THE INFLUENCE OF VEGETATION CONTROL ON THE GROWTH AND PULPING PROPERTIES OF A *Eucalyptus grandis x camaldulensis* HYBRID CLONE.

by

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"The fair question is, does the newly proposed view remove more difficulties, require fewer assumptions, and present more consistency with observed facts, than that which it seeks to supersede? If so, the philosopher will adopt it, and the world will follow the philosopher."

Sir William Robert Grove (1811-1896). Address to the British Association for the Advancement of Science .....Nottingham, August 22, 1866.

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ABSTRACT

In order to determine if 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, a *Eucalyptus* hybrid clone (GC304) was planted in a field trial in 1990. The trial was situated in the coastal Zululand region near the KwaZulu-Natal town of Mtunzini. Nine different vegetation management treatments were imposed from establishment. These included a weedy control, a manually weeded treatment, a chemically weeded treatment, a 1.2 m row and 1.2 m inter-row 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, *Mucuna puriens* (cowpea) and *Vigna sinensis* (velvet bean). Initial improvements in tree performance from these competition control treatments were detected from 60 days after planting, and were maintained over seven growing seasons. This occurred despite the absence of competitive vegetation after the first growing season due to reduced light, following crown canopy closure. There were strong indications that initial competition was mainly for moisture and possibly also for nutrients, rather than competition for light. Initially those trees that had weeds within their immediate vicinity were most affected (weedy control, inter-row weeding and the complete weeding except for a 0.5 m radius around the tree). With time, tree performance was more closely related to an increase in the percentage of the area kept free of weeds. The best performing treatment at felling, the manually weeded control, produced 17.1 % and 38.5 % more merchantable timber than the 1.2 m row weeding and the weedy control, at an increased profit of 8 % and 27 %, respectively.

Two forms of competition (interspecific and intraspecific competition) were evident in the weedy control at different stages of tree development in contrast to the one (intraspecific competition) in the manually weeded treatment. Interspecific competition resulted in greater variability between the trees in the weedy control by the time canopy closure had occurred. This differentiation in tree size was further enhanced by asymmetric intraspecific competition once the trees had become established. The onset of intraspecific competition was first detected 995 days after planting for the manually weeded treatment and 1641 days after planting for the weedy control. Of the various competition indices that were tested in order to try and explain this differential growth in terms of individual tree performance, none was able to do so to complete satisfaction. The growth rates of different tree size classes were therefore compared for the weedy control and manually weeded treatment. The diverging slopes of the different stem area classes indicated that the larger trees were growing at the expense of the smaller trees. This type of competition is known as asymmetric intraspecific competition. In addition, a comparison was made between the slopes for the weedy and weedfree treatments for similar stem area classes. No significant difference was detected, indicating that similar size classes in these two treatments grew at similar rates.

Trees from three treatments were selected (manually weeded treatment, 1.2 m row weeding treatment and the weedy control) and tested for the wood and pulping properties of density, active alkali consumption, extractable content, screened pulp yield, pulp yield per hectare and fibre length and coarseness.

The use of Canonical Variate Analysis to determine if there were differences between the three treatments for the variates measured, indicated that they were significantly different. There was a significantly positive trend of an increase in density, extractable content and active alkali consumption with increased weed control. A possible explanation for this could be that the larger trees of the manually weeded treatment were under more stress (from increased intraspecific competition) during the latter phase of their growth. This was demonstrated by comparing the growth rates for these three treatments. The smaller trees of the 1.2 m row weeding treatment and the weedy control exhibited a lower rate of decline. As no significant difference was detected for screened pulp yield between the treatments, any differences in the pulp yield per hectare values could be attributed to differences in the merchantable volume. There was a 22.6 % and 40.8 % increase in the pulp yield per hectare for the manually weeded treatment in comparison to the 1.2 m row weeding treatment and the weedy control.

The planting of cover-crops, although beneficial in terms of weed suppression, caused significant tree suppression. This occurred despite the fact that their initial biomass accumulation was slower than that of the natural weed population. Of the two cover-crops, the use of the velvet bean was not considered suitable due to its vigorous vining habit which affected the growth form of the trees. Subsequent work suggests that if the beneficial qualities of cowpeas are to be realised (that of weed suppression, erosion control and nitrogen fixation), a delay in their planting by three months after establishment of the trees should alleviate any negative impacts on tree growth.

DECLARATION

This thesis was supervised by Professor J. van Staden, Professor G.P.Y. Clarke, Professor R.P. Beckett and Professor P.J.T. Roberts

I hereby declare that this thesis, submitted for the degree of Doctor of Philosophy at the University of Natal, Pietermaritzburg, is the result of my own investigation, unless acknowledged to the contrary in the text.

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NOVEMBER, 1999

We the undersigned certify that the above statement is correct:

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CONFERENCES ATTENDED RELATED TO THESIS

15th National Weed Science Congress at San Lameer (KwaZulu-Natal) held from the 11th to 14th May 1998. An oral presentation was made entitled: "The response of a *Eucalyptus* hybrid clone to nine different vegetation management treatments" by K. Little, J. van Staden, P.J.T. Roberts and G.P.Y. Clarke.

Third International Conference on Forest Vegetation Management at Sault Ste. Marie, Ontario (Canada) held from the 23rd August to 4th September 1998. A poster was presented entitled: "The response of a *Eucalyptus* hybrid clone to nine different vegetation management treatments" by K. Little, J. van Staden, P.J.T. Roberts and G.P.Y. Clarke.

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CHAPTER 1

GENERAL INTRODUCTION AND OVERVIEW OF WEED COMPETITION

1.1 General introduction

Vegetation management practised during the establishment of plantations is of the utmost importance. Some of the benefits include reduced seedling mortality, increased stem and stand uniformity, reduced time to canopy closure, increased yields and reduced rotation times, as well as allowing for improved access into the compartment for various silvicultural operations. Vegetation management in the Zululand region of South Africa is even more critical due to the sub-tropical climate which favours an extended period over which the weeds are able to grow and the susceptibility of the tree species grown (*Eucalyptus* hybrid clones) to competition from these weeds.

In South Africa, eucalypt species grown as a source of hardwood pulpwood make up 14.8 % of the total area planted to trees (1486 923 ha), with 5.9 % of the eucalypts grown for this purpose occurring in the subtropical region of Zululand in the South African province of KwaZulu-Natal (DIRECTORATE FORESTRY DEVELOPMENT 1996). *Eucalyptus grandis* was introduced into South Africa late in the 19th century, initially as a source of timber for the mining industry (POYNTON 1979), but has since become the most important of the hardwood plantation tree species grown for pulp. Until the late 1980's *Eucalyptus grandis* was virtually the only eucalypt species grown in the district of Zululand. Since the early 1990's the areas of site-species matching (DARROW 1995a) and tree breeding (DENISON and KIETZKA 1993a) have received much attention in Zululand, resulting in the development of a number of cloned hybrids to match specific sites. The most common of these are the cloned hybrids of *Eucalyptus grandis* combined with either *Eucalyptus camaldulensis, E. urophylla* or *E. tereticornis*.

In Zululand these *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 (BROWN and HILLIS 1984; KIMMINS 1994). Present and future land use policies are likely to restrict the conversion of non-afforested land to plantations. The factors influencing an increase in yield and pulpwood from an existing land base can be achieved by different means, some of which are discussed briefly below.

1.1.1 Improvement through site-species matching

Through the improvement of site-species matching, the full potential can be gained from existing sites. Within the various eucalypts there is evidence of genetic variation between different species as well as between the same species from different locations (MALAN 1988). Because this variation is frequently the result of adaptation and is inherited, the collection of seed from stands in a particular locality may confer a distinct advantage in subsequent silviculture (TURNBULL and PRYOR 1984). Within South Africa various species of eucalypts are planted on representative sites according to the different climatic and soil variables (DARROW 1995a; DARROW 1995b). From these trials the most suitable species for a particular site may be selected, based upon various growth and pulping parameters. CLARKE, GARBUTT and PEARCE (1997) assessed the growth and wood properties of provenances of trees of nine eucalypt species on one site in South Africa. *Eucalyptus fraxinoides*, *E. oreades* and *E. smithii* were judged the best, exhibiting the best growth as well as desirable wood properties for pulp manufacture. Similar trials looking at the effect of site on *Eucalyptus* species pulping properties in South Africa have yielded similar information, indicating the importance of this aspect (TAYLOR 1972a; MALAN 1993; BEADLE, TURNBULL and DEAN 1996; RETIEF, MALE, MALAN, DYER, CONRADIE, TURNER, HAVENGA and GAMA 1997).

1.1.2 Improvement through tree breeding and clonal propagation

As an extension of site-species matching, selected trees exhibiting desirable properties may be further exploited through gene transfer and clonal propagation. Clonal propagation of high-value, fast growing trees along with gene transfer to improve trees will decrease wood costs and increase wood quality (PULLMAN, CAIRNEY and PETER 1998). Depending on the species selected, clonal propagation may result in volume gain, increased uniformity and desirability, improved rooting (ZOBEL 1993) and an increased resistance to disease (DENISON and KIETZKA 1993b). ZOBEL (1988, 1993) reported that the capturing of desirable characteristics through vegetative propagation in Aracruz has resulted in a 25 % increase in the amount of desirable cellulose per 1 m^3 of wood.

