Scientific Paper

The effects of remedial fertilizer treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand coastal plain

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SYNOPSIS

Remedial fertilizer applications were applied to nutrient-poor stands of *Eucalyptus grandis* growing on infertile (ex-agricultural) land of the Zululand coastal plain. Two nitrogen-rich fertilizer mixtures were applied in one year-old stands at rates ranging from zero to 160 kg N ha^{-1}. Foliar nitrogen levels increased highly significantly at the higher levels of fertilization. A highly significant response to height, diameter and basal area growth was observed within 6 months of treatment initiation which was sustained until clear felling (8.3 years). A comparison of the unfertilized control with the optimum treatment (*i.e.* a single fertilizer dose equivalent to 80 kg N ha^{-1}) yielded the following results: Utilizable wood volume increased from 136.7 to 264.3 m^3 ha^{-1}. The wood density showed a weakly significant increase from 448 to 472 kg m^{-3}. The pulpability factor (defined as the pulp yield / kappa number) decreased significantly from 2.63 to 2.32. The net effect of fertilization on pulping properties is a non- significant increase in pulp yield per unit volume of timber (chiefly due to increases in wood density). The combined effects of fertilization on both volume growth and pulping properties resulted in an increase in the pulp yield on a plantation area basis from 32.03 to 63.43 t pulp ha^{-1} in the 8.3 year-old stand.

INTRODUCTION

Commercial forestry has expanded dramatically on the Zululand coastal plain during the last three decades. The soils of the Zululand coastal plain are comparatively young, of aeolian origin with low cation exchange capacities. Despite being poor in nutrients (especially N), nutrient turnover is rapid, yielding a litter decay constant (k) with a value of approximately 0.85 year $^{-1}$ (Noble, 1992). Exceptional growth rates have been recorded for eucalypts on the better sites (Jacobs *et al*., 1989). However, there are several soil bodies that are extremely infertile and which support very poor tree growth. Several such areas had been identified in the greater Mtunzini area which ultimately led to the establishment of the experiment described in this paper. A variety of factors (pedogenic and anthropogenic) may have contributed to the nutritionally impoverished condition of these soils: These are:

1) Gradients in soil fertility. In recently formed soils from aeolian origin it is common to find large fertility gradients from crest positions to bottomland positions in the topography. Accumulation of plant matter in combination with wetter conditions creates this gradient which is apparently associated with the soil organic matter content.
2) Several historic land uses have had an impact on the soil fertility on the coastal plain. Intensive agricultural management operations (e.g. burning of harvesting residues of sugar cane as well as intensive soil cultivation for production of crops such as cassava, sugar cane and pineapples) will increase the mineralisation of labile soil carbon in the short term. Repeated cultivation may lead to a pronounced drop in soil carbon levels, particularly in the labile carbon fraction.
3) Mining operations where topsoils are removed and later replaced, could also lead to decreases in fertility.

Nutritionally poor areas need to be managed differently to the remaining forestry sites on the coast. A silvicultural management regime aimed at improving the nutrient supply on the sites could include some or all of the following elements:

- Supply additional nutrients through fertilization.
- Slash conservation (i.e. a no-burn policy) to minimise nutrient losses.
- Intensive vegetation management practices to effectively reduce the competition for limited resources.
- Biological N fixation (through inter-cropping or crop rotation) to enrich the site with nitrogen.

In this experiment, only the first option (i.e. the use of fertilizer supplements to improve productivity) was investigated on an infertile (ex-agricultural) site on the southern tip of the Zululand coastal plain. In addition to an extremely infertile soil, the trial suffered from a severe drought during the first half of the rotation. The growth of this trial is thus different from stands growing under more average or “normal” conditions, and the discussion will be used to elaborate on this theme.

MATERIALS AND METHODS

Site and stand description

The Zululand coastal plain is situated between latitudes 27° and 29° south and has an altitude ranging between zero and 200 m above sea level. The area planted to commercial plantations covers approximately 93 000 ha of which 66 000 ha is planted to hardwoods, mainly eucalypt species and their hybrids (DWAF, 1998). The area has a sub-tropical climate with mean monthly temperature ranging between 16° and 27°C. The average rainfall is approximately 1200 mm a^{-1} (range 900 to 1450) and the rainfall concentration index varies between 15 and 45% (Schulze, 1997).

The specific site chosen for the experiment was situated on Stormy Ridge estate, near Mtunzini, and had a mean annual precipitation of 1160 mm over the duration of the study period **(Table 1)**. The period 1992-1994 was particularly dry, with only 56, 75 and 65 percent of the long term mean annual rainfall falling in each of these years. The soil is classified as a Fernwood soil family according to the Taxonomic system of the Soil Classification Working Group (1991) and as an arenosol in the FAO-classification. Soil samples were collected both at the trial site (infertile area with poor growth) and on a more fertile area adjacent to the trial site where tree growth was acceptable **(Table 2)**.

The stand within which the trial was implemented has been described by Noble *et al.* (1991) as follows: “Young leaves were small and chlorotic and in some instances premature shedding of the older leaves were observed. Older leaves were characterised by the presence of anthocyanin. Canopy closure had yet to be attained although the trees were 12 months of age.” Stand details at the time of treatment implementation are shown in **Table 1**.

