	10.9b	10.4b	3.0b	3.0a	14.7c	12.2c	2.3a	2.0b	11.5ac	11.7b	2.2b	2.4
ET	6.7a	7.4a	1.7ab	2.7d	8.4a	6.3e	3.1b	3.7b	12.7b	9.3b	1.8a	1.6a	8.3b	9.3ac	1.7a	2.6
GC14	8.9c	11.2c	1.9ab	1.7a	11.7c	11.7c	3.1b	2.7c	17.7ef	13.2cd	2.9bc	2.4b	11.4ac	11.1a	2.0b	2.4
GC15	9.9de	11.0c	2.0a	2.1b	10.5b	10.7b	3.1b	3.1a	18.2f	14.0d	3.1c	2.5b	10.4a	11.1a	2.2b	2.7
GC581	10.1e	13.0d	2.2c	1.7a	12.1c	12.5d	3.0b	2.3d	16.1d	13.2cd	2.2b	2.1b	11.4ac	13.1bd	2.1b	2.5
GC642	9.4e	10.9c	1.7b	2.4c	12.1c	11.7c	3.1b	3.3a	17.0e	13.1cd	2.5c	2.5b	12.2c	12.6abd	2.0b	2.6
GC3	10.1e	10.9c	2.2c	1.9a	-	-	-	-	-	-	-	-	-	-	-	-
GC10	-	-	-	-	-	-	-	-	15.6cd	12.6cd	2.1b	2.1b	10.3a	13.0bd	2.1b	2.4
GC522	-	-	-	-	-	-	-	-	17.3ef	14.2d	2.9b	2.1b	12.3c	13.1bd	2.5c	2.4
s.e.d	0.645	0.730	0.219	0.226	0.465	0.582	0.159	0.233	1.166	0.721	0.238	0.304	0.650	0.866	0.197	0.299
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.009	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.731

Values with different letters are significantly different ($p<0.05$)

Machakos recorded the highest mean MAI at 4 years of 4.2 m followed by Hombe at 2.8 m (Table 4). Among the genotypes, both EG and GC15 attained the highest MAI of 4.7 m in Machakos.

Table 4: Mean Annual Increment for the high altitude sites

Treatment	Hombe MAI_4	Embu MAI_4	Machakos MAI_4	Timboroa MAI_4
EG	3.0	2.6	4.7	1.7
ES	2.7	2.3	3.8	2.1
ET	1.8	2.2	3.4	1.4
GC14	2.9	2.8	4.3	2.2
GC15	2.7	2.4	4.7	2.4
GC581	3.1	3.0	3.8	2.6
GC642	3.5	2.9	4.3	2.3
Mean	2.8	2.6	4.2	2.1
Grand total for all sites		2.9		

For across site variation, AMMI bi-plot results showed that values for Embu and Timboroa were closest to zero, indicating that they had the least mean site variation, while Hombe and Machakos had large mean site variation (Figure 1). GC14 had minimal height variation within Timboroa and Embu compared to other genotypes, which showed large variation on all sites. Similarly, GC 642, GC 581 and EG had minimal average height variation within Hombe (Figure 1). The same results were obtained when DBH was used as the response variate.

The AMMI results also showed that genotypes and sites were significantly different, accounting for 31.3% and 21.9% of the variation with p values of 0.00351 and 0.01307, respectively. The GEI, which accounted for 12.2% of the variation, was not significant. These results concur with those for ANOVA (Table 3) where various genotypes performed differently at various sites.

The IPCA scores for various genotypes gave different interpretations on their levels of stability in the trial sites (Table 5). All ASVs were not close to zero implying that none of the genotypes had stabilized at four years on high altitude sites.