1.1.3 Improvement through the use of interspecific hybrids

The use of selected hybrid combinations of *Eucalyptus grandis* crossed with *E. camaldulensis*, *E. urophylla* or *E. tereticornis* in South Africa has made it possible to extend tree planting to areas traditionally considered off site for plantation forestry. On these peripheral sites, the hybrids growth and survival has outperformed the pure species, and they are consistently more resistant to diseases, pests, cold, heat and drought (DENISON and KIETZKA 1993b). DENISON and KIETZKA (1993b) and MALAN (1993) noted an increase in basic wood density, the single most important factor influencing pulp yield and quality, in *Eucalyptus grandis* hybrids when compared to *E. grandis* grown in Zululand.

The hybrid used in the trial for this thesis was that of *Eucalyptus grandis* Hill ex Maiden and *Eucalyptus camaldulensis (Eucalyptus G x C).* It is grown on a commercial basis under marginal rainfall conditions, and in the hotter parts of afforestable land in South Africa (DARROW 1995b). This combination is favoured for these areas due to the attributes that this hybrid offers, namely *Eucalyptus grandis* for its pulping properties and *Eucalyptus camaldulensis* for its tolerance to the hotter and dryer areas of Zululand. Both these eucalypt tree species are of Australian origin. *Eucalyptus camaldulensis* is the most widely distributed of all eucalypt species in Australia, ranging from the monsoonal tropics to the temperate areas of southern Australia, and from near coastal areas to the arid interior, whereas *Eucalyptus grandis* is limited to the wetter parts of the subtropical-tropical east coast of Australia (FLORENCE 1996).

1.1.4 Improvement through silvicultural practices

Through the consolidation and improvement of existing silvicultural management practices, increased timber output can be ensured. Silvicultural management embraces those practices carried out to ensure the successful establishment of a plantation and has been defined as the science and art of cultivating trees, the theory and practice of controlling the establishment and the growth of forests (WENGER 1984). In closely planted and fast growing eucalypt plantations in South Africa, the period of intensive silvicultural management extends from after harvesting until canopy closure. Intensive silvicultural practices are implemented during this phase in order to achieve the highest maximum yield that is possible on a long term site-sustainable basis. Some aspects of silvicultural management which may influence timber yield and hence the pulping properties are:

- The manner in which the post harvest plantation residues are managed (FLINN 1978). For example, the burning of these residues may result in initial and short term growth benefit (SCHOCH and BINKLEY 1986) but may not be sustainable on a long term basis.
- The method of site preparation. Various methods of site preparation are employed in order to prepare a planting position for the tree seedling. These methods may range from minimal site disturbance (pitting) to intensive site preparation (de-stumping, discing, ripping and mounding) where large portions of the plantation floor are disturbed, resulting in large differences in tree performance (NORRIS 1995).
- Seedling quality and the method and timing of planting. The age of the seedling and the depth at which the seedling is planted as well as the season during which it is planted may all have an important influence on early survival and growth (ZWOLINSKI, SOUTH, CUNNINGHAM and CHRISTIE 1995; ALLAN 1998). Water and gels which retain water may be applied to the planting pit to ensure that these objectives are met (ANONYMOUS 1998).
- The addition of relatively small quantities of fertilizer at planting may have a beneficial impact on timber yield as well as on pulping properties (CROMER, DARGAVEL, HENDERSON and NELSON 1977; WILKINS 1990; CROMER, BALODIS, CAMERON, GARLAND, RANCE and RYAN 1998; TURNBULL, BEADLE, BIRD and McLEOD 1988).
- The management of competing vegetation. WILKINS (1990) looked at the

effect of various silvicultural treatments (untreated control, application of insecticides, fertilization, weed control and a combination of the latter three) on *Eucalyptus grandis* grown in New South Wales. Silvicultural treatments resulted in increased growth rates as well as increased basic density of the wood at 11.3 years of age. The greatest response was produced by fertilizer, weed control and insecticide applied in combination, and to a lesser extent, fertilizer and weed control in isolation.

SCHÖNAU (1990) estimated that a 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. 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 the most important (SQUIRE 1977; FLINN 1978; COGLIASTRO, GAGNON, CODERRE and BHERUER 1990; NEARY, ROCKWOOD, COMERFORD, SWINDEL and COOKSEY 1990; TURVEY 1996). These have also been shown to have an influence on the rate of growth and hence the pulping properties of trees (WILKENS 1990; WILKENS and KITAHARA 1991).

Of the silvicultural management practices that may affect tree performance, there is an absence of information linking the impact of vegetation management on longer term tree growth, especially for that of eucalypts grown in South Africa. To address this lack of information, a study relating vegetation management and *Eucalyptus* growth was undertaken in 1990 in Zululand by the Institute for Commercial Forestry Research with specific objectives as outlined below.

1.2 Overall objectives

The implementation of this trial coincided with three major shifts that had recently occurred within the Zululand forestry sector. The first was the development of the many *Eucalyptus* hybrids which could be rapidly propagated from clonal hedges. These clonal hybrids were disease resistant and could be matched to specific sites, allowing for the re-establishment of old coppice stands with improved genetic material. Prior to the development of these clonal hybrids much of the forestry in this region consisted of *Eucalyptus* plantations managed for regeneration by coppice. These coppice stands (of up to five rotations) required little or no weed control due to the stools having a well established root system, resulting in the existence of a weak weed management culture amongst the foresters in the region. The second major shift resulted from an expansion of forestry into previously non-afforested areas which included virgin grass veld or bush as well as ex-agricultural fields. This meant that large areas of newly established land would need to be managed. There was a need to develop silvicultural practices for the intensive short rotation forestry that was to be practised on these sites and which would be different to that required for coppice regrowth. The third major shift arose from the need to develop more cost-effective and ecologically sound methods of weed control on a more sustainable basis. Until the implementation of this trial most of the weed control techniques centred around the use of minimum weeding with hoes. As the management of vegetation contributes a major portion to establishment costs, these minimum weeding practices needed to be tested together with alternatives in a statistical manner so as to determine their impact on tree performance.

With this in mind the trial used in this study was established in 1990 with the following objectives:

- to determine the onset of early weed competition from several weed proximity treatments and to evaluate two leguminous cover-crops for cultural weed control. The weed control treatments (outlined in Chapter 2, Table 2.4) selected for use in this trial reflected then current (at the time of trial initiation) methods of vegetation management,
- to determine the influence of weed control on post-establishment tree growth,
- to determine the influence of these weeding treatments on stem form, volume and associated treatment costs when the trees were felled and,
- to assess the relationship between vegetation management and wood and pulping properties.

Each of these objectives is dealt with in greater depth in separate chapters. As this study covers many different aspects involved with vegetation management, a general overview will first be given on the theoretical background to competition, the mechanisms of competition, as well as existing individual techniques that are used in weed control.

1.3 Overview of weed competition

1.3.1 Definition of a weed

One of the most widely used definitions as to whether a plant is a weed is given by BUCHHOLTZ (1967) as "A weed is a plant growing where it is not desired." This definition incorporates two important issues. Firstly what characterises a weed, and secondly, why is it not desired? These two issues cannot be separated, as often it is the characteristics of the plant that make it undesirable. According to ZIMDAHL (1995) a plant is not just a weed by virtue of its location but also due to its interference with human activities. Mc NABB, SOUTH and MITCHELL (1995) propose that within a plantation, plants are not inherently undesirable, they only become unwanted when they prevent the plantation manager from reaching his desired goal. This would be applicable within a forestry context where reasons for plants being considered undesirable could include one or a combination of the following:

- the plants in question may be a declared weeds or invader plant and therefore be required by legislation to be controlled (GOVERNMENT GAZETTE 1984),
- weeds may be controlled for aesthetic reasons,
- weed control may be carried out in order to improve access for various silvicultural operations, or,
- weeds may be controlled if they reduce the resources available to the planted crop.

If plantations are to be managed for profitable timber production, then it will be the latter two of the above reasons that will be the most important and the ones that receive most attention. If plants are to be recognised as weeds for the above reasons then there is a need for a definition that recognises all of the above elements. An example of such a definition is given by NAVAS (1991) as "a weed is a plant that forms populations that are able to enter habitats cultivated, markedly disturbed or occupied by man, and potentially depress or displace the resident plant populations which are deliberately cultivated or are of ecological and/or aesthetic interest".

1.4 Classification of weeds

Many different methods exist whereby weeds can be classified. ANDERSON (1996) suggests that the classification of weeds would involve the grouping together of those weed species whose similarities are greater than their differences. The method ultimately chosen, must fulfill the criteria of the field of study. Some examples of different criteria used are:

- The classification of weeds may be based on their taxonomic criteria, morphology, origin, adaptation or life cycle (BRIDGES 1995).
- Based upon the length of their life cycle, season of growth and timing of reproductive activity, weeds can be classified as either annuals, biennials, or perennials (BRIDGES 1995).
- Weeds may also be classified upon the basis of their growth form, such as being herbaceous or woody, prostrate or upright.
- NAVAS (1991), in a review on the determination of common characteristics of weeds, found that the only common attributes of weeds are their occurrence in habitats disturbed by man and their undesirability. He therefore proposed a classification system based on the nature of the damage caused to human activities, where the degree of weediness is defined according to the mechanisms responsible for interactions with other plants.