Soil and foliar sample collection and analyses

Soil samples collected prior to treatment implementation were air dried and ground to pass through a 2 mm sieve. Soil pH was determined in 1M KCl using a soil solution ratio of 1:2.5. Exchangeable cations were extracted in 1M ammonium acetate at pH 7 and their concentrations were determined using atomic absorption spectroscopy. Organic C was determined

TABLE 1. Site and stand details at the time of treatment implementation (after Noble et al., 1991).

Category	Stand and site characteristics
Estate	Stormy Ridge
District	Mtunzini
Latitude	28^{O} 58.5' S
Longitude	31^{O} 42.5' E
Mean annual precipitation[1]	1160 mm
Range in mean monthly maximum temperature[1]	23.6 - 30.0 ^{O}C
Range in mean monthly minimum temperature[1]	10.9 - 21.1 ^{O}C
Initial spacing	2.5 x 3.0 m
Uniform fertilizer treatments	75 g LAN (28) + 30 g superphosphate (10,5%) per tree at planting
Weed control	Complete weed control in all plots
Previous crop	Sugarcane
Age of trees at trial establishment	12 months
Mean tree height at trial establishment	1.85 m
Plot size	5 x 6 tree rows

[1] Data from S.A. Sugar Association propagation Station, Mtunzini, averaged for the period 1989-1998.

through loss on ignition while available P was extracted with the Bray-2 solution and determined through the molybdenum blue method. Particle size was determined by the pipette method after dispersion and sieving. Details of the above methods of analysis are given in Donkin *et al.* (1993b).

Foliar samples were collected on 6 December 1990, i.e. 190 days after the first fertilizer treatment had been implemented. Fully expanded leaves were collected from the top third of the crown in the inner plots. Leaves were washed with de-ionised water, dried at 65°C and N was determined by the Kjeldahl method. After dry ashing, P was determined in a segmented flow auto-analyser while Ca, Mg, K, Na, Cu, Zn, Mn and Fe were determined by atomic absorption spectroscopy. Details of the methods of foliar analysis are given in Donkin *et al.* (1993a).

Trial design

Prior to this experiment, Noble and Herbert (1990) conducted a survey of sites with either poor or good growth in the Mtunzini area. At nine months of age, mean tree height in the poorer stands of this area was 1.3 m while the better performing stands had already attained a mean height of 2.7 m. The corresponding values for foliar N on poor and good sites were 1.4 and 2.3 %, respectively. Foliar N values of lower than 1.8 % in young *E. grandis* trees are regarded by most authors as less than adequate (Schönau, 1981; Dell et al., 1995; Boardman et al., 1997), while Herbert (1996) has proposed an *optimum* N level of 2.8 %. It was thus clear from this initial evaluation of the stand that the N supply was sub-optimal (Noble *et al.*, 1991). Two fertilizer sources that are rich in N but that also supply a substantial quantity of other macronutrients as well as micronutrients, Humac® and Agrofert®, were used in the experiment. Both sources can be described as inorganic fertilizers that are pre-enriched with organic substances. The chemical compositions of the mixtures used are given in **Table 3**.

Each fertilizer source was applied at rates corresponding to either 40 or 80 kg N ha^{-1}. Each of these treatments were either applied as a single application or as two equal doses six months apart **(Table 4)**. These treatments plus an unfertilized control were replicated three times and arranged in a randomised block design. The treatments together with the abbreviations used in the body of the text are listed in **Table 4.**

TABLE 2. Comparison of soils data for the trial site and an adjacent, more fertile area.

Soil description	Exchangeable cations (cmol$_c$ kg^{-1})				Σ Exch. cations	Organic C (%)	Available P (mg kg^{-1})	pH		Texture (%)		
	Ca	Mg	K	Na				KCl	H_2O	Cl	Si	Sa
Trial site (infertile)	0.77	0.11	0.09	0.32	1.36	0.14	4.5	4.0	5.3	9	2	88
Adjacent land (more fertile)	0.73	0.16	0.15	0.32	1.36	0.25	4.8	4.0	5.3	10	3	87

TABLE 3. Chemical composition of the pre-enriched organic fertilizer sources used in the trial.

Fertilizer source	N	P	K	Ca	Mg	Zn	Cu	Mn	B	Mo	Fe
	%					mg kg^{-1}					
Agrofert®	11.81	2.38	5.40	3.23	0.56	1.0	3.4	38	504	4.6	148
Humac®	5.59	2.8	6.61	5.43	0.59	73.4	14.0	110	-	-	301

TABLE 4. Fertilizer treatments imposed in the trial with abbreviations used in the text.

Fertilizer source	Application rate (kg N equivalent per ha) [1]				
	Zero	40	40 + 40	80	80 + 80
Agrofert® Humac®	Control (no fertilizer)	A 40 H 40	A 40+40 H 40+40	A 80 H 80	A 80+80 H 80+80

[1] Note that both fertilizer sources consist of a mixture of several nutrients but that the rates of application are given with respect to the N content only.

