Ann. For. Sci. 60 (2003) 673–680
© INRA, EDP Sciences, 2004
DOI: 10.1051/forest:2003061

Original article

The relationship between vegetation management and the wood and pulping properties of a Eucalyptus hybrid clone

Keith M. Little[a]*, Johannes van Staden[b], G. Peter Y. Clarke[c]

[a] Institute for Commercial Forestry Research, PO Box 100281, Scottsville, 3209, South Africa
[b] Department of Botany, University of Natal, South Africa
[c] Agriculture Western Australia, South Perth, Australia

(Received 24 June 2002; accepted 7 April 2003)

Abstract – When felled at 7 years of age, *Eucalyptus grandis* × *camaldulensis* trees from three vegetation management treatments (manually weeded treatment, 1.2 m row weeding treatment and a weedy control) were tested for selected wood and pulping properties in a trial in Zululand, South Africa. Weed control significantly improved merchantable volume of the manually weeded (230 m^3 ha^{-1}) treatment over that of the 1.2 m row weeding (171 m^3 ha^{-1}) or weedy control (138 m^3 ha^{-1}). A significant increase in fibre length, density, extractable content and active alkali consumption was recorded with increased weed control. As no significant treatment differences were detected for screened pulp yield, differences in the pulp yield ha^{-1} could be attributed to differences in the merchantable volume, with a 22.6% and 40.8% increase in the pulp yield ha^{-1} for the manually weeded treatment in comparison to the 1.2 m row weeding treatment and the weedy control.

vegetation management / eucalypt / wood properties / pulping properties

Résumé – **Relations entre gestion de la végétation et les propriétés du bois et de la pâte d'un clone hybride d'Eucalyptus.** On a testé un certain nombre de propriétés du bois et de la pâte de sujets d'un hybride d'*Eucalyptus grandis* × *camaldulensis* soumis à trois traitements de la végétation concurrente (désherbage manuel, désherbage de bandes de 1,2 m, terrain enherbé) abattus à l'âge de 7 ans dans un essai situé dans le Zululand en Afrique du Sud. Le contrôle de la végétation a significativement amélioré la production de volume marchand dans le cas du désherbage manuel (230 m^3 ha^{-1}) qui s'est révélé supérieur au désherbage en bande de 1,2 m (171 m^3 ha^{-1}) et au témoin enherbé (138 m^3 ha^{-1}). Le contrôle de la végétation s'est accompagné d'un accroissement significatif de la longueur des fibres, de la densité, du contenu de produits extractibles, et de la consommation d'alkali active. Aucune différence n'a pu être détectée entre traitements pour le rendement papetier, les différences de production de pâte à l'hectare résultent de celles de production de bois marchand ; ce qui donne un gain de production de pâte de 22,6 % et 40,8 % pour le traitement désherbage manuel, comparé au traitement désherbage en bande de 1,2 m et au témoin enherbé.

gestion de la végétation / eucalyptus / propriétés du bois / propriétés de la pâte

1. INTRODUCTION

Wood is one of man's most important resources, with its significance increasing in a world of limited resources [6]. Pulp is an important end use of wood, amounting to 653 million m^3 or 20% of total wood consumption in 1991. In the 1950's, 95% of paper was made of wood fibre, with 90% of that wood fibre obtained from coniferous wood. Forty years later, with a five-fold increase in world consumption, wood fibre still accounts for 90% of total fibre input. Non-coniferous species now contribute 30%, with an increasing fraction of this made up of eucalypts, which are grown mainly in the subtropics and tropics [7]. In Zululand *Eucalyptus* hybrid clones are grown over short rotations, ranging from six to nine years. In order to meet the increasing demand for pulpwood from this source, forestry companies will need to increase their timber output. This may be done either by increasing the amount of timber attainable from the existing land base, or through the acquisition of additional land [6, 31]. In South Africa, present and future land use policies are likely to restrict the conversion of non-afforested land to plantations. Factors that may contribute to an increase in yield and pulpwood from an existing land base include the use of site-species matching [24, 35], tree breeding and clonal propagation [37], interspecific hybrids [16, 18] and improved silvicultural practices. An estimated 40% increase in timber yields in South Africa could be achieved through the consolidation and improvement of present silvicultural management practices when combined with an improvement in present site-species matching and the breeding of superior trees [38]. Of the silvicultural management practices which have been shown to increase the potential volume obtained at harvest, combinations of appropriate site preparation, fertilization and weed control are considered to be most important [12, 14, 23, 36, 41, 45]. These have also

* Corresponding author: keith@icfr.unp.ac.za

been shown to have an influence on the rate of growth and hence the pulping properties of trees [46, 47].

Of the silvicultural management practices that may affect tree performance, there is an absence of information linking the long-term impact of vegetation management on eucalypts grown in South Africa and how this may influence pulpwood quality and yield. End of rotation data from a vegetation management trial were used to quantify if any negative or positive impacts on pulpwood quality and yield resulted from different methods of controlling competitive vegetation.