1.4.1 The effects of vegetation management on the possible classification of weed interference in South African forestry

The presence or absence of weeds and the type of weeds occurring within a eucalypt plantation are affected by, amongst other factors, various silvicultural practices. Any method of weed classification within eucalypt plantations will therefore need to take this into consideration. The management of weeds during a full rotation can be divided into three distinct phases, all of which have a direct bearing on the type and development of weeds and therefore their control. A brief description of each of these phases is given as:

- The period between the planting of trees until canopy closure: A pre-plant herbicide is sprayed just prior to the re-establishment of a plantation. This results in the almost complete eradication of all weeds as a non-selective, broad-spectrum herbicide is used. After the trees are planted, regular (three to five spraying operations) non-selective, weed control is carried out during the nine to eighteen month establishment period. These spraying operations are normally timed to reduce the negative impact the weeds may have on tree performance.

- The period between canopy closure (post-establishment period) and harvest: The close espacement of the newly planted trees combined with their rapid growth and their ability to capture the site in terms of shading by the tree crowns, results in the almost total exclusion of any competitive vegetation occurring after eighteen months of tree growth. Very seldom is weed control carried out during this phase.
- The period between harvesting and prior to planting: Plantations are managed in order to keep this period to a minimum. Seldom is land left in an unproductive state for any length of time. This can be achieved in the Zululand region due to the sub-tropical climate allowing for the re-planting of trees at any time of the year. Any weeds that do develop during this period will be sprayed during the pre-plant weeding operation.

This type of weed control strategy restricts the development of weeds in terms of species, growth form, and longevity. This restriction in the development of weeds occurs irrespective of the different weed communities that may develop relative to any site characteristics. Most weeds that do grow tend to develop from seed, the most notable exception being the development of yellow nutsedge *(Cyperus esculentus)* from corms in ex-agricultural lands. In addition, weeds are controlled before being allowed to overtop the seedlings. Weeds that do grow will tend to exhibit rapid growth, with the emphasis on seed production early on in their life cycle. Weeds in eucalypt plantations therefore tend to be either annuals, perennials that are controlled early on in their life cycle, or “difficult to control” perennials that propagate by specialised vegetative structures.

1.5 Characteristics of a weed

Weed definitions and their subsequent classification have incorporated within them the characteristics of weeds. By defining a weed, one is implying common characteristics which allow them to be grouped. In a description of weeds occurring mainly in agricultural lands, ANDERSON (1996) characterises weeds as being the pioneer plants of disturbed soil. This definition may hold true for those few forestry sites where intensive site preparation is carried out before re-establishment. For the majority of forestry sites this definition may not apply, especially where minimum tillage is practised and post-harvest residue is left on site. On such sites, increased light and temperature in terms of site disturbance, rather than soil disturbance, may be the most important factors influencing the development of weeds.

GRIME (1986) characterises weeds according to their ability to adapt to varying degrees of both stress and disturbance. Of the four permutations that emerge when comparing high and low levels of both stress and disturbance in a habitat, only three are viable as plant habitats. Plants able to exploit conditions of low stress and disturbance are called competitors, those that are able to tolerate high stress and low disturbance, the stress-tolerators; and ruderals are those which tolerate low stress and high disturbance. The characteristics enabling plants to live in any one of these habitats would have to be different. Depending on which of the three the weeds belong to, they may exhibit differences with respect to their morphology, lifehistory, and physiology (GRIME 1986).

Of the many characteristics that have been put forward as to the determination of whether a weed is a good competitor or not, BRIDGES (1995) proposed that some are common to most weeds. These can be grouped into those features related to their establishment, their growth and development, weed crop interactions and their population dynamics:

- Factors of importance during establishment include the production of a large number of seeds, seed dormancy, discontinuous germination, effective dispersal mechanisms and population heterogeneity.
- Factors important during growth and development include the ability to rapidly capture and occupy space. This is often linked to their competitive ability as rapid growth requires the early and efficient conversion of resources into biomass. The ability of weeds to tolerate widely divergent environmental conditions through physiological, anatomical and/or biochemical changes ensures a greater chance of survival.
- Weed crop interactions may either be beneficial or detrimental. The combined effect of all the negative interactions is called interference and includes competition, allelopathy and parasitism.

1.6 Definition of successful competition

As with the definitions relating to the determination of a weed and various methods of classification, many definitions of competition have been postulated, ranging from broad to very narrow. These definitions are generally linked to a specific theoretical framework developed for a specific type of system in which the competition is studied (KROPFF 1993). Two of the more widely recognised definitions are those of GRIME (1986) and TILMAN (1988). GRIME(1986) defines competition as "the tendency of neighbouring plants to utilize the same quantum of light, ion of a mineral nutrient, molecule of water, or volume of space", whereas, TILMAN (1988) defines competition as "the utilization of shared resources in short supply by two or more species". GRACE (1990) highlights the differences between these two definitions as follows: GRIME describes competition in terms of resource capture where he predicts that the species with the highest maximal growth rate of vegetative tissues (maximum capacity for resource capture) will be the superior competitor. TILMAN defines competition in terms of tolerance to low resource levels where the species with the minimum resource requirement (R^*) will be the superior competitor.

KEDDY (1989) argues that the definition of competition may be emphasised in different ways to highlight the aspects under study. For example the definition may emphasize the postulated mechanism of the interaction, or it may be more operational and emphasize responses to experimental perturbations. If the treatments used within this study are considered whereby vegetation has been manipulated on a spatial basis, then the latter of the two would be more applicable.

For the purposes of this study the definition as defined by ANDERSON (1996) as that which occurs between two or more neighbouring plants when the supply of one or more factors essential to growth and development falls below the combined demands of the plants. Successful competition occurs with the disproportionate acquisition of one or more growth factors by one plant that proves detrimental to another's growth.

1.7 Types of competition

KEDDY (1989) implies that, when distinguishing between different types of competition, one should consider the mechanism of interaction between the competitors as well as the kinds of entities interacting (species orientated approach) rather than just the depletion of resources.

The mechanisms by which interaction occurs between competitors may be divided into; those of direct interference where one individual directly influences another and those of indirect exploitation through the reduction of the pool of available resources (CONNELL 1990). These may be further sub-divided into as many as six kinds, of which four are applicable to competition between plants (SCHOENER 1983). These are:

- consumptive competition, which occurs when some quantity of resources (water, nutrients) is consumed by an individual, thereby depriving other individuals of it (exploitation),
- pre-emptive competition, which occurs when a unit of space is passively occupied by an individual, thereby preventing other individuals from occupying that space before the occupant disappears (exploitation and interference),
- overgrowth competition which occurs when another individual or individuals grow over or upon a given individual, thereby depriving that individual of light, and possibly harming that individual by some consequence of physical contact (interference), and,
- chemical competition which occurs when an individual produces some chemical (toxin) which diffuses into the medium or substrate and harms other individuals (interference).

The second method of definition (species orientated approach) involves the studying of the competitive interactions between species. This study may be classified in one of two main ways: Interspecific competition which occurs when individuals belonging to different species compete against each other, and intraspecific competition which occurs when individuals belonging to the same species compete against each other (KEDDY 1989).

Throughout the natural development of any stand of trees from planting through to felling, both interspecific and intraspecific competition is likely to occur, albeit at different times. Interspecific competition will occur between the weeds of different species and the weeds and trees during initial stand development. During this stage intraspecific competition between the weeds of the same species may also occur. Intraspecific competition between the trees will only occur at a later stage due to the wide planting espacement. The time when this occurs is normally associated with canopy closure where the crowns of adjacent trees meet and suppress the development of subsequent weed growth through the effects of shading.

Intraspecific competition has been described according to two basic models (TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA 1994). With asymmetric or one-sided competition, larger individuals are able to obtain a disproportionate share of the resources (relative to their size differences) and suppress the growth of smaller individuals. In two-sided competition, resources are shared equally or in proportion to size. If there is a perfect sharing relative to size then competition is symmetric (BRAND and MAGNUSSEN 1988).

1.8 Degree of competition as affected by weed growth

The maximal vegetative growth rate is the greatest growth rate that a plant can attain in a habitat in which resources essential for growth are not in any way limited. In such a habitat, growth is an exponential process due to the continual compounding of growth through the reinvestment of production (TILMAN 1988). In reality it is very seldom that a plant is able to grow at a maximal rate for any length of time, if at all, due to a number of factors.

Plants need to allocate some of their growth to stems, roots or other non-photosynthetic structures. The amount allocated to these parts will be dependent on their rate of growth, morphology and mechanism of growth. GRIME and HUNT (1975) measured the maximum relative growth rates of seedlings of 132 species of flowering plants. As a group, seedlings of annual plants which do not allocate resources to perennating structures (woody stems, woody roots, energy and nutrient stores, buds) had significantly higher maximal growth rates than herbaceous perennials. Herbaceous perennials had higher maximal growth rates than woody perennials. This progression from annuals to herbaceous perennials to woody perennials represents a gradient from low to high allocation of production to non-photosynthetic structures. This differentiation in maximal growth rates may influence the form and severity of competition through competition for resources. RICHARDSON, VANNER, RAY, DAVENHILL and COKER (1996) in a study on interspecific competition between *Pinus radiata* and some common weed species found that the herbaceous broadleaves and the fast growing tall species of buddleia (*Buddleja davidii* Franchet) and pampas (*Cortaderia selloana*) resulted in the most severe competition when compared to the slower growing woody perennials of gorse (*Ulex europaeus* L.) and broom (*Cytisus scoparius* L.). MORRIS, MOSS and GARBETT (1993) found a similar growth response when *Pinus taeda* L. was subjected to competitive interference between selected herbaceous and woody weeds, with the slower growing woody weeds being least competitive. It is these annuals and herbaceous perennials that form the predominant vegetation type that occur during the establishment of eucalypt plantations in South Africa.