Tree growth

The stand was one year old at time of treatment implementation. Height measurements were collected immediately before treatment implementation (tree age one year) and thereafter at 1.4, 1.6, 2.1, 2.5, 3.0 and 8.3 years. The last measurement was taken with a tape measure immediately after each tree was felled to ensure an accurate determination of final height. Stocking was determined on a plot basis using the number of live trees present at each measuring date. A fair number of trees were too small to yield a meaningful dbh measurement at the time of trial initiation. The first complete set of dbh measurements was therefore only collected at 1.9 years of age and thereafter at 2.1, 2.5, 3.0, 5.1, 7.3, and 8.3 years (i.e. at clear felling). Basal area was calculated as the sum of the cross sectional stem area at breast height (1.3 m) for all trees in a plot. Volume was calculated as the sum of the individual tree volumes per plot, using the volume equation of Bredenkamp and Loveday (1984).

Silviculture and harvesting

At the time of treatment implementation, the average height of the one year-old trees was 1.85 m **(Table 5)**. The site was devoid of any competing vegetation at trial initiation, and virtually no weeds developed during the period up to canopy closure (Noble, 1991; McInnes[1]). This was probably due to the extremely poor fertility of the site. No weed control was thus necessary. The stand was not thinned since the timber was grown for pulpwood production, and the stand was clear felled at an age of 8.3 years.

Timber properties analyses

Five trees per plot in the control and A 80 treatments of each of three replications were selected and felled at 8.3 years, yielding 30 sample trees of which the wood properties were tested. The selection was done in such a way as to cover the range in dbh classes occurring in the plot. Paired disc samples (approximately 25 mm wide and spaced at one metre intervals along the tree length) were cut from the 30 sample trees, starting at the base of the stem and ending at a thin end diameter of 70 mm over bark. One disc of each pair was used for wood density determination while the second disc was used for pulping and chemical analysis.

An average value for wood density was obtained through the use of a composite sample of discs representing the entire tree. The densities of these composite samples were determined from the oven-dry mass (105 ^{O}C) and by estimating the wet volume from the displacement of water (Modified Tappi test method T285 om-85).

Discs from five trees were bulked and chipped for pulping analysis. A sub-sample was ground and screened through a 40 mesh screen in preparation for the determination of hot water and alcohol / benzene extractives (Tappi methods T207 and T204). Each sample was pulped according to the following standardized kraft cooking procedure: One kilogram of oven dry wood was pulped using 15% active alkali (expressed as Na_2O on oven dry wood chips). The heat up time to the cooking temperature of 170 ^{O}C was set at 90 minutes, and the cooking time was approximately 90 minutes and was set at 900 H factor units[2]. The sulphidity of the kraft cooking liquor was 25% and the ratio of liquor to oven dry wood was 4.6 to 1.

Screened pulp yield refers to the mass of pulp relative to the original oven dry mass of wood at the start of the cook, that passed through a 0.2 mm slotted screen. The rejects was that portion that was retained on the slotted screen. Kappa sheets were made from 10 grams of a well mixed pulp sample which was prepared on a British hand sheet machine prior to Kappa number[3] determination (Tappi test T236). Weighted fibre length, fibre coarseness and number of fibres per unit mass of pulp were determined using a Kajaani FS 200 fibre analyser.

Statistical analyses

The growth results were subjected to an analysis of variance test using the Genstat® for Windows™ statistical package (Lane and Payne, 1996). The trial was analysed as a randomised complete block in three replications. The tree height at initiation of the experiment was evaluated for use as a covariate in the analyses of variance of height data. This covariate proved to be significant only for the first measurement event at 1.4 years (i.e. 161 days after treatment). For this reason, the results from analyses for all subsequent height measurement events were not adjusted through the use of the covariate. At time of treatment implementation (one year old stand), small variations in stocking already existed between plots. These differences were not treatment induced, and for this reason, basal area data were analysed using the stocking per plot as a covariate. Means adjusted for stocking are presented for basal area data in the text that follows. The use of stocking per plot as a covariate in the analysis of volume at 8.3 years was not significant and consequently, unadjusted means are presented. For this reason, the unadjusted volume data may show more variability than the adjusted basal area data. Tree survival data were not normally distributed and were transformed for the purposes of conducting an ANOVA. De-transformed means are presented in the results section.

Due to constraints on capacity for pulping tests, only composite samples from each treatment plot (a total of six composite samples) could be submitted for pulping. The net result was that the power of the test for significance of differences between pulp samples was low. Nonetheless, the treatment means, F- probabili-

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[1] Personal communication with Mr. A.C. McInnes, ICFR Technician at time of trial implementation.

[2] The H factor is used as an indicator of the energy used in the process and is calculated by integrating the cooking time and temperature.

[3] The Kappa number is an indication of the ease of delignification during pulping and is of particular relevance if compared to other pulps cooked under the same conditions.

ties and least significant difference values at the 5% level (lsd) are listed to provide the reader with an indication of the magnitude and variation of the responses observed.

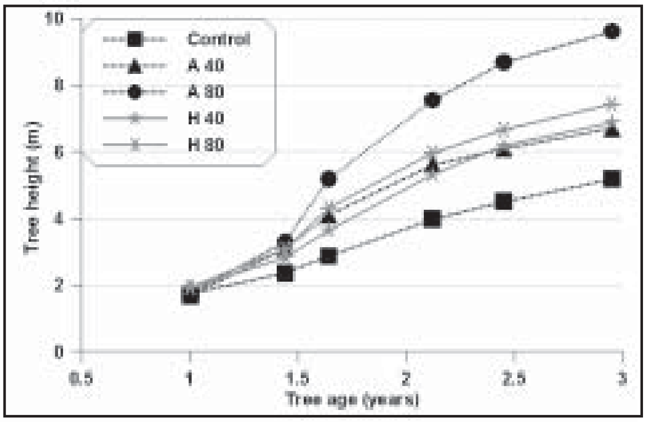

FIGURE 1. Height growth development for treatments that received single applications of fertilizer. Refer to Table 4 for the treatment codes.