Table 5: Genotype means, IPCA scores and ASV values for clones and species in high altitude sites at four years

Genotype means	Genotype [1]	IPCAg [2]	IPCAg	ASV
EG	12.00	1.38471	-0.51075	1.862
ES	11.06	0.41615	0.83213	1.174
ET	7.90	-0.29585	0.41807	0.646
GC14	11.78	-0.97505	0.16538	1.248
GC15	11.25	0.12503	0.71786	0.919
GC581	12.86	-0.78178	-0.83856	1.447
GC642	12.35	0.12679	-0.78414	1.002

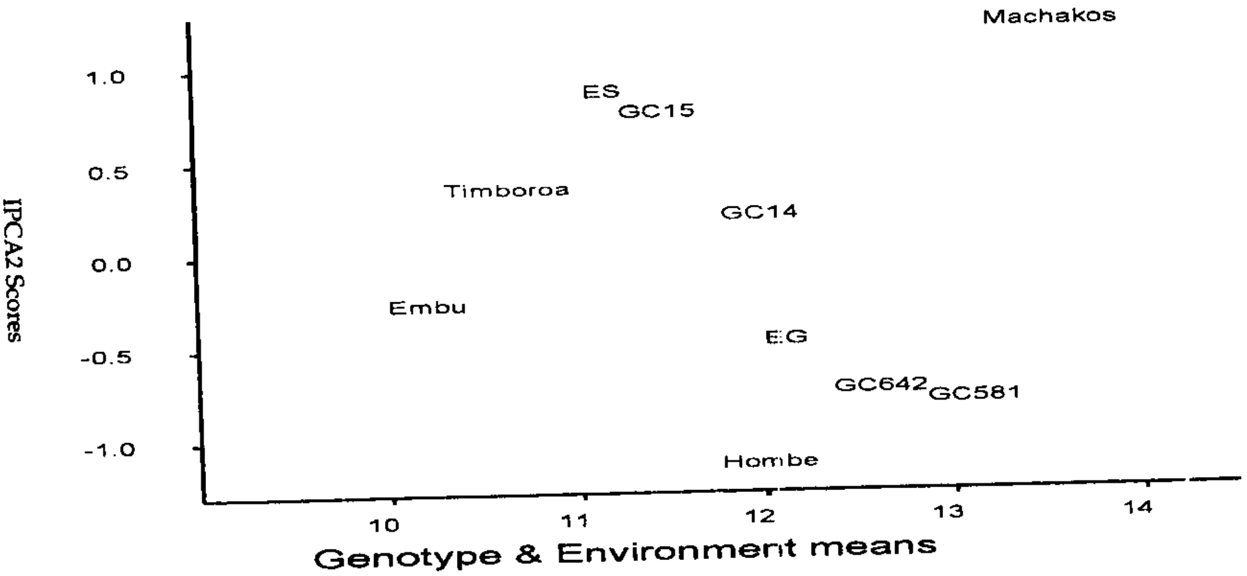

Figure 1: Genotype and Environment means versus IPCA2 scores of the Genotypes across the high altitude sites at four years.

Low altitude sites

As for the high altitude sites, result ANOVA for low altitude sites showed significant differences (p<0.01) between genotypes within sites for height, DBH, stem-form and branching habit (Table 6). Among the local land-races, *E. camaldulensis* had the highest mean height of 11 m at Gede, but the same species had the lowest height of 6.2 m at Msambweni. GC167 and GC581 had the highest mean height of 14.3 m and 14.2 m, respectively at Gede, and performed equally well across the sites, while GU7 had the lowest mean height of 5.3 m at Msambweni (Table 6).

Table 6: Mean Height (Ht in m), DBH in cm), Stemform (SF) and Branching Habit (BH) of the low altitude sites for species and clones