In addition to competition from different weed species, CHRISTIE (1994) showed that the degree of tree suppression may also be related to the relative abundance of a single competing weed species. In a replacement series field trial using *Pinus patula* with increasing competition regimes of *Setaria megaphylla*, CHRISTIE (1994) was able to demonstrate that an increase in the abundance of *Setaria megaphylla* resulted in an increasing degree of tree suppression.

1.9 What are the weeds competing for ?

One of the most effective ways to influence the growing environment of trees for increased production is by the manipulation of the vegetation surrounding the trees (NAMBIAR and SANDS 1993). According to RADOSEVICH and HOLT (1984) space (including soil) is an indication of the composite of all resources available for growth and is an interactive resource, since the plant becoming established must compete for growing space, soil air, soil water and soil nutrients. An increase in growth can usually be explained in terms of improved moisture and nutritional conditions or reduced competition for light (RICHARDSON 1993) as these factors enhance physiological processes such as leaf area development, carbon assimilation, diffusive conductance, and water use efficiency (BOOMSMA and HUNTER 1990).

1.9.1 Competition for light

The leaves of a plant are the principle organs of photosynthesis, the process by which carbohydrates are produced from carbon dioxide and water in the presence of chlorophyll by using light energy. Carbohydrate assimilation is critical for plant growth and any process that limits carbohydrate production through a reduction in available light will have a negative impact on tree growth. Plants compete for light by positioning their leaves to intercept available light more favourably than their neighbours. Plants that are most successful in competing for light are those which are able to position their leaves for greater light interception by starting growth earlier in the season and by growing taller than neighbouring plants. Weed density and morphology affect both the light distribution in the crop canopy and the light absorption by the crop. Broadleaved weeds have a distinct advantage over narrow leaved plants in competing for light.

Eucalypts are regarded as "light-demanding" or "shade-intolerant" species (FLORENCE 1996). Studies comparing the tolerance of various eucalypt and other species have been conducted, indicating that they may be placed in the light demanding category (ASHTON and TURNER 1979; BARRETT and ASH 1992). In a study where *Eucalyptus grandis* seedlings were grown from establishment under conditions of low light intensity, less carbon dioxide was assimilated and fewer photosynthetic substrates were converted to dry matter than seedlings grown under high light conditions (DOLEY 1978). This adversely affects dry matter production, the distribution of dry matter between different parts of plants as well as the morphology of these parts. Due to the rapid initial growth rate of competing vegetation, eucalypts are extremely susceptible to competition for light during the period soon after planting. Not only will this reduce the amount of light that a plant receives but it will also restrict the crown growth and development by providing a physical barrier for growth. This has been demonstrated where *Eucalyptus grandis x camaldulensis* crown growth and development was severely restricted when no weed control was carried out (SCHUMANN 1992a). DOLEY (1978) found that although the allocation of dry matter to different parts of the plant was the same in *Eucalyptus grandis* seedlings subjected to high and low light conditions, the utilization of these resources was different. Under low light, the rate of root growth was less and shoot growth greater. A similar response was detected in *Eucalyptus* *regnans* F. Muell seedlings with a reduction in light intensity (ASHTON and TURNER 1979). Although DOLEY (1978) judged the adaptation of *Eucalyptus grandis* seedlings to shading to be limited, this adaptation is common in fast growing plants which compete for light. This poor adaptation will have an influence on the underground functioning of the plant, as low levels of light may reduce the extent of the root system and thus jeopardize the ability of the seedlings to survive periods of water stress and nutrient competition (FLORENCE 1996). In many situations, the seedlings may die before they experience a lethally low intensity of light.

1.9.2 Competition for below-ground resources

Just as competition for light occurs above ground, below-ground competition between the roots for shared resources also occurs. When a tree is subject to competition, the amount of space available from which it can gather water and nutrients and the degree of competition from nearby competitors become determinants of growth (NAMBIAR and SANDS 1993). Water deficits and nutrient deficits are caused by water and nutrients not being supplied to the plant at a rate required for maximum growth. This can be caused by primary deficiencies of water and nutrients in the soil as well as by competition from other plants in soils without deficiencies, and the combined effects will be additive (NAMBIAR and SANDS 1993). For a plant to have a competitive advantage over others for water and nutrients, it must be able to (i) acquire a greater portion of the water or nutrients; (ii) use water and nutrients more efficiently for biomass production, and/or (iii) allocate assimilates in ways that will maximise capacity for survival and growth (NAMBIAR and SANDS 1993).

1.9.2.1 Competition for water

Biomass production in plants is correlated to water use. HUNTER and GIBSON (1984) found that in New Zealand increasing amounts of rainfall led to improved growth of *Pinus radiata.* The type of competitive vegetation occurring on the site may have an important bearing on the development of water stress as competition between roots of different species for the uptake of water depends on whether they coexist in the same soil zone and whether their demands are segregated spatially and/or temporally. According to FLINN, HOPMANS, MOLLER and TREGONNING (1979) different weed species (grasses versus broadleaves, woody versus herbaceous broadleaves) exhibit variable water use patterns due to their growth habit and physiological characteristics, resulting in differential competition for soil moisture.

Differences in the morphological and anatomical features of the root system may also be important. CARBON, BARTLE, MURRAY and MACPHERSON (1980), in a study on the distribution of *Eucalyptus marginata* Sm. root length with depth, found that the tree root system consisted of dense lateral roots (root length of 7 cm per unit soil volume cm^3) confined to the upper soil horizon (10 cm) with fewer vertical roots which penetrate to greater depth (0.07 cm per unit soil volume cm^3). They found that the surface horizon has the best conditions for soil water flow to roots, with the soil water potential being close to zero. In times of water stress it will be the first horizon that dries out, so that any weed roots occurring in this zone will result in an even more rapid depletion.

EASTHAM and ROSE (1990) and EASTHAM, ROSE, CAMERON, RANCE, TALSMA and CHARLES-EDWARDS (1990) examined tree and pasture interactions in an agroforestry trial and found an interaction between tree density and grass and tree root density. In that trial *Eucalyptus grandis* W. Hill ex Maiden was planted at a continuous range of spacings (Nelder design) in an established pasture dominated by *Setaria*. Pasture roots were found to decrease as tree density increased. Tree roots penetrated deeper than pasture roots. In a replacement series field trial using *Pinus patula* with different competition regimes of *Setaria megaphylla*, CHRISTIE (1994) was able to demonstrate an increasing degree of tree suppression with an increase in the abundance of *Setaria*. CHRISTIE (1994) was also able to demonstrate through studies on soil moisture content, plant water potential, water stress integral and water balance, that competition for water was the most limiting factor during the early growth of *Pinus patula*.

SANDS and NAMBIAR (1984) found, in a study on *Pinus radiata* D. Don trees, severe water stress with consequent productivity loss occurred in trees with weed competition but the severity of stress decreased progressively with increasing tree age. Transplanted seedlings in their first growing season had shallow root systems which could not efficiently exploit water at depth. By contrast, seedlings in their second and third growing seasons extracted water from a depth of at least 2m. Therefore in general the effects of weed competition on crop trees are most severe and the beneficial effects of weed control are very large during the development of a stand from planting to canopy closure.

1.9.2.2 Competition for nutrients

ELLIS, WEBB, GRALEY and ROUT (1985) showed that *Eucalyptus delegatensis* (R.T. Baker) growth responded positively to vegetation removal due to an increase in the supply of nitrogen since it was accompanied by increased concentrations of nitrogen in leaves, stems and roots of seedlings. WOODS, NAMBIAR and SMETHURST (1992) found that an increasing width of weeding had little effect on tree water status, but increased the uptake of nitrogen by the trees.

The improvement in the nutrient status of the soil through the application of fertilizer is often accompanied by an improvement in tree growth. Du TOIT (1994) has shown positive *Eucalyptus grandis* and *Eucalyptus grandis x camaldulensis* growth benefits to the application of fertilizer at establishment in the coastal Zululand soils. The low organic carbon content (0.35%) of these sandy soils has resulted in the greatest and most consistent responses to be obtained from those fertilizers high in nitrogen. Weed competition in soils low in nitrogen, which is the element most often reported to be in short supply through competition with weeds, will have an adverse impact on tree growth. For this reason, weed removal facilitates the growth benefits obtained from trees which have been fertilized. In a trial with various combinations of weed removal, site preparation and fertilizer with *Eucalyptus regnans* F. Muell., SQUIRE (1977) showed that weed control can be as important as fertilizer in enhancing tree growth. For *Eucalyptus grandis* grown in South Africa, SCHÖNAU (1984) has shown that the soil should be weed free for maximum fertilizer efficiency and that fertilizer will normally increase the necessity for weeding.

1.9.2.3 Competition for water and nutrients

When interpreting the mechanism of underground competition it is often very difficult to separate out competition for water from that of nutrients. The presence of water is the key mechanism for controlling the mass flux of nutrients from mineral and organic-matter exchange sites to root and mycorrhizal surfaces (NEARY, ROCKWOOD, COMERFORD, SWINDEL and COOKSEY 1990).