2. MATERIALS AND METHODS

2.1. Study site and treatments

The study was conducted near the coastal town of Mtunzini, KwaZulu-Natal (28° 59' S and 31° 42' E). The climate is classified as sub-tropical, with a mean annual rainfall and temperature of 1144 mm and 22 °C respectively. The trial was located at an elevation of 45 m on an east facing slope. Soil parent material is of aeolian origin and is classified as an arenic lixisol and arenic kandiustult, respectively. A pre-plant spray with a non-selective herbicide (glyphosate) was undertaken prior to the establishment of *Eucalyptus grandis* × *camaldulensis* clonal hybrids (GC304). Trees were planted on 22nd October 1990 at an interrow espacement of 3 m and an intrarow spacing of 2.5 m that resulted in a stocking rate of 1333 stems ha^{-1}. Each tree was fertilized at planting with 60 g limestone ammonium nitrate (LAN) (28% N), applied in a 0.2 m diameter ring around each tree. Nine treatments replicated four times were imposed on the stand of hybrids. These included a weedy control, a manually weeded treatment, a chemically weeded treatment, a 1.2 m row and 1.2 m interrow weeding, a 0.5 m radius ring weeding, a complete weeding except for a 0.5 m radius ring around the tree, and the use of two legume cover-crops, *Vigna sinensis* (cowpea) and *Mucuna puriens* (velvet bean). Each treatment plot consisted of 30 trees (5 rows × 6 trees in each row) with the inner net plot of twelve trees being measured (3 rows × 4 trees in each row). Each treatment plot covered an area of 225 m^2, with the total size of the trial being 6750 m^2.

2.2. Determination of tree volume and wood and pulping properties

At 7 years of age, trees from three treatments (manually weeded treatment, 1.2 m row weeding treatment and the weedy control) were tested for selected wood and pulping properties. These treatments represented a diverse range in terms of tree growth and performance, the factors most likely to affect wood and pulping properties. Five of the twelve measured trees were randomly selected in a stratified manner from each treatment plot using the diameter at breast height measurements taken prior to felling. As each treatment was replicated four times, twenty trees per treatment and sixty for the whole trial were assessed. When felled, the height to a minimum over bark stem diameter of 0.07 m ($H_{0.07}$) was determined as were under bark diameter measurements at one metre intervals, from the base of the stem to the $H_{0.07}$. From each one metre section, the under bark volume (V_{sec}) was calculated using the formula for a truncated cone. The sum of these were used to determine the merchantable underbark volume (V_m in m^3) on an individual tree basis. The V_m equating to an underbark volume up to the minimum overbark diameter (0.07 m) that can be utilized. From this, the total merchantable volume per hectare (V_{mha}) was calculated with the use of the stocking obtained for the respective treatment plots.

After the trees were felled, 0.12 m discs were cut at breast height (1.3 m above ground level), 5%, 15%, 35% and 65% of the total tree height. Wedges cut from these discs were used to determine either whole tree density (TAPPI test method T258 om-89) or extractable content of the wood. The product of the merchantable volume per hectare (m^3 ha^{-1}) and the density (kg m^{-3}) divided by 1000 gives an indication of the timber yield per hectare (tons ha^{-1}). For the determination of the extractable content, individual wedges from each disc were chipped and Wiley milled in order to obtain a sample of air dried sawdust to pass through a 0.40 mm screen (TAPPI test method T 257 cm-85). The ground wood from these wedges per tree were combined and the ethanol-benzene (T 204 om-88) and hot water (T 207 om-88) extractable content of each sample was determined.

Individual tree samples for pulping were made up by combining 0.02 m discs cut at one metre intervals up the height of the tree in order to obtain a sample of 4.5 kilograms. The discs were chipped by a guillotine-type laboratory chipper to produce chips of a uniform size. Samples were pulped in an electrically heated, batch type, rotating digester using the Kraft process. The pulping conditions used in this study were selected to achieve a Kappa number of between 20 and 22 and a pulpability factor (screened pulp yield divided by the Kappa number) of greater than 2.34.

Pulping conditions were as follows:

- Active alkali charge (% Na_2O) of oven dry wood = 16%;
- Sulphidity of the cooking liquor = 25%;
- Liquor : wood ratio = 4.5 mL : 1 g;
- Pulping cycle: Ambient to 170 °C = 90 min;
- Time at 170 °C = 50 min;
- Degassing was carried out at 115 °C and at 135 °C to remove gasses not condensible in water at such a rate that no liquor was lost from the digester;
- Blowdown to atmospheric pressure at end of cook = 20 min.

A spent (black) liquor sample was taken through a coil condenser at the end of the cook but prior to blowdown and this was analyzed for residual alkali content (TAPPI test method T625 om-85). After the chips from each tree had been pulped the Kappa number was determined (TAPPI test method T236 cm-85). The Kappa number is the volume (mL) of 0.1 N potassium permanganate solution consumed by one gram of moisture-free pulp. The results are corrected to 50% consumption of the permanganate added. Immediately after removal from the digester, the pulp samples were screened through a 10 mesh screen onto a 60 mesh receiving screen by means of a water jet. From this the screened pulp yield and total pulp yield could be determined. The screened pulp yield excludes any pulping rejects. The pulp yield is the mass of pulp produced per mass of oven dry wood and is expressed as a percentage. This gives an indication of the amount of pulp produced relative to the amount of wood pulped. Using the data obtained from the screened pulp yield (%) and timber yield (tons ha^{-1}) the pulp yield per hectare (tons ha^{-1}) was calculated.

A single sub-sample was taken from the pulp of each individual tree for the determination of the fibre length and fibre coarseness using a Kajaani FS-200 optical fibre length analyser. The analyser provides the arithmetic mean length (mm) of the fibres per sample as well as the total number of fibres in the mass (mg). From this the weighted mean fibre length (mm) and the fibre coarseness can be calculated as the mass of fibres per unit length (mg m^{-1}).