RESULTS

Tree survival and growth

Tree survival at time of treatment implementation was 95.7% and did not differ significantly between the randomly allocated treatment plots at the time of treatment implementation. The total number of trees in the trial that died since treatment implementation amounted to four, which effectively decreased the survival percentage in the trial from 95.7% to 94.4%. With such a high survival rate, no significant effects of treatments on tree survival could be detected (data not presented). The early response in height growth to increasing levels of applied fertilizer is illustrated in **Figure 1.** Tree height, measured at the time of

TABLE 5. Treatment means, standard errors, F probabilities and lsd's (5%) of tree height, breast height diameter over bark, basal area and volume measurements at various stages during the growth of the tree crop in the experiment.

Variate	Age (yrs)	Control	Agrofert®				Humac®				Grand mean	F prob.	s.e.d.	lsd (p<0.05)
			40	40+40	80	80+80	40	40+40	80	80+80				
Height (m)														
H 05/90	1.0	1.75	1.68	1.75	1.74	1.77	1.92	2.06	1.94	2.00	1.85	0.170	0.147	0.311
H 11/90[1]	1.4	2.36	3.09	3.23	3.29	3.34	2.82	3.03	3.08	3.14	3.04	<0.001	0.137	0.292
H 01/91	1.6	2.87	4.10	4.79	5.18	5.27	3.64	4.21	4.31	4.58	4.32	<0.001	0.228	0.483
H 07/91	2.1	3.98	5.61	7.50	7.55	8.39	5.31	6.38	5.96	6.90	6.40	<0.001	0.436	0.925
H 11/91	2.5	4.51	6.09	8.25	8.68	9.57	6.18	7.10	6.67	7.45	7.17	<0.001	0.639	1.354
H 05/92	3.0	5.18	6.70	8.99	9.61	10.06	6.88	7.90	7.43	7.88	7.85	<0.001	0.785	1.665
H 09/97	8.3	16.65	16.79	19.29	19.87	19.84	18.06	18.26	18.40	18.82	18.44	0.033	0.972	2.060
Diameter at breast height (cm)														
D 04/91	1.9	3.83	5.37	7.33	7.57	7.90	5.13	6.30	5.87	7.00	6.26	<0.001	0.417	0.881
D 11/91	2.5	5.13	6.87	9.33	9.63	10.20	6.97	8.00	7.50	8.50	8.01	<0.001	0.596	1.257
D 05/92	3.0	6.07	7.67	10.17	10.57	10.83	7.80	9.07	8.37	9.03	8.84	<0.001	0.725	1.530
D 07/94	5.1	9.30	11.17	12.97	13.67	12.83	10.57	11.80	12.03	11.23	11.73	0.007	0.925	1.952
D 09/96	7.3	12.63	13.87	15.77	15.73	16.13	13.93	15.43	15.43	15.17	14.90	0.015	0.873	1.843
D 09/97	8.3	13.47	14.67	16.57	16.50	17.00	14.87	16.33	16.30	16.17	15.76	0.024	0.929	1.961
Basal area (m^2 ha^{-1})														
B 07/91[2]	1.9	2.25	3.97	6.87	6.78	8.45	3.56	5.71	4.48	6.50	5.40	<0.001	0.668	1.410
B 11/91[2]	2.5	3.02	5.06	8.61	8.84	10.67	4.54	7.20	5.60	7.88	6.82	<0.001	0.898	1.894
B 05/92[2]	3.0	3.78	6.44	10.33	10.68	12.16	5.65	8.64	6.77	8.76	8.13	<0.001	1.186	2.503
B 07/94[2]	5.1	8.76	12.41	17.88	18.23	17.86	9.75	14.39	15.68	13.16	14.25	0.002	2.037	4.298
B 09/96[2]	7.3	17.63	21.79	26.41	27.44	27.01	21.08	25.49	25.32	24.75	24.10	0.012	2.396	5.055
B 09/97[2]	8.3	20.14	24.42	29.39	30.33	30.34	24.18	29.24	28.78	28.26	27.23	0.018	2.726	5.752
Volume (m^3 ha^{-1})														
V 09/9	3020	136.7	188.3	230.7	264.3	227.3	191.7	234.7	206.3	223.0	211.4	0.031	30.14	63.60

[1] denotes the use of initial height measurement (H 05/90) as covariate in the analysis of variance and the calculation of adjusted means.

[2] denotes the use of stocking per plot at the time of measurement as covariate in the analysis of variance and the calculation of adjusted means.

treatment implementation (age one year), was not significantly different between treatments **(Table 5).** There was no benefit to applying fertilizer in two doses over that of a single application. For example, the growth response to the optimum level (80 kg N ha^{-1}) applied as single doses (treatments A 80 and H 80) attained similar height, basal area and volume growth to that of the respective split applications (treatments A 40+40 and H 40+40 - see Table 5). For this reason and for clarity, early height growth is shown only for those treatments that were applied as single doses in ***Figure 1***. A pronounced divergence between fertilized and control treatments can be seen immediately after the initial treatment application (***Figure 1***). This resulted in a highly significant response to fertilization as early as the first measurement event which took place only 161 days after treatment implementation (i.e. tree age 1.4 years).