The relative importance of competition for water, nutrients, or both on the growth of the crop tree is likely to vary widely between ecosystems, depending on site, soil and the vegetation characteristics. Often, a positive influence of water or nutrients on the tree following vegetation control has been reported. NAMBIAR and ZED (1980) found that a lack of weed control in *Pinus radiata* D. Don resulted in severely water-stressed plants with low needle water potentials, reduced nutrient concentrations in the needles and a subsequent reduction in growth.

The effects of weed control also interact with the effects of other silvicultural practices, including slash and residue management, fertilization, and thinning, in most cases enhancing the beneficial growth response to silviculture (NAMBIAR and SANDS 1993). NAMBIAR and SANDS (1993), in a summary on the difficulty associated with the interpretation of competition for soil resources on tree performance, highlighted the following:

- Many of the site preparation techniques (ripping, ploughing, burning, residue retention etc.) will have an influence on weed growth,
- Weed control influences nutrient availability by altering soil water availability and temperature levels.

Thus any move towards the intensive management of eucalypts should include a selection of site, species and silvicultural practices that ensure sufficient availability and efficient use of the sites resources (HONEYSETT, BEADLE and TURNBULL 1992).

1.10 Methods of weed control

The three fundamental objectives of vegetation management include the prevention, the eradication and the management of weeds (SMITH and MARTIN 1995):

- Preventative weed control is concerned with measures taken to prevent the introduction, establishment and/or spread of weeds into areas not already infested. Preventive weed programs usually require community action through the enactment and enforcement of appropriate laws and regulations (WALKER 1995). Preventative weed control is essential for the prevention of new weed species being introduced into new areas. This type of weed control is only indirectly applicable to forest plantations as current vegetation management techniques deal with existing weed species already on the site where often the problematic weeds may be made up entirely or in part by indigenous species.

- Eradication is the elimination of a weed species after it has become established in an area. Because of the difficulty and high cost, eradication is usually only attempted in the case of small-scale infestations.
- Vegetation management is the suppression of the weed population to or below a predetermined level. This is a containment approach which implies that the target weed may still have an effect on the growth of the trees, but the benefit to cost ratio is acceptable. Thus the concept of an economic or action threshold for weeds is central to their management.

It is the last of these approaches which is the most applicable within plantations. Many different management techniques exist that involve the manipulation of the vegetation to an acceptable level. These include biological, physical, chemical and cultural weed control (ANDERSON 1996). Of the different management techniques available, the use of physical, chemical and cultural techniques have received the most attention.

1.10.1 Biological weed control

Biological management is a broad term for the exploitation of living organisms, or their products, to reduce or prevent the growth and reproduction of weeds (CARDINA 1995). Biological management is a type of weed management that uses organisms other than the associated crops to reduce the growth and adverse effects of weeds. Biological management uses biological processes that are already present, but that can be increased and manipulated to the detriment of the weeds. Although biological weed management has been successfully implemented for the control of weeds in non-afforested areas, its application within eucalypt plantations has never been exploited for various reasons. It is normally associated with the control of target weed species and not for the control of diverse weed species as found in eucalypt plantations. If a potentially competitive species is controlled then the vacated niche will be occupied by other weeds. Once released, biological agents take a while to become established to such a level that they may have a negative impact on the development of weeds. As weed growth in eucalypt plantations is only of one growing seasons duration, it is unlikely that any biological agent will have a significant impact on weed development within one season.

1.10.2 Physical weed control

Physical methods of weed control rely on the use of hand-held implements, tractor-drawn implements, smothering with non-living material or with the application of artificially high temperatures.

1.10.2.1 Manual weed control

Manual weed control relies on manual labour to remove weeds by hoeing or pulling out by hand. Within South Africa the high costs associated with the manual removal of weeds restricts the use of this practice to that area immediately adjacent to the trees in the form of either a ring or row weeding. The rest of the area would receive a chemical weeding with a non-selective herbicide. These ring or row weeding operations are carried out due to the susceptibility of *Eucalyptus spp.* to most of the non-selective herbicides used for weed control. Manual weed control with the use of hoes is almost impossible in a stand where the post-harvest plantation residue has not been burnt.

1.10.2.2 Mechanical weed control

Mechanical weed control utilizes tractor drawn implements such as rotary slashers or rotary hoes to either cut the weeds or incorporate them into the soil. Despite the obvious advantages associated with mechanical weed control, whereby large areas can be weeded rapidly and cost-effectively, there are also disadvantages with its use. Access into plantations may be hindered by the retention of post-harvest plantation residue where the site has not been burnt, the close planting espacement (seldom more than three metres) between the rows in stands grown for pulpwood, the existence of stools from the previous crop as well as the slope of the land. Additional disadvantages associated with mechanical and manual weed control include damage to the root systems of the tree, soil disturbance resulting in conditions conducive to the stimulation of seed germination, and soil compaction resulting from the use of tractors.

1.10.2.3 Smothering with non-living material

The smothering of weeds with non-living materials may be seen as a form of physical weed control. These may be either of synthetic or organic origin. Mulches are effective in weed management because they exclude light, provide a physical barrier to emergence of existing weeds as well as the germination of incoming weeds, and affect soil temperature and moisture (SCHUMANN, LITTLE and ECCLES 1995). McDONALD, FIDDLER and HENRY (1994) showed a growth benefit over five years with the use of synthetic mulches when placed around *Pinus ponderosa* seedlings at planting. Large, long-lasting polyester squares proved more effective than smaller short-lived laminated paper mulches in the suppression of competing vegetation, thus enhancing tree growth for a longer period. The retention of post-harvest plantation residue on the site as opposed to its removal by placing in windrows or by burning may also be seen as a form of physical mulch aiding weed control (FLINN 1978; SQUIRE, FLINN and FARRELL 1979; CELLIER and STEPHENS 1980).

1.10.2.4 Artificially high temperatures

Two methods exist whereby high temperatures may be used for the control of vegetation in plantations. The first method relies on the release of latent heat from steam when applied directly to the vegetation or as a soil sterilising agent for the killing of weed seeds (ZACKRISSON, NORBERG, DOLLING, NILSSON and JÄDERLAND 1997; GITTENS 1998). Although this method has been used widely within nurseries, its application for the control of living vegetation within plantations is still being developed (ZACKRISSON, NORBERG, DOLLING, NILSSON and

JÄDERLAND 1997). The second method relies on the use of prescribed burning to kill existing vegetation. This may either be carried out prior to planting or under mature trees. When carried out prior to planting the primary objective would be to improve site access by the removal of post-harvest residues. This results in the killing of any vegetation that may be present on the site. The use of fire under mature stands is reserved for those species whose growth will not be adversely affected. The primary reasons for fire under these stands would be for fuel hazard reduction (CAIN 1996), for the control of hardwoods in pine plantations (BRENDER and COPPER 1968; HAYWOOD 1995; CAIN 1996), as a means of reducing the total number of trees in naturally generated stands (HAYWOOD 1995), for the release of nutrients resulting from such practices (SCHOCH and BINKLEY 1986) and for aiding in the preparation of seedbeds in naturally regenerated stands (BRENDER and COPPER 1968).

The potential for the use of fire as a management tool in South African forestry is limited due to the sensitivity of the tree species grown. Fire is thus only used prior to establishment, so as to improve site access for the various silvicultural operations.

1.10.3 Chemical weed control

Chemical weed control is the most widely used form of vegetation management and relies on the use of herbicides for the removal of the target vegetation. Herbicides are phytotoxic chemicals used to kill or suppress plant growth. Depending on their mode of action and the method of uptake, herbicides can be grouped into various categories. Herbicides may be either selective or non-selective with respect to the kinds of plants affected. Herbicides may kill on contact (normally as a result of dessication due to tissue damage) or they may need to be translocated to target sites within the plant, following absorption. Soil active herbicides may be applied to the soil where they may remain relatively unaffected for various periods of time. Herbicides applied in this manner, target either the root systems of existing plants or affect the germination of existing seeds (pre-emergent herbicides). Most post-emergent herbicides used in eucalypt plantations are applied to the foliage of existing weeds as a full cover spray.

The most commonly used herbicide in South African plantations is glyphosate (isopropylamine salt). Glyphosate is a non-selective herbicide that is applied to the foliage of the vegetation to be controlled. It is readily absorbed by the leaves and disrupts the photosynthetic functioning of the plant. Once absorbed into the plant, it is translocated in the symplast resulting in the killing of the underground buds as well as apical meristems (ASHTON and CRAFTS 1981). Phytotoxic symptoms of glyphosate injury include foliar chlorosis followed by necrosis (FERNANDEZ and BAYER 1977). Glyphosate is not a soil active herbicide and has practically no leaching tendency (RAMSEY 1991). It binds tightly to the soil where it is highly susceptible to degradation by micro-organisms, being rapidly broken down and converted to natural products such as carbon dioxide and water (RUEPPEL, BRIGHTWELL, SCHAEFER and MARVEL 1977). Being non-selective, it is used extensively in South Africa for the control of the common weed species (grasses, herbaceous or woody) occurring in forestry situations. These factors, in combination, have made glyphosate one of the most popular of all chemicals available in South Africa for use during establishment weed control for forest vegetation management. Another benefit of chemical weed control over other forms of weed control includes the killing of vegetation without soil disturbance.