2.3. Statistical analyses

Bartlett's test [40] was used to test the assumption of homogeneity of variance in order for a valid analysis of variance to be performed. Only the properties of active alkali consumption and fibre coarseness were significantly different ($P < 0.05$) indicating the presence of heterogeneous variance. The Fisher-Behrens test [8] where separate variance estimates for the samples, was used to determine differences of

Table I. Summary of analyses of variances and data for wood and pulping properties.

Source of variation	DF	Merchantable volume (m^3 ha^{-1})	Fibre length (mm)	Fibre coarseness (mg m^{-1})	Extractable content: Hot water (%)	Extractable content: Ethanol Benzene (%)	Density (kg m^{-3})	Timber yield (tons ha^{-1})	Active alkali (%)	Kappa number	Pulpability factor	Screened pulp yield (%)	Pulp yield (tons ha^{-1})
Mean Squares													
Rep	3	8458^{ns}	0.0009^{ns}	0.00003^{ns}	0.70^{ns}	0.0924^{ns}	1702.1*	3099^{ns}	6.29 ^{ns}	1.54^{ns}	0.037^{ns}	2.04^{ns}	786^{ns}
Treat	2	43450*	0.0036*	0.00002^{ns}	1.06^{ns}	0.9176*	1376.5*	11805*	18.9*	15.27*	0.213*	0.29^{ns}	3167*
Residual	6	7770	0.0006	0.00001	0.30	0.0992	263.2	2014	5.73	0.84	0.020	0.20	525
Total	11												
Summary of data													
Manual weeding		230^{a}	0.7720^{a}	0.065	2.85	1.766^{a}	519.6^{ab}	119.6^{a}	92.31^{a}	21.59^{a}	2.390^{b}	51.52	61.5^{a}
1.2 m row weeding		171^{b}	0.7545^{b}	0.063	2.84	1.522^{b}	526.0^{a}	92.3^{ab}	90.37^{b}	21.09^{a}	2.455^{b}	51.66	47.6^{ab}
Weedy control		138^{b}	0.7455^{b}	0.065	2.44	1.339^{b}	509.6^{b}	71.1 ^{b}	91.39^{ab}	19.89^{b}	2.593^{a}	51.42	36.4^{b}
Mean		180	0.7573	0.065	2.71	1.542	518.4	94.3	91.6	20.86	2.479	51.53	48.5
Standard error		27.9	0.0075	0.002	0.17	0.099	5.1	14.2	0.76	0.276	0.045	0.21	7.3

Note: * $P < 0.05$; within each column, values followed by the same letter are not significantly different; $P < 0.05$ according to Students *t*-test, except for Fibre coarseness and Active alkali where the Fisher-Behrens test was used to detect for any significant differences ($P < 0.05$).

means for these two variates. All the rest of the variates were analyzed using Genstat® for Windows™ [32] with analysis of variance. Where significant differences were detected, treatment differences were further investigated using least significant differences (*lsd*'s) [42]. Canonical Variate Analysis (CVA), also known as linear discriminant analysis, was used to make comparisons between the groups of variates rather than between individual units or between individual treatments [44]. For the CVA a permutation test (Monte Carlo test) was used to determine whether the differences between the clusters were significant.

3. RESULTS AND DISCUSSION

Both the short and long term influence of the different weeding treatments on the development of tree growth over time have been reported [33, 39]. Tree growth differences detected following establishment were still evident at felling resulting in significantly ($P < 0.043$) improved merchantable volume for the manually weeded (230 m^3 ha^{-1}) treatment over that of the 1.2 m row weeding (171 m^3 ha^{-1}) or weedy control (138 m^3 ha^{-1}). Significant differences were also detected between treatments for selected wood and pulping properties as well as between the groups of variates for each treatment. A summary of the analysis of variance and treatment means for tree growth and the various wood and pulping properties is shown in Table I.

3.1. Fibre length and coarseness

No significant differences were detected for the variate of fibre coarseness, however the manually weeded treatment produced fibres that were significantly longer ($P < 0.05$) than the other two treatments (Tab. I). Anatomical differences in fibres differ with species, within species, with height, as well as from pith outwards [1]. In a study linking various wood to pulpwood properties for *Eucalyptus grandis* grown in South Africa, cell wall thickness was the one property that appeared most frequently in the multiple regression equations [19]. Generally the thinner the cell wall the lower the wood density. Thin-walled fibres collapse and become ribbon-like thus providing a large surface area for bonding. In a review of literature on the relationship between fibre morphology and paper properties, the three principle factors controlling paper strength are fibre density, fibre length and fibre strength with the average fibre length increasing from the pith outwards until a constant level is attained [17]. The manually weeded treatment with the longest fibres indicated a beneficial trait in terms of paper making. In two separate studies carried out on the influence of fertilizer on *Eucalyptus* growth and wood properties, no significant differences of fibre length were found between treatments [20, 26].

3.2. Extractable content

The extractable content of wood gives an indication of the amount of impurities that need be removed from the wood during the pulping process. Depending on their composition, these extractives may be either soluble in water or in alcohol. The hot water and ethanol benzene extractable contents give an indication of the amount of chemicals in order to reach a level where an acceptable quantity of extractives have been removed. The higher the extractive content the more costly the removal process. The manually weeded and the 1.2 m row weeding treatments had higher water soluble extractable content than the weedy control, but this was only significant at $P < 0.10$. The alcohol extractive content between the different treatments was significant ($P < 0.05$) with the manually weeded treatment being significantly different from the weedy control. The manually weeded treatment produced the most extractives and the weedy control the least.