Immediately following this measurement event, a second divergence between the growth rates of treatments can be observed. The treatments receiving fertilizer mixtures at a rate of 80 kg N equivalent per ha or more showed an increased growth response over those treatments receiving dosages containing only 40 kg N ha^{-1}. The response in height growth to the application of fertilizer at a rate of 80 kg N ha^{-1} or more remained significant up to clear felling age at 8.3 years **(Table 5)**.

The treatments with Agrofert® and Humac® fertilizer sources showed slightly different responses to fertilization, particularly in the short term. The Agrofert® treatments yielded a more pronounced and more rapid response to fertilization than the Humac® treatments by 1.4 years of age (***Figure 1***). This difference was most obvious and was sustained for longer at the higher dosage levels. **Table 5** shows that when the trees reached maturity (8.3 years) the difference in height between fertilized and control plots was still significant (p=0.033). However, at 8.3 years, the differences in height growth response between fertilizer sources and dosages, were insignificantly small **(Table 5)**.

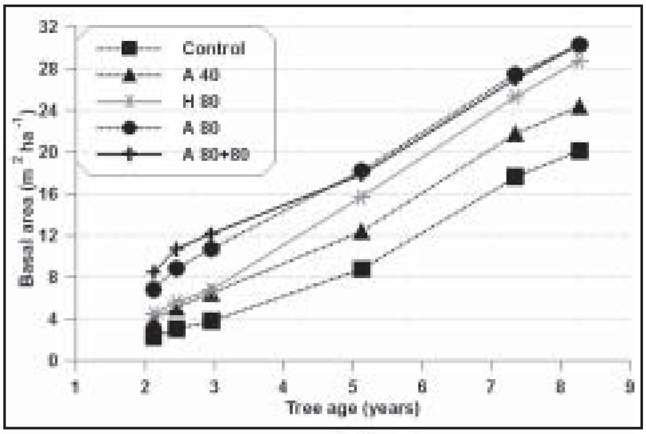

FIGURE 2. Basal area development of selected treatments over time. Refer to Table 4 for the treatment codes.

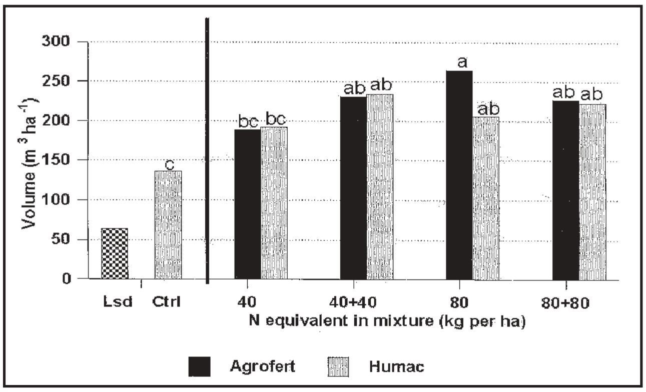

FIGURE 3. Volume response at time of clear felling (8.3 years) for all treatments. Refer to Table 4 for treatment codes. Bars capped by the same letter are not significantly different at the 5 % probability level.

TABLE 6. Foliar nutrient concentrations at tree age 1.5 years .

Treatment	Macronutrient concentrations (%)					Micronutrient levels (mg kg^{-1})			
	N	P	K	Ca	Mg	Mn	Fe	Zn	Cu
Control	1.50	0.19	0.91	1.31	0.33	976	186	16	8
A 40	1.65	0.18	0.93	1.05	0.31	724	198	14	6
A 40+40	1.82	0.20	0.97	1.10	0.31	732	199	14	6
A 80	2.32	0.19	1.05	0.91	0.29	581	160	13	7
A 80+80	2.20	0.20	1.00	0.99	0.30	692	198	13	6
H 40	1.37	0.20	0.96	1.22	0.31	1062	178	15	7
H 40+40	1.60	0.21	1.07	1.07	0.34	847	189	14	7
H 80	1.58	0.20	1.15	1.02	0.31	715	189	13	7
H 80+80	1.58	0.20	1.14	1.02	0.31	693	182	13	6
F prob.[1]	**<0.001**	- [2]	0.164	**0.035**	0.249	**0.022**	0.464	0.375	- [2]
s.e.d	0.08		0.09	0.10	0.02	119	17	1.3	
Lsd.(5%)	0.17		0.20	0.21	0.04	252	37	2.7	

[1] Values where the F statistic indicates a significant difference are printed in bold

[2] Analysis of variance not conducted, as data violated the assumptions of ANOVA.