As glyphosate is non-selective, the tree seedlings are as susceptible to herbicide damage as the surrounding vegetation. For this reason the trees, when small, are protected by large plastic cones during routine spraying operations. Once the trees are too large for "coning", glyphosate is applied as a directed spray away from the trees. This is a preferred treatment and makes an important contribution to the management of forests, particularly in the initial and critical stages of tree growth.

1.10.4 Cultural weed control

The cultural control of weeds utilizes practices common to good land, crop and water management. Some of these practices include the manipulation of crop-row spacing, crop cultivars and crop populations, the maintenance of critical weed-free periods and distances, using crop rotations and smothering crops (ANDERSON 1996).

1.10.4.1 Crop-row spacing and cultivar choice

Crop-row spacing as well as species choice affects the rapidity of the foliar-crown development and hence the time after planting that canopy closure is reached. The espacement at which trees are planted is determined from mensuration trials, and crop cultivar from trials in which species are matched to different sites. Although the suppression of vegetation is not the primary objective in this situation, both may have a dramatic effect on the rate of site capture. The closer espacement, as practised within pulpwood rotations in contrast to sawlog stands, and the selection of trees with denser crowns (for example *Eucalyptus grandis* as opposed to the hybrid of *Eucalyptus grandis x E. camaldulensis*) both result in the rapid shading of the soil.

1.10.4.2 Optimum timing for weed control

Optimum timing and duration of vegetation control during the early development of forest plantations can be assessed using critical-period analysis. The determination of the critical-period thresholds within forestry, requires an understanding of how the temporal effects of interspecific competition affect seedling survival and growth (WAGNER, NOLAND and MOHAMMED 1996). According to WEAVER and TAN (1983) the critical period is composed of two components: the length of time weed control efforts must be maintained to prevent a loss in crop yield, and the length of time weeds can remain in a crop before they interfere with crop growth. Although much work has been dedicated to the study of critical-period thresholds in annual crops, WAGNER, NOLAND and MOHAMMED (1996) were unable to find any work specifically related to examining critical-periods for perennial cropping systems or forest stands.

1.10.4.3 Minimum row weeding distances

The determination of minimum weeding distances (distance from tree to weeds) over time is important for optimum tree performance. Previous weed management trials have shown that when compared to a complete weeding, row weeding may achieve similar gains in tree performance, with a resultant reduction in the areas to be weeded (SCHUMANN, LITTLE and SNELL 1993). This may be translated into economic as well as environmental gains. Results from three trials in Zululand to investigate the spatial and threshold aspects of interspecific competition on eucalypts supplied valuable quantitative information (LITTLE and SCHUMANN 1996). Row weeding was found to be preferable to inter-row weeding at all three of the sites, but the onset of weed-induced tree suppression differed according to the development of competitive weed levels. At these sites acceptable row weeding widths varied between 200 and 240 cm.

1.10.4.4 Cover-cropping

Cover-cropping involves the suppression of undesirable vegetation by sowing some desirable cover-crop in the areas which are open to invasion (COOLMAN and HOYT 1993). In addition to the vegetation control afforded by the cover-crop, the presence of plant cover has been shown to reduce runoff (with better water infiltration), and reduce erosion (EL-SWAIFY, LO, JOY, SHINSHIRO and YOST 1988). If a leguminous cover-crop species is used, levels of soil mineralizable nitrogen are likely to increase as a result of nitrogen fixation (GADGIL 1983; EL-SWAIFY, LO, JOY, SHINSHIRO and YOST 1988; HOLDERBAUM, DECKER, MEISINGER, MULFORD and VOUGH 1990). With vegetation control as the primary objective, the selected cover-crop species should have a vigorous, spreading growth habit as is found in several varieties of the leguminous cowpea *(Vigna unguiculata)* species (NOBLE and SCHUMANN 1990; SCHUMANN, LITTLE and SNELL 1993). This growth form allows the cover-crop to rapidly colonize all available ground.

1.11 Integrated forest vegetation management

With time, greater emphasis is being placed on long term site sustainability. For long term site sustainability to be achieved there needs to be the integration of the various acceptable methods of vegetation management available (not reliant on one method only) as well as the integration of vegetation management with all other disciplines associated with forest management. WAGNER (1994) defines integrated vegetation management as managing the course and rate of forest vegetation succession to achieve silvicultural objectives by integrating knowledge of plant ecology with a wide variety of complementary methods that are ecosystem-based, economical, and socially acceptable. Integrated vegetation management is a multi-disciplinary approach encompassing chemical, physical, biological and cultural methods of vegetation management together with effective education and extension of the management components (LOVETT and KNIGHTS 1996). Its purpose is to optimise the total benefits of various management techniques. It operates best in an environment where increasingly demanding social, economic and political pressures are exerted. Each method has its advantages and disadvantages and usually no single method is sufficient for an effective vegetation management programme at a reasonable cost. The development of integrated vegetation management systems is a complex task and must be supported by a thorough understanding of its components (LOVETT and KNIGHTS 1996). Achieving integrated forest vegetation management will require that forest researchers and managers adopt new perspectives, conduct research and technology development, and incorporate resulting methods and technologies into practice (WAGNER 1994).

1.12 Conclusions

This section describes the theoretical background to competition, the mechanisms of competition, as well as existing individual techniques that are used in weed control. After an evaluation of each of them, it is clear that weed management in the future, should be structured on an integrated approach. Before that can happen, the most important requirement will be to build up a base line of measured performance of the disparate techniques used at present. Only then, will it be possible to arrive at the most effective "integrated forest vegetation management" strategies. From this it should be possible to develop a programme of those most effective treatments at the different phases of growth, thus providing a comprehensive policy.

It is also clear that although the reasons for vegetation management are fairly well understood, and are similar for different tree species grown in different parts of the world, there are features which are unique to the management of vegetation in short rotation eucalypts. For example the predominant group of weeds that occur in young eucalypt plantations (mainly annuals), the sensitivity of eucalypts to most herbicides, the rapid time taken to canopy closure which reduces the weed control period and the susceptibility of eucalypts to weed competition. The management of vegetation in eucalypts will also have to be adjusted to take weed control costs and improved yield into account, as well as aspects such as wood quality, long term site sustainability and any ecological issues related to the use of individual techniques.

CHAPTER 2

GENERAL MATERIALS AND METHODS

2.1 Introduction

2.1.1 Experimental site, location and physical and environmental attributes

The site where this study was conducted is situated in KwaZulu-Natal near the coastal town of Mtunzini. The trial was on Mondi property at their Mtunzini plantation of Fairbreeze, the co-ordinates of which are 28^0 59' S and 31^0 42' E (Figure 2.1).

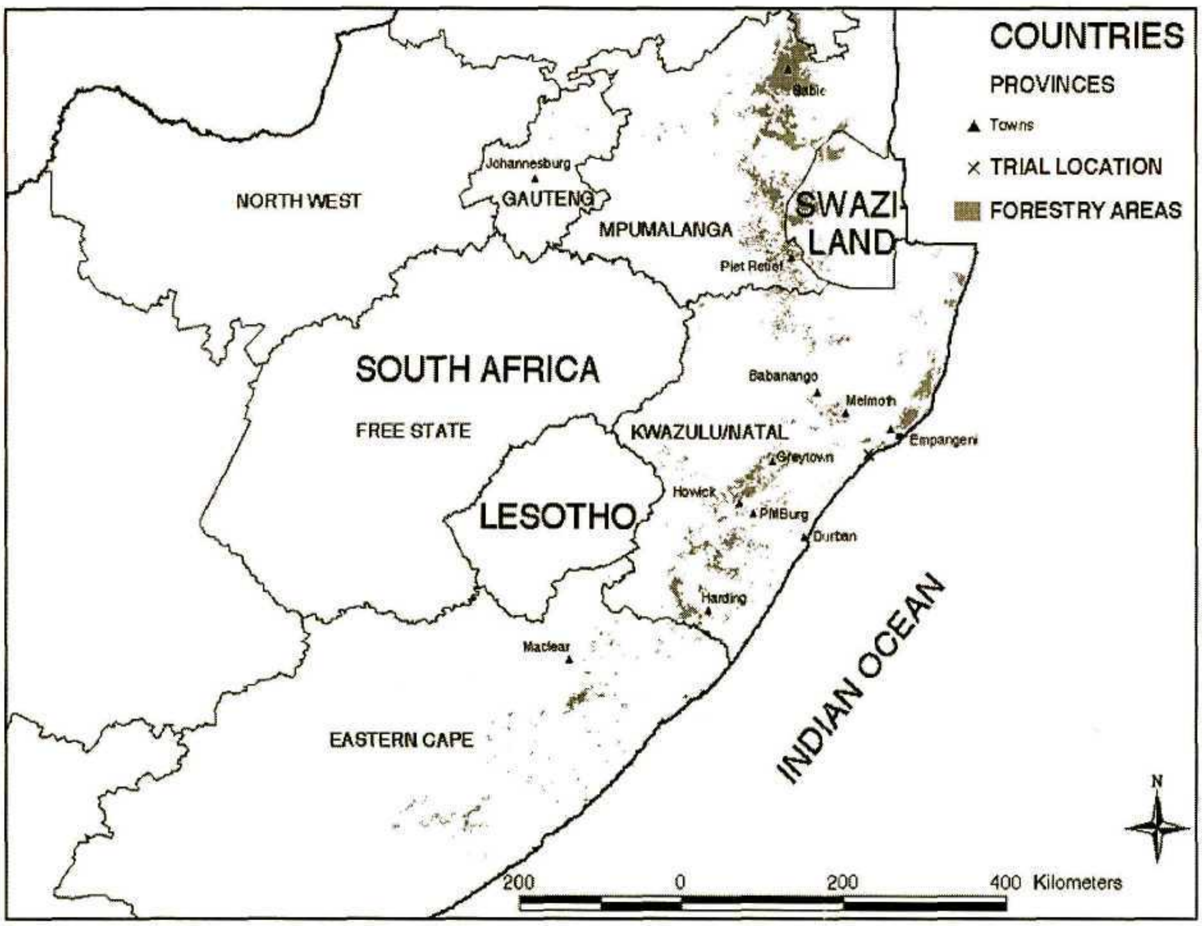


Figure 2.1: Location of the trial site in relation to commercial forestry practised in the summer rainfall regions of South Africa.