Relative to other pulp woods, eucalypts have a high extractive content, largely of the polyphenolic type, which are present in small but significant amounts in the sap wood [28]. Extractives are the non-structural or secondary constituents of plants which include ellagic acid, gallica acid, allagatinnins, gallotannins, flavonoids and their polymers [10]. An increase in the presence of extractives tends to increase the consumption of chemicals during pulping, as well as reducing pulp yield. Others can form complexes with metals, causing deposits on machinery and pipework or making pulp bleaching more difficult [27]. Extractives are found mainly in the heartwood and are present in larger proportions in older trees. Higher lignin content and extractive content are the reason for higher alkali requirement and lower yield [4]. In general, extractive content increases with the age of the tree and with slowness of growth and decreases from the pith outwards within the tree. In a study on eucalypts, faster growing trees were found to have lower extractive levels [29]. The penetration path of the alkaline pulping liquors in eucalypt wood is along the vessels and then through the pits to the adjacent fibres, vertical parenchyma and to the ray cells. Those pulpwood's requiring less active alkali to cook to a given degree of delignification will have a processing-cost advantage [10]. A study on three eucalypt species of different ages found an increase in basic density and pulp yield with age, and in two of the species alkali requirements decreased with age [9]. Alkali requirements were linked to pulp yield, with high alkali requirements associated with lower pulp yields. The properties most desirable for paper manufacture include a higher than average fibre length, higher proportion of thin walled cells, a percentage (15–50%) of late wood, low extractive content and high cellulose content [15].

3.3. Density

Of the wood properties measured relating tree growth to pulp yield, measures of wood density are of importance as they can be linked to strength properties of paper, with a decline in the strength properties of paper with increasing wood density [27]. Whole tree density was determined from discs taken at 5%, 15%, 35% and 65% of the total tree height. There was a significant response ($P < 0.05$) to both replication and the differences between the treatments (Tab. I), with both the manually weeded and 1.2 m row weeding treatments producing wood of a higher density than the weedy control.

The two characteristics most affecting pulp properties of different eucalypts are their density and the presence of extractives [48]. Density (basic wood density) is calculated from the mass of oven-dry wood per unit volume measured in a water soaked condition and is expressed as kg m^{-3} [30]. Basic wood density is a complex characteristic because it is dependent on numerous other factors [34], and is thus an important indicator of pulpwood quality [10]. A wide range of basic densities (300–1000 kg m^{-3}) is encountered from un-managed Australian forests, but in young fast grown plantations the range is greatly reduced as a consequence of species selection, limited heartwood formation and relatively high rates of growth [27]. Seldom will pulpwood with a basic density greater than 600 kg m^{-3} be under consideration. Some anatomical features affecting density include varying proportions of different types of cells of varying diameters, wall thickness, and length, as well as the amount of non-structural material such as extractives [29] of which the relationship between fibre wall thickness to the lumen or whole cell diameter is most important [1, 15]. As wood density rises above 300 kg m^{-3} there is a decline in the strength properties of paper in terms of tensile, burst and fold strength. This is related to the ratio of fibre diameter to wall thickness. Within individual *Eucalyptus grandis* trees there may also be a variation, with density increasing with distance from the pith as well as with height above ground level [3, 43].

3.4. Density as influenced by rate of growth, tree age and silvicultural treatment

Many factors affecting pulp quality originate well before the wood reaches the mill. These factors can be divided into those that affect pulp quality before and after the trees are felled. Before felling, factors may be divided into the age of the stand, species, portion of tree used, site from where felled and the silviculture practised [21].

There appears to be no general correlation between tree growth rate and wood density, although exceptions have been noted [30]. Studies carried out on eucalypts to assess the effect of fast growth on density found no relationship [2, 3, 5]. Although according to Higgins (1984), a growth rate lower than that which would be normal for the tree's environment, brought about by depravation of water, nutrients or light, will lead to suppression accompanied by a wood density that is higher than normal. It has been concluded that in terms of pulping, rate of growth by itself is of no consequence and therefore the forester can aim at the development of the highest possible volume yield per acre per annum [15].

As pulpwood, the younger, low density eucalypts are to be preferred to older and denser woods on most grounds: lower chemical consumption during pulping, higher pulp yields, easier chemical recovery, minimal extractives and higher bonding strength [27]. In two separate studies encompassing fourteen eucalypts, species and age were found to be the best indicators of pulpwood quality with an increase in basic density and pulp yield with increasing age [9, 25].

Variations in wood properties due to different silvicultural methods are related to changes in tree growth rates with an increase in growth rate normally leading to a lowering in basic density. In a study to assess the influence of various silvicultural treatments (weedy control, fertilizer, insecticide, weeded and the latter three combined) on growth and wood density on *Eucalyptus grandis*, an increase in wood density with increased growth rate was recorded [46]. A study was carried out on wood density and fibre length on *Eucalyptus grandis* (Hill) Maiden after application of NPK and boron fertilizers in Zambia [26]. The experiment revealed non-significant effects of fertilizer on wood properties. Forest fertilization, as a silvicultural practice, is employed to improve the growth rate and total yield of wood. Fertilization has probably no direct effect on wood properties but rather these are influenced through changes in vegetative growth of the crown. It was concluded that the study of wood properties was secondary to an improvement of growth. The effect of improved growth

Table II. Summary of analyses of variance and treatment means for the slopes of growth rate for stem area.