	Gede				Sokoke				Msambweni			
Genotypes	HT	DBH	SF	BH	HT	DBH	SF	BH	HT	DBH	SF	BH
EC	11.0c	8.1b	3.1a	2.8dc	-	-	-	-	6.2ab	5.3a	3.6a	2.5c
ET	9.2b	7.3b	3.1a	2.5dc	7.8a	7.0a	2.7a	1.9a	-	-	-	-
EU	9.9b	7.6b	2.9a	2.9dc	7.7a	7.5a	3.3b	2.5b	6.7b	5.9ab	3.6a	3.0d
GC14	13.3e	9.1c	3.7bc	2.3c	11.6c	9.1b	3.5b	4.0	8.4d	7.1c	4.0b	1.2a
GC167	14.3f	11.0d	4.0c	2.3c	11.9c	9.7bc	4.0c	3.0c	7.6c	7.1c	4.0b	2.3b
GC514	13.0e	9.0bc	3.2a	3.3e	12.3c	8.8b	3.9c	3.9e	8.1dc	6.9c	3.8ab	2.8d
GC540	12.6d	9.0bc	3.5b	3.3e	12.6c	9.8bc	4.0c	2.0a	7.3cd	6.8c	3.5a	2.0b
GC581	14.2f	10.5c	4.0c	1.7b	12.1c	10.5c	4.0c	3.5d	8.4d	7.6c	4.0b	2.0b
GC584	12.9d	10.5c	4.0c	2.0bc	12.0c	9.9bc	4.0c	4.0e	7.2c	6.5b	4.0b	2.0b
GC784	12.3d	9.2c	3.7bc	2.4c	11.3c	9.2bc	3.5b	2.5b	7.9cd	7.4d	3.7ab	2.3b
GC785	13.5e	9.6c	3.7bc	4.0f	11.5c	8.9b	4.0c	4.0e	7.9cd	6.6b	4.0b	3.9e
GC796	-	-	-	-	9.5b	7.7a	4.0c	2.5b	-	-	-	-
GU21	11.9d	9.6c	3.7bc	1.3a	12.3c	9.6bc	4.0c	3.0c	7.6c	7.4d	3.7a	1.5a
GU7	7.5a	5.7a	3.3a	2.0b	-	-	-	-	5.3a	4.8a	3.6a	2.3b
GU8	8.3a	6.8b	3.7bc	1.0a	-	-	-	-	-	-	-	-
s.e.d	0.471	0.419	0.100	0.127	0.4036	0.395	0.087	0.172	0.225	0.261	0.072	0.087
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Values with different letters are significantly (p<0.05) different

The average MAI was 2.4 m at Gede, followed by Sokoke with 2.3 m, whereas Msambweni had the lowest MAI of 1.7 m. Among the local land-races, *E. urophylla* had the highest MAI of 2.0 m at Gede, whereas GC 581 had the highest MAI of 2.8 m on the same site. Overall, clones had the higher MAI across sites compared to local land-races (Table 7).

Table 7: Mean Annual Increment of low altitude sites at four years

Treatment	Gede MAI_4	Msambweni MAI_4	Sokoke MAI_4
ET	1.8	1.3	1.8
EU	2.0	1.6	1.8
GC14	2.3	1.5	2.3
GC167	2.7	1.8	2.4
GC514	2.1	1.6	2.2
GC540	2.3	1.7	2.4
GC581	2.8	2.0	2.6
GC584	2.6	1.5	2.5
GC784	2.4	1.8	2.3
GC785	2.5	1.6	2.2
GU21	2.4	1.8	2.4
Total	2.4	1.7	2.3
Grand total for 3 sites	2.1		

AMMI results showed that some of the genotype and site means varied widely (Figure 2). Msambweni had low mean site variation compared to Gede and Sokoke. Furthermore, ET, GC784, GC584, GU21 and GC581 had low mean height variation compared to the other genotypes. GC784, GC 584 and GU21 had minimal mean height variation at Msambweni, whereas GC 785, GC 167 and GC 581 had minimal mean height variation at Gede. AMMI results also showed that 55.1% of the total source of variation was significantly accounted by sites, followed by genotypes (29.1%) both at p<0.01. The interactive component accounted for 5.9% and was not significant. This implied that site characteristics contributed greatly to growth.

The IPCA 1 and 2 scores indicated different stabilities for each genotype across sites, while ASV showed GC 784, GU 21 and GC 581 as the most stable on all the low altitude sites (Table 7).