The climate is sub-tropical, with a mean annual rainfall of approximately 1150 mm and mean annual temperature of 22^0 C. Mean monthly and annual rainfall and temperatures (for the site) for the duration of this study are shown in Tables 2.1 and 2.2.

Table 2.1: Annual rainfall (mm) and mean minimum and maximum temperatures (^0C) for the duration of the trial (October 1990 to October 1997).

Year	1990/1	1991/2	1992/3	1993/4	1994/5	1995/6	1996/7	Mean
Rainfall	1550.3	641.2	940.5	948.2	1156.5	1651.8	1118.9	1143.9
Min. Temp	16.3	16.9	17.1	16.1	16.3	16.5	16.7	16.6
Max. Temp	26.4	28.1	27.8	27.2	26.8	25.8	26.4	26.9
Mean Temp	21.4	22.5	22.5	21.6	21.6	21.1	21.6	21.7

Table 2.2: Mean monthly rainfall (mm) and mean minimum and maximum temperatures (^0C) for the duration of the trial (October 1990 to October 1997).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Rainfall	143	126	132	131	113	149	84.4	48.2	42.8	55.9	57.1	62.3
Max. Temp	26.1	28.1	28.9	30.1	30.2	28.9	27.4	25.8	23.7	23.4	24.4	26.2
Min. Temp	17.4	18.4	20.1	20.9	21.1	19.9	17.5	14.1	10.5	12.8	15.7	16.6
Mean Temp	21.7	23.3	24.5	25.5	25.6	24.4	22.5	19.9	17.1	16.9	18.6	20.9

The trial is located at an elevation of 45 m on an east facing slope. Parent material is regic sand of aeolin origin and classified as a deep Hutton Lillieburn 1100/Hutton Kelvin 1200 according to the taxonomic classification system for South Africa (SOIL CLASSIFICATION WORKING GROUP 1991). FAO and USDA equivalents would be arenic lixisols and arenic kandiustults respectively. Soil samples were collected from all treatments plots at two depths (0-15 cm and 50-65 cm). The physical and chemical properties were analyzed at the ICFR's soils laboratory in accordance with the procedures laid out by DONKIN, PEARCE and CHETTY (1993). The physical and chemical properties of the soil are summarised for the whole trial in Table 2.3. Treatment means for these soil properties are presented in Appendices 2.1 and 2.2.

The compartment within which the trial was situated was previously used for the production of sugarcane (*Saccharum officinarum*). Initially the predominant weed on the site was yellow nutsedge (*Cyperus esculentus*). This was subsequently dominated by *Panicum maximum*.

Table 2.3: Soil chemical and physical properties.

		Soil sample depth	
Physical properties		0-15 cm	50-65 cm
	Sand (%)	91.1	85.8
	Silt (%)	5	4.2
	Clay (%)	3.9	9.9
Chemical properties			
	pH (KCl)	4.058	3.952
	Organic carbon (%)	0.364	0.296
	Ca^{2+} ($cmol_c$ kg^{-1})	0.403	0.311
	Mg^{2+} ($cmol_c$ kg^{-1})	0.262	0.186
	K^{1+} ($cmol_c$ kg^{-1})	0.041	0.021
	Na^{1+} ($cmol_c$ kg^{-1})	0.061	0.078
	S_value ($cmol_c$ kg^{-1})	0.767	0.596

2.2 Trial description

2.2.1 Trial initiation

A pre-plant spray with a non-selective herbicide (glyphosate) was carried out in order to reduce the presence of weeds to zero at the time of planting. The trial was then superimposed on a stand of *Eucalyptus grandis x camaldulensis* hybrids (GC304) that had been cloned. The use of clones provided some degree of uniformity, with the hybrid combination selected by Mondi for its resistance to disease together with an adaptation to growth in the drier and hotter parts of the Zululand coastal region. The trees were planted on the 9^{th} October 1990 at an espacement of 3 m between the trees rows and 2.5 m within each row. This translates to a stocking of 1333 stems per hectare. Each tree was fertilized at planting with 60 g limestone ammonium nitrate (LAN) (28 % N), applied in a 0.2 m ring around each tree.

2.2.2 Design and treatments

Nine treatments, as listed in Table 2.4, were replicated four times and laid out in a randomized complete blocks design (Figure 2.2). Each treatment plot consisted of 30 trees (5 rows x 6 trees in each row) with the inner 12 trees being measured (3 rows x 4 trees in each row). Each treatment plot covered an area of 225 m^2, with the total size of the trial being 8100 m^2 (225 m^2 x 36 plots).

Table 2.4: List of weeding and cover-cropping treatments.

Number	Treatment	Method/species
1	Weedy	None
2	Weed free	Manual
3	Weed free	Chemical
4	Inter-row weeding (1.2 m width)	Manual
5	Ring weeding (0.5 m radius)	Manual
6	Complete weeding except ring[1] (0.5 m radius)	Manual
7	Row weeding (1.2 m width)	Manual
8	Cover-crop with weeding to establish	Cowpea
9	Cover-crop with weeding to establish	Velvet bean

[1] This treatment will subsequently be described in the text and tables as a "- Ring weeding"

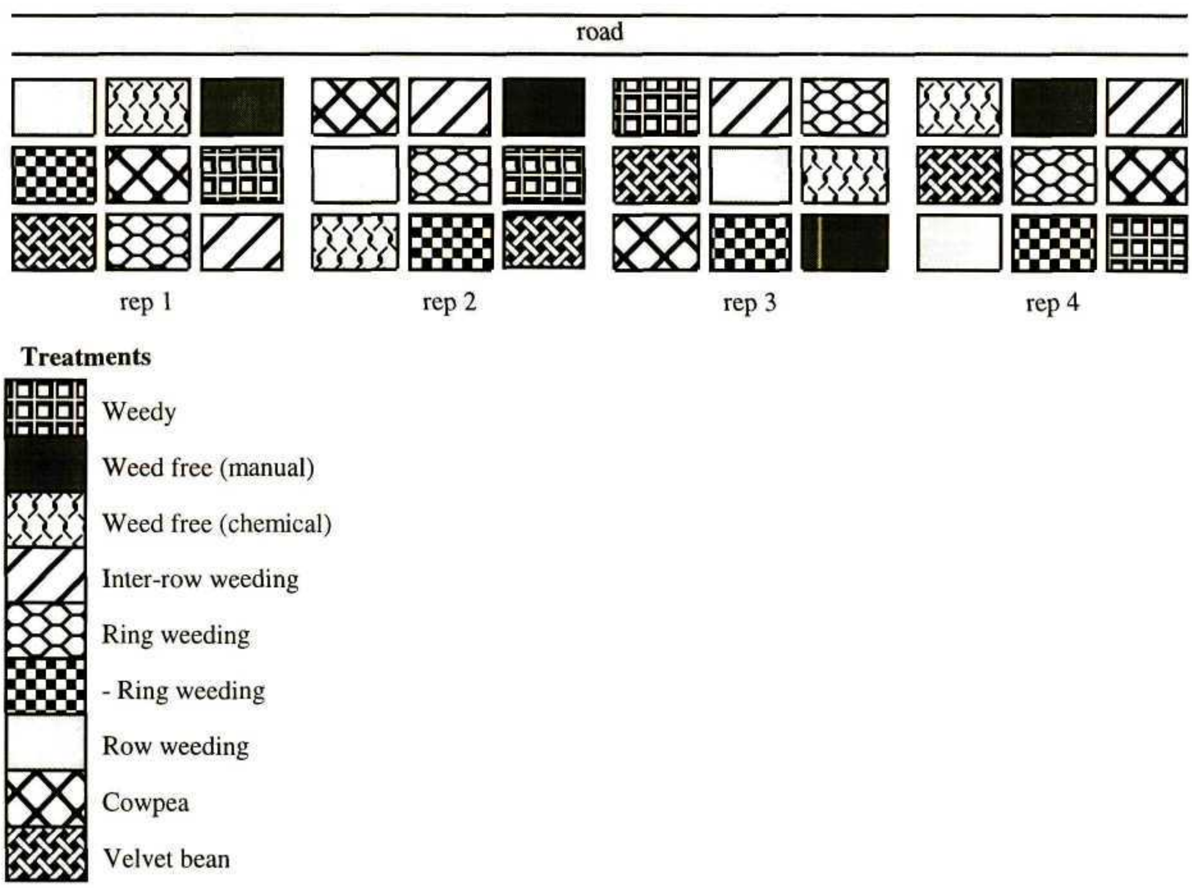


Figure 2.2: Trial layout showing location of individual treatment plots.