Summary of analysis of variance				
Source of variation	d.f.	s.s.	m.s.	*F.* prob
Replications	3	0.121^{-7}	0.404^{-8}	
Treatments	2	0.949^{-8}	0.474^{-8}	8.70***
Trees (residual)	54	0.294^{-7}	0.0545^{-9}	
Total	59	0.510^{-7}		
Summary of data				
Manual weeding		-0.0000665^{a}		
1.2 m row weeding		-0.0000474^{b}		
Weedy control		-0.0000360^{b}		
Mean		–0.00005		
Standard error		0.000007		

Note: *** $P < 0.001$. Within each column, values followed by the same letter are not significantly different; $P < 0.05$ according to Students *t*-test.

through fertilization was examined on 2-, 4-, and 6-year old *Eucalyptus globulus* [22]. The use of fertilizer produced a significant increase in wood yield per hectare without having a detrimental effect on pulp strength properties. In another study, the effect of fertilizer application on the growth and wood properties of 5.6 year old *Eucalyptus grandis* was determined [13]. Fertilization resulted in increased rates of growth together with an associated increase in pulp yield and wood basic density. It was concluded that the combined effect of these substantially improved the productivity of pulpwood from fertilized trees which would considerably enhance the economic viability of a pulp mill utilising wood from fast growing *Eucalyptus grandis* plantations.

3.5. Comparison between the rate of tree growth and density and extractable content

In order to determine if there was any relationship between the rate of tree growth and either the density (excluding extractives) or total extractable content (hot water and ethanol benzene extractives combined), the slope of the growth rate for each individual tree was determined. This was calculated from 784 days after planting onwards, since from this date, there was a general decline in the growth rate for the stem areas. There was a highly significant difference between the three treatments when an analysis of variance was performed on these slopes (Tab. II). This decrease in stem area for each treatment is highlighted in Figure 1, where it can be seen that the weedy control has the lowest rate of decline followed by that of the 1.2 m row weeding and manually weeded treatments. This could be related to the manually weeded treatment having larger trees of a uniform size. Although initial growth was rapid due to a lack of interspecific competition, the close espacement of these trees meant that resources would become increasingly limited, and thus unable to maintain sustained

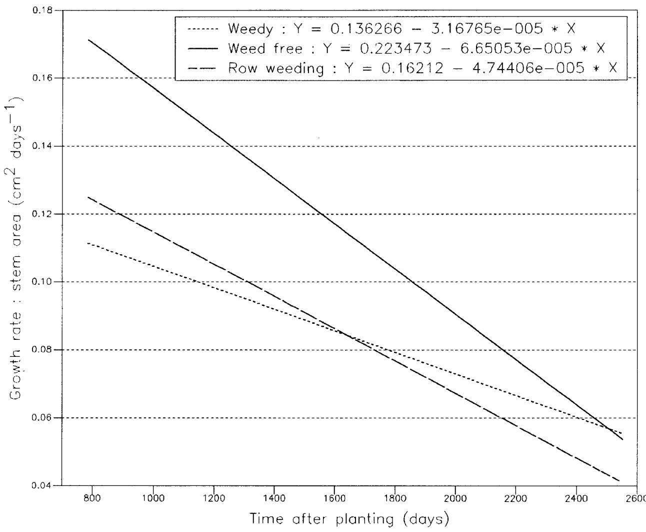

Figure 1. Growth rates for the different stem area calculations.

growth. In direct comparison the initial rate of growth of the trees in the weedy control was lower. However, the rate of decline was not as rapid once the maximum rate of growth had been attained. The smaller number of larger trees (due to the high number of suppressed trees) did not place as many demands on the sites resources, thus contributing to the lowest decline for the growth rate.

Simple linear regression with treatments as groups was first performed to relate the rate of growth (as indicated by the slope) with the density and extractable content. There was no significant difference between the treatment slopes for the density measurements, although there were indications that the weedy control and 1.2 m row weeding treatment had a lower slope. In this case a single line would be able to explain 34.2% of the variance with a slope that was significantly negative (Tab. III), indicating that irrespective of treatment the higher the rate of growth the lower the density.

In a similar fashion the rate of growth and extractable content were compared using simple linear regression with treatments as groups. There was a significant difference between the intercepts of the manually weeded and 1.2 m row weeding treatments and the weedy control although there were no significant differences between the slopes for the different treatments. This regression analysis could account for 37.8% of the variance with a slope that was significantly negative (Tab. III), indicating that irrespective of the treatments the higher the rate of growth the lower the extractable content.

3.6. Pulping properties

The different treatments had an influence on the Kappa number, the pulpability factor and the active alkali content. The Kappa number was higher and the pulpability factor lower for the manually weeded and 1.2 m row weeding treatment than the weedy control. The pulpability factor gives a good indication of the pulpwood quality without having to do multiple cooks and interpolate to the desired 20 Kappa number

Table III. Summary of simple linear regression of a) density (kg m^{-3}) (excluding hot water and ethanol benzene extractives) and b) extractable content (%) (hot water and ethanol benzene combined) against that of the slope of growth rate for stem area.

Source of variation	d.f.	Density (kg m^{-3})		Extractable content (%)	
		s.s.	m.s.	s.s.	m.s.
Regression	3	31024	31023***	12.97	4.3247***
Residual	56	56768	978	18.69	0.3338
Total	59	87792	1488	31.66	0.5367
r^2		34.2		37.8	
Std. error		31.3		0.578	
		Estimate	*t*(58)	Estimate	*t*(56)
Constant		498.6	62.22***	3.361	20.41***
Slope		–779593	–5.63***	–11736	–4.14***
Weed free		–	–	0.472	2.34*
Row weeding		–	–	0.446	2.4*

* $P < 0.05$. *** $P < 0.001$.

Table IV. Summary of Canonical Variate Analysis.