Accurate measurements of the tree diameter at breast height (and consequently, basal area) could only be obtained from age 1.9 years since some trees were still too small at the onset of the trial. By that time, most of the treatments had already shown some response to fertilization. For clarity, only selected treatments are shown to illustrate the development of basal area over time (***Figure 2***). Treatment H 40 responded in a similar way as A 40. The "40+40" treatments of both sources responded similarly to their respective treatments at level "80". It follows that three groups of treatments are evident: The control plots, the treatments that received 40 kg N equivalent per hectare, and the treatments that received 80 kg N ha^{-1} or more. The basal area development curve (adjusted for stocking differences; ***Figure 2***) showed that the responses to (a) 80 kg N ha^{-1} and (b) 80 + 80 kg N ha^{-1} are almost identical. It is concluded that the response to increasing dosages of fertilization appears to be quadratic and that an application of 80 kg N ha^{-1} is likely to be close to the optimum application rate.

Volume response to fertilization when clear felled at 8.3 years is shown in ***Figure 3***. The three groups of treatments (control, 40 kg N ha^{-1} and 80 kg N ha^{-1} or more) are clearly discernable. ***Figure 3*** also shows that there are only minimal differences between fertilizer sources at equivalent levels of application. The only exception is the H 80 treatment where the volume is much less than expected when compared to the trend shown by the other levels. A lower than normal survival rate (85% in this treatment) is most likely to be the single most important reason for this response. The low survival rate is not echoed in other treatments (even the higher levels) which suggests that the mortality is unlikely to be caused by fertilizer scorch.

Foliar samples were collected when the trees were 1.5 years old, i.e. 190 days after the initial fertilizer application and 8 days after the re-application treatments had been implemented. N foliar concentrations responded highly significantly ($p<0.001$) to the fertilizer applications **(Table 6)**. A value of 1.5% N in the foliage of the control plot shows that the trees were strongly deficient in N. Critical values for foliar N in *E. grandis* had been estimated by Barros and Pritchett (1979) as 2,2%. Note that the optimum level for foliar N for *E. grandis* proposed by Herbert (1996) is 2,8%. The average level of foliar N per treatment is shown in ***Figure 4***. The Humac® treatments did not result in significant changes to the foliar N concentration over the control. Tree size had already increased dramatically in all fertilized treatments by age 1.5 years (***Figure 1***) and therefore concentration of nutrients could have been diluted by the growth response. A small (non-significant) dilution effect relative to the control is visible for treatment H 40 in ***Figure 4***, while the other Humac® treatments maintained their N concentrations at the level of the control. As explained earlier, definite increases in N uptake would be needed to maintain N levels in the faster growing trees. The most dramatic effect on foliar N could be observed in the Agrofert® treatments, especially the higher application levels. Based on international literature, which suggests that ammonium is the preferred source of N for uptake by trees, Noble (1991) has suggested that the difference between treatments may be related to the N source. The Agrofert® mixture contains predominantly ammonium sulphate as opposed to the ammonium nitrate blend of the Humac® treatments. The treatment with the optimum volume growth response (A 80) is the only treatment where the N foliar concentration increased beyond the proposed critical level of 2,2 % after fertilization.

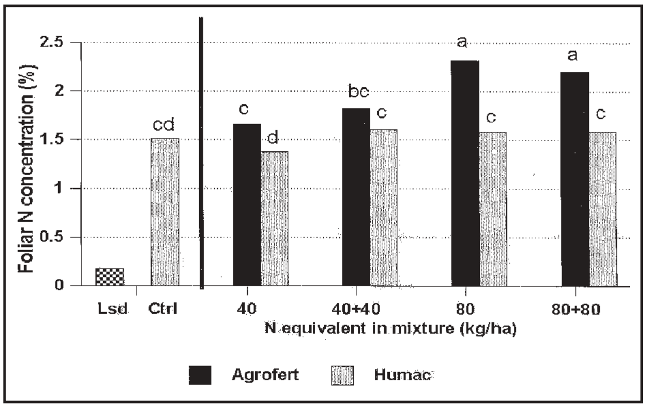

FIGURE 4. Foliar nitrogen concentrations across treatments at age 1.5 years. Refer to Table 4 for treatment codes. Bars capped by the same letter are not significantly different at the 5 % probability level.

There were insignificantly small differences between treatments with respect to foliar K and P levels (Table 6). An optimal level for foliar P of 0.15% has been proposed by Herbert (1996). Levels of foliar P

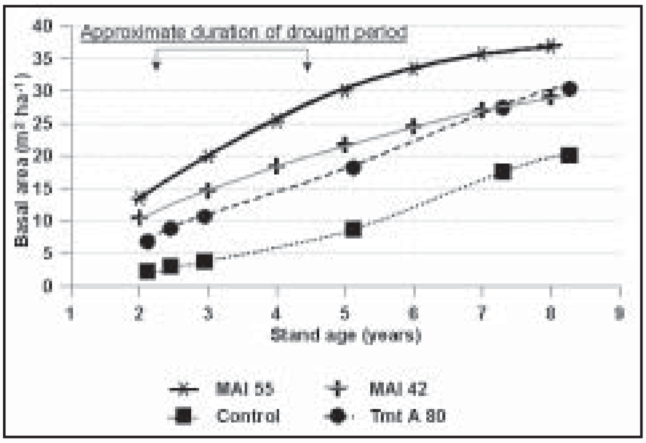

FIGURE 5. Contrasts in basal area development over time for two sets of curves. The solid lines represent spacing trials with peak mean annual increments of 55 and 42 m^3 ha^{-1} and were taken from external data (published by Coetzee, 1995, and Coetzee & Naicker, 1988). The dotted lines represent the control and optimum treatments from the fertilizer trial, which had been established on extremely infertile soil. The drought period indicated on the graph is applicable to the treatments of the fertilizer trial only.