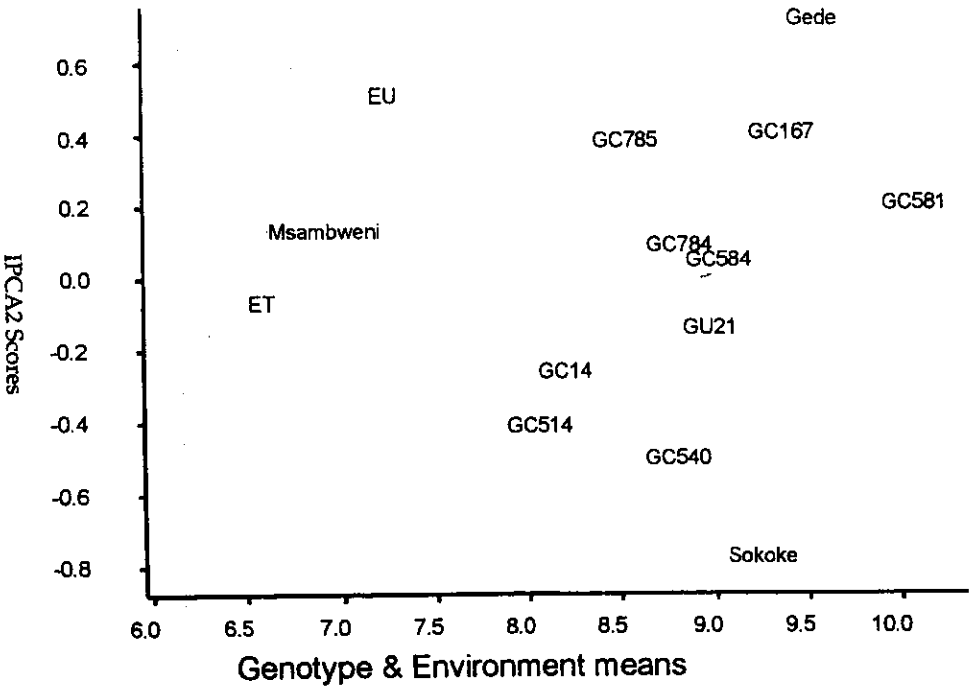

Figure 2: Genotype and Environment means versus IPCA2 scores of low altitude sites at four years

Table 7: Genotype means, IPCA scores and ASV values for clones and species in low altitude sites at four years

Genotype	Genotype means	IPCAg [1]	IPCAg [2]	ASV
ET	6.516	-0.54022	-0.08813	0.979
EU	7.168	-0.77085	0.48752	1.631
GC14	8.054	0.16071	-0.28384	0.584
GC167	9.204	0.30188	0.38355	0.873
GC514	7.890	-0.27130	-0.43423	0.916
GC540	8.615	0.07987	-0.52897	0.957
GC581	9.907	0.11710	0.17996	0.384
GC584	8.846	0.85651	0.02227	1.533
GC784	8.640	-0.21056	0.06391	0.394
GC785	8.359	0.38280	0.36165	0.942
GU21	8.842	-0.10594	-0.16369	0.349

Consequently, AMMI selected the first four genotypes with highest mean height in each site (Table 8).

Table 8: AMMI selections of the first four genotypes per site

			Rank			
	Environment	Mean Score	1	2	3	4
Gede	9.401	0.7027	GC581	GC167	GC584	GC785
Sokoke	9.069	0.4523	GC581	GC584	GC540	GC167
Msambweni	6.633	-1.1550	GC581	GU21	GC167	GC784

Gede showed the highest means of the first four genotypes compared to the other two sites (Table 7). GC581 was the best genotype for all the three sites.

Discussions

In the high altitude sites, no genotypes were identified to be adapted across sites, but performance among genotypes within sites was significantly different. However, GC581 and *E. grandis* were observed to perform well across sites although this was not captured statistically. Genotypic influence on performance was highest at 31.3%, followed by environmental influence at 21.9% and the interaction was lowest at 12.2%. This showed that most genotypes were more adapted to specific environments. Reports from other studies on Pine hybrids indicated a strong genetic relationship within but not across sites (Dungey *et al.*, 2000).

The range in altitude for the four sites was wide from 1800 m asl for Embu to 3000 m asl for Timboroa, while soils were volcanic except Embu, which had shallow soils. Thus, the high genotypic influence may have been a response to the varying environments, particularly altitude. Most of the genotypes consisted of GCs, which are expected to grow well in medium altitude areas. For the local landraces, *E. grandis* and *E. saligna* perform best on altitudes between 1200-2400 m asl, while *E. camaldulensis* and *E. tereticornis* grow well between 0-1600 m asl (Chikamai *et al.*, 2006; Maundu and Tengnas, 2005) and 600-1000 m asl (National Academy of Sciences, 1983), respectively. All the species and clones recorded the lowest growth in Timboroa, probably due to the high altitude, which appeared to also have a negative effect on stem-form and branching habit for all genotypes. Other species like *E. regnans* would be better suited for this site (Mbuya *et al.*, 1994).