Summary of CVA ordination		
Axes	1	2
Eigenvalues	0.549	0.306
Treatment/wood properties correlations	0.741	0.553
Cumulative percentage variance		
– of treatment data	27.4	42.7
– of treatment/wood property relations	64.2	100

[24]. In general the requirements of the Mondi Kraft Mill (Richards Bay) are a screened pulp yield of 51.5% or higher with a Kappa number of 22 or less. The pulpability factor needs to be greater than 2.34 with the ideal basic density between 460 and 520 kg m^3 [24]. There was greater variability between the replications than between the treatments, for the screened pulp yield, with no significant differences being recorded. Screened pulp yield, expressed as a percentage, is the ratio of oven-dry pulp produced from oven-dry wood [5]. Pulp yield per hectare is a function of the screened pulp yield and the timber yield per hectare. As there were no significant differences between the screened pulp yield for the different treatments, the differences in pulp yield per hectare are accounted for by the larger volume and higher density associated with the manually weeded treatment (Tab. I).

Pulp yield has an important influence on the profit realised from timber grown for pulp and paper manufacture. A one percent increase in pulp yield for *E. grandis* with a mean annual increment of 37.5 t ha^{-1} $year^{-1}$ would result in an eleven percent increase in profit per hectare at no extra cost [11], and as such pulp yield is the most important indicator of pulpwood quality.

Table V. Latent vectors (loadings) for the x and y axis.

Density	0.1571	–0.2209
Alcohol extractive content	0.5693	0.0249
Water extractive content	0.3486	–0.1818
Fibre length	0.4859	0.075
Fibre coarseness	–0.0082	0.2449
Active alkali	0.2152	0.3365
Screened pulp	0.0599	–0.1645
	TREAT AX1	TREAT AX2

3.7. The use of Canonical Variate Analysis to compare the properties between groups of variates

Canonical Variate Analysis (CVA), also known as linear discriminant analysis, was used to make comparisons between the groups of variates rather than between individual units or between individual treatments [44]. CVA as a method, examines the degree of separation among a set of groups of units by seeking linear combinations of the variates that have the greatest between-group variation relative to their within-group variability. In order to do this, the data were analyzed using CANOCO [44], a program for canonical community ordination. Results for the CVA are presented in Tables IV and V and displayed graphically in Figure 2. The first eigenvalue corresponds to 64 % of the variation and is apparently most heavily influenced by the alcohol extractable content and fibre length (Fig. 2 and Tabs. IV and V). The second eigenvector, which accommodates the remaining 36% of the variation, is a contrast between the active alkali and fibre coarseness versus the density, screened pulp and the water extractable content. A permutation test (Monte Carlo test) was used to determine whether the differences between the clusters were significant. This test uses the *F*-ratio as the test statistic and does not require the assumption that the variables are normally distributed. The permutation test was highly significant, indicating that there were differences between the properties tested for the different treatments. These differences are illustrated in Figure 2 by the cluster means which are separated along the x-axis.

4. CONCLUSION

Weed control as practised during the establishment phase of tree growth had a beneficial and long-term (over a six to eight year rotation) impact on tree performance. This is reflected in the significantly improved merchantable volume of the manually weeded treatment over that of the 1.2 m row weeding or weedy control. As there were no significant differences between the screened pulp yield, the main benefit related to the improved pulp yield was that of volume. There was a 22.6% and 40.8% increase in the pulp yield ha^{-1} for the manually weeded treatment in comparison to the 1.2 m row weeding treatment and weedy control. The use of Canonical Variate Analysis to detect differences between the treatments in terms of the variates measured, indicated that they were significant. The importance of this is that wood volume, pulp

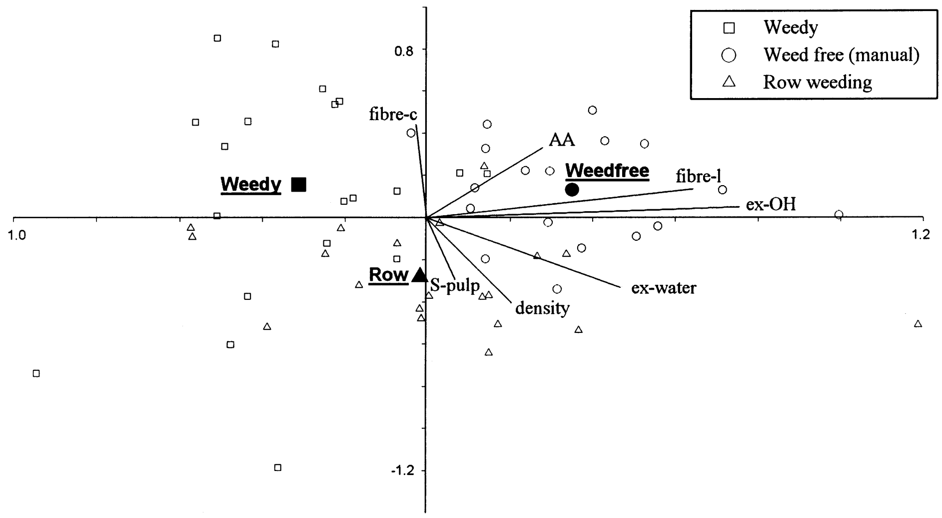

Figure 2. CVA showing the correlation between groups of wood and pulping variates for three vegetation management treatments. The unfilled symbols indicate individual trees in relation to the measured variates (lines) with the filled symbols indicating the treatment centroid. The vectors (lines) apply to the variates active alkali (AA), fibre length (fibre-l), alcohol extractive content (ex-OH), water extractive content (water-ex), density (density), screened pulp (S-pulp) and fibre coarseness (fibre-C). The x-axis accounts for 64.2% of the variability between the groups of variates, with the scale adjusted to take this into account.

yield and pulp quality were influenced by different vegetation management techniques. However any negative impacts associated with the manually weeded treatment in terms of the wood and pulping properties (higher density, extractable content and active alkali consumption) may be minor in comparison to the significantly improved pulp yield per hectare. The economic relationship between these factors needs to be evaluated in further studies before an overall understanding is obtained. The negative impacts of a lowered growth rate during the latter stages of tree development were associated with poorer pulping properties (as occurred in the manually weeded treatment). This could be further reduced, provided the trees are felled at the correct age, thereby reducing the effect of intraspecific competition.