were high in all treatments, probably due to repeated P applications during earlier agricultural land use. Foliar calcium levels decreased significantly in the fertilizer treatments with higher levels of application **(Table 6).** A value of > 1% has been proposed by Herbert (1996) as an optimum level. The A 80 treatment level is similar to that level. The critical level below which Ca would be deemed deficient is < 0,05% (Dell *et al*., 1995). Foliar concentrations of the micronutrients tested in fertilized treatments show slight changes relative to the control **(Table 6)**, but only the change in Mn level is statistically significant. The difference in concentration relative to the control is most marked in the fastest growing treatment (A 80). Despite the differences, none of the Mn values is deemed to be either deficient or toxic since the range of optimum Mn concentrations in eucalypts and many other tree species is wide.

Timber properties of selected treatments

Wood properties of bulked samples (consisting of five trees per plot) were analysed for the control and treatment with optimum growth (treatment A 80). Due to capacity constraints at the time, individual tree samples could not be used for pulping properties tests. The only test carried out on individual tree samples was that of wood density. For eight of the twelve test variables, the differences between treatments were fairly small and were not statistically significant **(Table 7)**. Four tests showed more substantial differences between treatments **(Table 7)**:

- Wood density of the fertilized treatments was greater than that of the unfertilized controls, although this was only weakly significant (p=0.052). Results obtained by Wilkens (1990), Cromer *et al*. (1998) and Little (1999) show that increases in the growth rate of young *E. grandis* stands brought about by improved silvicultural practices such as weeding and fertilization may lead to increases in basic wood density.
- Fertilized plots had a lower screened pulp yield than the control plots. The effect was weakly

TABLE 7. Results of statistical analysis of pulping properties of selected treatments.

Number of tests per plot (samples)	Variable	Grand mean	Control	Fertilized (treatment A 80)	F prob.	s.e.d.
Five tests per plot (n=30)	Wood density kg m^{-3}	460.1	448.2	472.0	0.052	8.73
One test per plot (n=6)	Hot water extractives (%)	1.617	1.538	1.695	0.247	0.1161
	Alcohol/benzene extractives (%)	1.442	1.425	1.459	0.591	0.0596
	Klason Lignin (%)	32.77	31.80	33.73	0.227	1.354
Two cooks per plot (n=12)	Weighted fibre length (mm)	0.7267	0.7333	0.7200	0.374	0.0133
	Fibre coarseness (mg per 100m)	6.600	6.567	6.633	0.579	0.1106
	No. of fibres per gram (10^6)	25.07	24.70	25.43	0.296	0.605
	Screened pulp yield (%)	51.59	52.32	50.87	0.059	0.553
	Rejects (%)	1.011	0.921	1.101	0.136	0.0966
	Kappa number	20.97	19.93	22.00	0.032	0.642
	Pulpability factor [1]	2.475	2.633	2.317	0.041	0.1067
	Pulp yield per volume of timber (kg m^{-3})	237.2	234.3	240.0	0.227	3.97
	Pulp yield on a plantation area basis [2] (t ha^{-1})		32.029	63.432		

Note:

[1] Pulpability factor = screened pulp yield / kappa number. Traditionally pulpwood samples are cooked three times to obtain kappa numbers of approximately 20. The screened pulp yield is then interpolated to a kappa number of 20. However, when the standard method is not adjusted for specific incoming material (which is standard practice in most mills), the kappa numbers of different batches of pulp may vary. The pulpability factor is a simple way of "correcting" the screened pulp yield and has merit when comparing pulpwood samples with slightly different kappa numbers. Since most pulp mills cook to a standard procedure, interpolating to a kappa number of 20 does not indicate the pulpwood quality as experienced by the pulp mill. Determination of the pulpability factor for standard recipe laboratory pulping will yield a more process related comparison.

[2] Product of the mean volume yield per hectare (Table 5) and the mean pulp yield per volume of timber for the two treatments.

significant (p=0.059). This finding is contrary to that of Cromer *et al.* (1998), who found a significant increase in screened pulp yield with increasing level of fertilization.
- Pulp made from trees in the fertilized plots had significantly (p=0.032) higher Kappa numbers than the control plots. Little (1999) found that trees in a strip weeded treatment produced greater volumes of timber but yielded pulps with higher kappa numbers than weedy controls, which is consistent with the findings in this trial.
- The pulpability factor is significantly higher (p=0.041) in control plots than in fertilized plots.