Genotype-Environment Interaction did not have a significant influence on the genotypes in high altitude sites. Wei and Borralho (1998) also reported low GEI for *E. urophylla,* while Kanzler *et al.* (2003) and Lavoranti (2003) reported high GEI for *P. patula* and *E. grandis* in South Africa and Brazil, respectively.

Low altitude sites also showed high significant differences among genotypes within sites. Generally, growth performance for the local landraces was lower than that for hybrid clones, indicating that the clones were better adapted to these sites. However, the local land-races had better form and branching habit than hybrid clones. This showed that performance could be improved through selection for fast growth and hybridization. Growth performance for *E. urophyla* was comparable to other studies. For example, the MAI for this species was 1.6 m in Msambweni, while Wei and Barralho (1998) reported MAI of 1 m for the same species in tropical climate zone at the coast in China. *E. urophyla* grows best at altitudes between 300-3000 m asl (National Academy of Sciences, 1983) and in this study, it performed relatively well compared to the other local land-races. Generally, growth performance at Msambweni was half that at Gede and Sokoke, probably due to the high rainfall at Msambweni compared to the other two sites.

Unlike the high altitude sites, hybrid clones GC581, GC784 and GU21 were shown to be adapted across low altitude sites. Van Wyk *et al.* (1991) and Verryn (2000) also identified specific genotypes that performed well across sites for *Eucalyptus* in South Africa. Performance for all the other genotypes, including the local land-races, was variable across sites, showing that they may be site-sensitive.

Environmental influence towards performance of the various genotypes was high at 55.1% for the low altitude sites compared to the genotypic influence, which was 29.1% and the interaction, which had the lowest at 5.9%. Sokoke and Msambweni were planted on arenosols, which are characterized by heavy leaching, low cation exchange capacity and decalcified soil (FAO, 2001). Gede on the other hand, had solonetz soils, which are characterized by progressive leaching of salts (FAO, 2001). In addition, the mean annual rainfall for Sokoke, Gede and Msambweni were 700 mm, 940 mm and 1175 mm, respectively. Thus, the soil and rainfall patterns may have affected the performance of site sensitive genotypes leading to the high percentage influence of the environmental factors.

The GEI had no significant influence on the genotypes. This was also reported for *E. urophyla* (Wei and Borralho, 1998), where less than 5% of phenotypic variance was due to GEI. Other studies on *Pseudotsuga menziesii* (Campbell, 1992) showed high GEI in growth attributed to the variable environments to which they were grown.

Generally, the MAI was much higher in high than low altitude sites. The highest mean height in high altitude sites was 18.2 m, which was 4 m higher than that for low altitude sites at 14.3 m. Stem-form and branching habit were also better in the high than the low altitude sites. This shows that the environment, probably rainfall and altitude, plays a big part in the expression of *Eucalyptus* genotypes.

Conclusion and Recommendations

GC581 was stable in five out of seven of the study sites, namely Gede, Msambweni, Sokoke, Timboroa and Embu, while *E. grandis* was the best for Hombe and Machakos, followed by GC642 and *E. saligna*, respectively.

As no clones or local landraces were stable across high altitude sites, this suggests a breeding strategy with the main objective of producing specific genotypes for each environment. The use of genotypes that show average performance across sites would result in less growth and reduced genetic gain. The good performance of some clones across low altitude sites suggests that the same selection strategy could be used for these areas. Therefore, breeding and selection of clones and local land-races should be based on performance across sites within a target environment. The best scenario would be to breed for genotypes that perform well across sites to reduce costs.

It is recommended that for sites above 1200 m asl and mean annual rainfall of more than 1000 mm, local land-races such as *E. grandis* and *E. saligna* should be grown. However, for greater economic and genetic gain, select material should be used.

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