Acknowledgements: The Forestry Industry, and in particular the field staff of the Mtunzini Plantation for their assistance in the implementation, maintenance and felling of the trial. Dr. C. Clarke (Sappi Research) and A. Arbuthnot (Mondi Mill, Richards Bay) for their advice with respect to the sampling procedures and interpretation of the results obtained from the pulp and paper tests. J. Male, A. Havenga, J. Retief and D. Gama of the Forestry and Forest Products section of CSIR for the testing of the pulp and paper properties.

REFERENCES

[1] Bamber R.K., The wood anatomy of eucalypts and papermaking, Appita J. 38 (1985) 210–216.

[2] Bamber K., Horne R., Graham-Higgs A., Effect of fast growth on the wood properties of *Eucalyptus grandis*, Aust. For. Res. 12 (1982) 163–167.

[3] Bamber R.K., Humphreys F.R., A preliminary study of some wood properties of *Eucalyptus grandis* (Hill), Maiden, J. Inst. Wood Sci. 11 (1963) 66–70.

[4] Batchelor B.K., Prentice F.J., Turner C.H., The assessment of a forest for pulping, Appita J. 24 (1971) 253–260.

[5] Beadle C.L., Turnbull C.R.A., Dean G.H., Environmental effects on growth and kraft pulp yield of *Eucalyptus globulus* and *E. nitens*, Appita J. 49 (1996) 239–242.

[6] Brown A.G., Hillis W.E., General introduction, in: Hillis W.E., Brown A.G. (Eds.), Eucalypts for wood production, Academic Press, Sydney, 1984, pp. 2–5.

[7] Brown A.G., Nambiar E.K.S., Cossalter C., Plantations for the tropics – Their role, extent and nature, in: Nambiar E.K.S., Brown A.G. (Eds.), Management of soil, nutrients and water in tropical plantation forests, ACIAR, Canberra, 1997, pp. 1–23.

[8] Campbell R.C., Statistics for biologists, Cambridge University Press, Cambridge, 1974.

[9] Clark N.B., The effect of age on pulpwood quality. Part 2. The kraft properties of Victorian *Eucalyptus regnans*, *Eucalyptus delegatensis* and *Eucalyptus sieberi*, Appita J. 43 (1990) 208–212.

[10] Clark N.B., Pulpwood quality and value, in: Kerruish C.M., Rawlins W.H.M. (Eds.), The young eucalypt report – some management options for Australia's regrowth forests, Microdata Pty. Ltd., Victoria, 1991, pp. 210–244.

[11] Clarke C.R.E., The estimation of genetic parameters of pulp and paper properties in *Eucalyptus grandis* Hill ex Maiden and their implications for tree improvement, M.Sc. thesis, University of Natal, Pietermaritzburg, 1990.

[12] Cogliastro A., Gagnon D., Coderre D., Bheruer P., Response of seven hardwood tree species to herbicide, rototilling, and legume cover at two southern Quebec plantation sites, Can. J. For. Res. 20 (1990) 1172–1182.

[13] Cromer R.N., Balodis V., Cameron D., Garland C.P., Rance S., Ryan P., *Eucalyptus grandis* fertilizer trials: growth, wood properties and kraft pulp yield, Appita J. 51 (1998) 45–49.

[14] Cromer R.N., Dargavel J.B., Henderson V.T., Nelson P.F., More pulpwood from less land, Appita J. 31 (1977) 49–54.

[15] Dadswell H.E., Wardrop A.B., Growing trees with wood properties desirable for paper manufacture, Appita J. January (1959) 129–136.

[16] Denison N.P., Kietzka J.A., The use and importance of hybrid intensive forestry in South Africa, S. Afr. For. J. 165 (1993) 55–60.

[17] Dinwoodie J.M., The relationship between fibre morphology and paper properties: A review of literature, Tappi J. 48 (1965) 440–447.

[18] Duncan E.A., van Deventer F., Kietzka J.E., Lindley R.C., Denison N.P., The applied subtropical *Eucalyptus* clonal programme in Mondi forests, Zululand coastal region, in: International Union of Forestry Research Organisations. Proceedings: Forest genetics for the next millennium: IUFRO Working Party 2.08.01, Tropical Species Breeding and Genetic Resources, International Conference Centre: Durban, South Africa, 8 to 13 October 2000, Pietermaritzburg, Institute for Commercial Forestry Research, 2001, pp. 95–97.

[19] du Plooy A.B.J., The relationship between wood and pulp properties of *Eucalyptus grandis* (Hill ex-Maiden) grown in South Africa, Appita J. 33 (1980) 257–264.