DISCUSSION

To illustrate the potential development curve of basal area over time on sites in south-eastern Zululand, in the absence of the strongly limiting influences of extreme infertility or drought, additional data are presented. Coetzee (1999) has established spacing trials with optimum silvicultural treatments across a wide range of sites that approximate the range in productivity potential of eucalypts grown on the eastern seaboard of South Africa. Trials with site index (SI) values of 26, 21 and 13 m at 5 years (classed as having a high, medium and low productivity potential, respectively) yielded approximate peak mean annual increments (MAI's) of 55, 42 and 18 m^3 ha^{-1}. The south-eastern portion of the Zululand coastal plain generally has very good climatic conditions for tree growth. The area surrounding the trial site, for example, has a long term mean annual precipitation (MAP) of approximately 1200 - 1300 mm which is well spread through the year. If the nutrition of the site is good and if general silvicultural management and genetic quality of the planting stock is adequate, fairly high yields can be expected (certainly MAI's in excess of 40). To illustrate the potential productivity that can be expected in the area (given adequate levels of rainfall, soil fertility and silvicultural inputs) two curves have been plotted in ***Figure 5:*** those of trials that produced a peak MAI's of 42 and 55 m^3 ha^{-1} a^{-1} (after Coetzee, 1995; Coetzee and Naicker, 1998). The development of basal area from age two to eight years for the control and optimum treatment in the fertilizer trial (Agrofert® @ 80 kg N ha^{-1}) is also shown in ***Figure 5***. The approximate duration of the period of sub-optimal rainfall has been annotated on the graph. The following important issues are borne out by the graph:

- One of the most dramatic effects is the separation in basal area growth that already existed between the treatments and potential productivity curves at age two years. This separation had developed from planting time and is thought to be primarily due to poor stand nutrition on the infertile trial site, since rainfall over this period, silvicultural management and genetic material were all conducive to high yields. Fertilization had largely overcome the limitation posed by the extremely infertile site. Foliar results presented earlier have shown that the Agrofert® treatments that supply 80 kg N ha^{-1} or more can elevate the N concentrations to levels of approximately 2.2%, which is considered a minimum level for any productive *Eucalyptus grandis* plantation. The effect of improved stand nutrition (difference between optimum and control treatment curves in ***Figure 5***) can clearly be seen.
- A decrease in basal area growth corresponding to the drought period is evident for the treatments of the fertilizer trial. From tree age 3 to 5 years, the slopes of the basal area development curves for both treatments in the fertilizer trial are slightly flatter than the slopes of the potential productivity curves over the corresponding period. This appears to be a response to the drought. Early height growth results have shown the dramatic response to high levels of N application. The subsequent drought that persisted in this region from 1992-1994 had a very definite depressive effect on the yield. It is possible that the response to the high N dosages applied as Agrofert® could have been greater had it not been for the drought, although it cannot be proven from the data sets presented.

The effect of site quality on a range of pulping properties for an *E. grandis* clone have been documented by Retief *et al.* (1997), working with wood produced on sites where the site index ranged between 14 and 21 m at 5 years of age. That study clearly indicated that trees growing on better sites (higher SI's) were associated with improved screened pulp yields, pulps with lower kappa numbers, longer weighted fibre lengths, lower extractives and lower lignin content. However, fast growing trees cannot always be associated with superior screened pulp yields: Little (1999) found that an increase in the level of weed control in a young stand of an *E. grandis x camaldulensis* hybrid resulted in increases in volume growth at rotation age. The growth response was mostly due to the rapid rate of growth in *young* weed free stands, since the rate of growth in this treatment declined markedly towards the end of the rotation. The growth response was associated with increases in the extractives content and active alkali consumption of the pulp. These negative effects on pulping properties were attributed to a decrease in the growth rate towards the end of the rotation.

The growth rate of the treatment A 80 increased rapidly from treatment implementation up to 2.5 years of age, after which the response was essentially maintained until maturity **(Figure 2)** Increases in the kappa number and extractives content as well as a decrease in the screened pulp yield were recorded for treatment A 80 relative to the control. These slight deteriorations in some of the pulp characteristics followed the same trend as the weed free treatments in Little's (1999) study. It is possible and indeed likely that treatment A 80 in the fertilizer trial and the weed free treatment in Little's trial had allocated more resources to above ground growth and less to root growth. Such a change in biomass allocation could render these treatments increasingly vulnerable to water stress as the trees mature, thus impacting negatively on some pulping properties.

CONCLUSIONS

Application of high levels of N (up to an optimum level of 80 kg ha^{-1} and applied in the presence of smaller amounts of P, K and other nutrients - see Treatment A 80 in Table 4) has had a rapid effect on stand growth and this effect was sustained until 8.3 years of age. The response was associated with a sharp increase in foliar N levels. The response was obtained despite the late application of fertilizer (at stand age one year) and despite a severe drought which followed immediately after treatment, and can thus be recommended with confidence in young, established stands where foliar N levels are critically low.

Wood density increased slightly with fertilization, but the screened pulp yield was decreased. Economically, a one percent increase in screened pulp yield is equivalent to an increase of 10 kg m^{-3} in basic wood density. The reduction in screened pulp yield of 1.5 % in the fertilized treatment is more than compensated for by the 24 unit increase in basic wood density. This resultant net improvement is indicated by the slight increase in pulp yield per volume of timber **(Table 7)** from 234 to 240 kg m^{-3}.

In the big picture, the small positive result with wood density and the small negative result obtained with pulping properties were overshadowed by an extremely large positive response in volume growth. The combined response in tree growth and pulp yield per volume of timber was expressed as the increase in pulp yield on a plantation area basis. This combined response increased the final screened pulp yield from 32.0 to 63.4 tons per ha of trees at age 8.3 years (Table 7). The optimum fertilizer treatment (A 80) thus virtually doubled the final yield per hectare.

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