[20] du Toit B., Arbuthnot A., Oscroft D., Job R.A., The effects of remedial fertiliser treatments on growth and pulp properties of *Eucalyptus grandis* stands established on infertile soils of the Zululand coastal plain, S. Afr. For. J. 192 (2001) 9–18.

[21] Farrington A., Wood and digester factors affecting kraft pulp quality and uniformity, Appita J. 34 (1980) 40–46.

[22] Farrington A., Hansen N.W., Nelson P.F., Utilization of young plantation *E. globulus*, Appita J. 30 (1977) 313–319.

[23] Flinn D.W., Comparison of establishment methods for *Pinus radiata* on a former *P. pinaster* site, Aust. For. 41 (1978) 167–176.

[24] Gardner R.A.W., Alternative eucalypt species for Zululand: Seven year results from site:species interaction trials in the region, S. Afr. For. J. 190 (2001) 79–88.

[25] Hall M.J., Hansen N.W., Rudra A.B., The effect of species, age and wood characteristics on eucalypt kraft pulp quality, Appita J. 26 (1973) 348–354.

[26] Hans A.S., Burley J., Wood quality of *Eucalyptus grandis* (Hill) Maiden in a fertilizer trial at Siamambo, Zambia, East Afr. Agric. For. J. October (1972) 157–161.

[27] Higgins H.G., Pulp, Paper, in: Hillis W.E., Brown A.G. (Eds.), Eucalypts for wood production, CSIRO/Academic Press, Melbourne, 1984, pp. 290–316.

[28] Hillis W.E., The contribution of polyphenolic wood extractives to pulp colour, Appita J. 23 (1969) 89–101.

[29] Hillis W.E., Properties of eucalypt woods of importance to the pulp and paper industry, Appita J. 26 (1972) 113–122.

[30] Hillis W.E., Wood quality and utilization, in: Hillis W.E., Brown A.G. (Eds.), Eucalypts for wood production, CSIRO/Academic Press, Melbourne, 1984, pp. 259–289.

[31] Kimmins J.P., Identifying key processes affecting long-term site productivity, in: Dyck W.J., Cole D.W., Comerford N.B. (Eds.), Impacts of forest harvesting on long-term site productivity, Chapman and Hall, London, 1994, pp. 119–150.

[32] Lane P.W., Payne R.W., Genstat® for Windows™, an introductory course, Lawes Agricultural Trust, Rothamsted Experimental Station, 1996.

[33] Little K.M., The influence of vegetation control on the growth and pulping properties of a *Eucalyptus grandis* × *camaldulensis* hybrid clone, Ph.D. thesis, University of Natal, Pietermaritzburg, 1999.

[34] Malan F.S., The wood properties of South African grown *Eucalyptus grandis*, Wood South. Afr. March (1989) 61–67.

[35] Miranda I., Pereira H., Variation of pulpwood quality with provenances and site in *Eucalyptus globulus*, Ann. For. Sci. 59 (2002) 283–291.

[36] Neary D.G., Rockwood D.L., Comerford N.B., Swindel B.F, Cooksey T.E., Importance of weed control, fertilization, irrigation and genetics in slash and loblolly pine early growth on poorly drained spodosols, For. Ecol. Manage. 30 (1990) 271–281.

[37] Pierce B.T., Verryn S.D., Five year results from a site by clone interaction series of *Eucalyptus grandis* in the summer rainfall areas of South Africa, in: International Union of Forestry Research Organisations. Proceedings: Forest genetics for the next millennium: IUFRO Working Party 2.08.01, Tropical Species Breeding and Genetic Resources, International Conference Centre: Durban, South Africa, 8 to 13 October 2000, Pietermaritzburg, Institute for Commercial Forestry Research, 2001, pp. 186–191.

[38] Schönau A.P.G., Role of eucalypt plantations in timber supply and forest conservation in Sub-Saharan Africa, invited paper presented at the 19th IUFRO World Congress, 9 August 1990, Montreal, 1990.

[39] Schumann A.W., The impact of weeds and two legume crops on *Eucalyptus* hybrid clone establishment, S. Afr. For. J. 160 (1992) 43–48.

[40] Snedcor G.W., Cochran W.G., Statistical methods applied to experiments in agriculture and biology, The Iowa State College Press, Iowa, 1956.

[41] Squire R.O., Interacting effects of grass competition, fertilizing and cultivation on the early growth of *Pinus radiata* D. Don, Aust. For. Res. 7 (1977) 247–252.

[42] Steel R.G.D., Torrie J.H., Principles and procedures of statistics. A Biometrical approach, McGraw-Hill International Book Company, Singapore, 1981.

[43] Taylor F., Anatomical wood properties of South African grown *Eucalyptus grandis*, S. Afr. For. J. 84 (1972) 20–24.

[44] ter Braak C.J.F., Šmilauer P., CANOCO reference manual and user's guide to Canoco for Windows, Centre for Biometry, Wagening, 1998.

[45] Turvey N.D., Growth at age 30 months of *Acacia* and *Eucalyptus* species planted in *Imperata* grasslands in Kalimantan Selata, Indonesia, For. Ecol. Manage. 82 (1996) 185–195.

[46] Wilkins A.P., Influence of silvicultural treatment on growth and wood density of *Eucalyptus grandis* grown on a previous pasture site, Aust. For. 53 (1990) 168–172.

[47] Wilkins A.P., Kitahara R., Silvicultural treatments and associated growth rates, growth strains and wood properties in 12.5-year-old *Eucalyptus grandis*, Aust. For. 54 (1991) 99–104.

[48] Zobel B., Wood quality from fast-grown plantations, Tappi J. 64 (1981) 71–74.