2.2.3 Treatment initiation and maintenance

The entire trial area received a complete weeding with glyphosate applied as a pre-plant spray. The nine treatments were first imposed on 22nd October 1990 with the weedy control receiving no further weed management. The weed free (manual), row weeding, inter-row weeding, ring weeding and complete weeding except ring (-ring weeding) treatments were kept manually weeded in their respective zones with the use of hoes. Initial weed control for the weed free (chemical) treatment was carried out with the use of glyphosate sprayed at 4 $l\ ha^{-1}$ through knapsack sprayers. Care was taken to protect the trees with the use of inverted plastic cones. Subsequent chemical weeding operations were carried out on the inter-row with a hand drawn shielded spray boom. The cover-crops of cowpea (*Vigna sinensis*) and velvet bean (*Mucuna pruriens*) were planted in double rows, 1 m from the tree rows. The cowpea seeds were planted at an espacement of 100 mm and the velvet beans at 200 mm. These were then fertilized at 10 $g\ m^{-1}$ with 2:3:2 (22) + 0.5 % Zn. The cover-crops were manually weeded on two occasions until a full plant cover had been established, thus reducing the need for further weed control.

Weed control operations were carried out on a monthly basis in all the manually weeded treatments except the weedy control and the cover-cropping treatments. This continued until canopy closure occurred, after which the limited light available for growth restricted further weed development.

2.3 Measurements

2.3.1 Tree variates measured in the standing crop

The units used for any of the measured or derived variates is listed in Table 2.6. The tree variates of either height, crown diameter or diameter at breast height were measured at regular intervals during the development of the stand. These were used to determine the performance of the different treatments over time. Tree height of each individual tree was measured twelve times during the first 20 months and then again when the trees were felled. After 20 months the measurement of tree heights became increasingly inaccurate and were thus discontinued until they could be measured when felled. The tree crown diameter was measured four times during the first five months. This was determined as the mean of the diameter through the widest part of the crown and the diameter of the crown perpendicular to the first reading. The diameter at breast height (1.3 m above ground level) could only be determined when most of the trees from the different treatments were above 1.3 m in height. The suppression of trees in the weedy treatments meant that this measurement was delayed until 20 months after planting. From 20 months, the diameter at breast height was measured nine times until felling. Treatment means are shown for the height, crown diameter and diameter at breast height variates in Appendices 3.1, 3.3 and 4.1 respectively. The sequence and timing of measurements is outlined in Table 2.5.

Table 2.5: Sequence and timing of measurement of tree variates whilst trees standing.

Date measured	Tree Height	Crown diameter	Diameter at breast height	Days after planting	Days between measurement
22/10/90				0	
19/12/90	✓	✓		58	58
20/01/91	✓	✓		90	32
20/02/91	✓	✓		121	31
22/03/91	✓	✓		151	30
25/04/91	✓			185	34
22/05/91	✓			212	27
19/06/91	✓			240	28
25/07/91	✓			276	36
05/09/91	✓			318	78
04/12/91	✓			408	90
17/03/92	✓			512	104
16/06/92	✓		✓	603	91
28/09/92			✓	707	104
14/12/92			✓	784	77
24/03/93			✓	884	100
13/07/93			✓	995	111
11/05/94			✓	1297	302
20/04/95			✓	1641	344
29/05/96			✓	2046	405
18/10/97	✓		✓	2553	507

2.3.2 Derived tree variates whilst standing

The stem area per tree is calculated by converting the diameter at breast height measurements as shown in Equation 2.1:

$$Stem\ area = \Pi \times \left(\frac{Dbh_{ob}}{2}\right)^2 \qquad (2.1)$$

where Dbh_{ob} is the over bark diameter at breast height. From this the basal area per hectare can be calculated with the use of the stocking obtained for the respective treatments. Treatment means for stem area and basal area calculations are shown in Appendices 4.3 and 4.5 respectively. From the tree variates of height, crown diameter and diameter at breast height and stem area, the growth rates were derived. The growth rate for height (GR_{ht}) is calculated as shown in Equation 2.2:

$$GR_{ht} = \frac{ht_2 - ht_1}{t_2 - t_1} \qquad (2.2)$$

where $ht_2 - ht_1$ is the difference in the growth of tree height over the time period $t_2 - t_1$. In a similar fashion the growth rate for crown diameter (GR_{cr}), diameter at breast height (GR_{dbh}) and stem area (GR_{stem}) can be calculated. Treatment means for the growth rates of height, crown diameter, diameter at breast height and stem area are shown in Appendices 3.2, 3.4, 4.2 and 4.4 respectively.

2.3.3 Tree variates measured when felled

Prior to felling, the over bark diameters at breast height (Dbh_{ob}) were measured and marked on all the trees. The trees were felled as close as possible to the ground ($\leq$0,05 m). Once felled, the height to the top of each tree (H_{top}) and height to a minimum over bark stem diameter of 0.07 m ($H_{0.07}$) were measured. Under bark diameter measurements were taken at breast height (Dbh_{ub}) as well as at 2.4 metre intervals, from the base of the stem up to and including the diameter at $H_{0.07}$. Treatment means for the height variates are shown in Appendix 3.1 and diameter variates in Appendix 4.1.

2.3.4 Derived tree variates when felled

The minimum over bark stem diameter of 0.07 m at $H_{0.07}$ is supposed to equate to an under bark diameter of 0.05 m, the minimum diameter that can be utilized economically. In order to determine if this was the case, the under bark diameter ($d_{0.07}$) at $H_{0.07}$ was measured. The bark thickness at breast height was calculated by subtracting under bark (Dbh_{ub}) measurements from the over bark (Dbh_{ob}) measurements.

From each 2.4 metre section, the under bark volume (V_{sec}) was calculated using the formula for a truncated cone (CAILLIEZ 1980) as shown in Equation 2.3:

$$V_{sec} = \frac{\pi}{12} (d_1^2 + d_1 d_2 + d_2^2) \times l \qquad (2.3)$$

where d_1 and d_2 are the under bark diameters of the lower and upper ends of each section and l is the length of each section. The volume of the last section (V_{last}) of the tree (from $H_{0.07}$ to the top of the tree H_{top}) was calculated using the formula for a cone (CAILLIEZ 1980) as follows (Equation 2.4):

$$V_{last} = \frac{\pi}{12} (d_{0.07}^2) \times l_{0.07} \qquad (2.4)$$

where $d_{0.07}$ is the under bark diameter taken at the end of the last section of the stem and $l_{0.07}$ is the length of the stem from $H_{0.07}$ to the top of the tree (H_{top}). The total volume for each individual tree (V_{tot}), was then calculated from the sum of the volumes of each section. From this the total volume per hectare (V_{totha}) was then calculated with the use of the stocking obtained for the respective treatments. In a similar manner the merchantable volume for each individual tree (V_m) and the total merchantable volume per hectare (V_{mha}) were then calculated from the sum of the volumes of each section excluding the volume from the last section(V_{last}).

To give an indication of the decrease in diameter with tree height, the taper of individual trees was calculated as shown in Equation 2.5:

$$Taper = \frac{d_{base} - d_{0.07}}{H_{0.07}} \qquad (2.5)$$

where d_{base} is the under bark diameter of the tree at 0.05 m above ground level, $d_{0.07}$ is the under bark diameter corresponding to an over bark diameter of 0.07 m and $H_{0.07}$ is the height to a minimum over bark diameter 0.07 m.

2.3.5 Additional variates measured

In addition to the various tree variates measured, vegetation biomass, soil moisture content and the nutrient content of the vegetation sampled were also determined at selected intervals.

Above ground vegetation biomass samples were taken from a 0.5 m^2 quadrate in the weedy control and from a 1 m^2 section for the cowpea and velvet bean cover-crops. These biomass samples were taken from the border rows so as not to impact on the performance of the measured trees. One sample was collected from each treatment plot each month. The samples were oven dried for 48 hours at 80^0C and their mass determined. Treatment means are shown in Figure 3.1. Foliar nutrient contents were determined from the biomass samples from the weedy control (30 day after planting) and from the cover-crops (120 days after planting). From this the approximate nutrient content per hectare contained in the biomass was calculated. The foliar nutrient content and approximate nutrient content per hectare contained in the biomass are shown in Table 3.1.

On four occasions from January 1991 gravimetric soil moisture measurements were taken from treatments in the first replicate. A CPN 503DR Hydroprobe® was used by taking count ratios (measured count/standard count) at six soil depths up to 0.8 m and correlating these with gravimetric soil moisture determinations. These changes in the soil moisture content with depth are shown in Figure 3.5.

Table 2.6: Variates used for the determination of treatment differences.

Property measured	Variable	Unit
Height to top of tree	H_{top}	m
Crown diameter		cm
Over bark diameter at breast height (1.3 m)	Dbh_{ob}	cm
Under bark diameter at breast height (1.3 m)	Dbh_{ub}	cm
Bark Thickness		cm
Stem area		cm^2
Basal area		$m^2\ ha^{-1}$
Growth rate of tree height, crown diameter, diameter at breast height and stem area	Gr_{ht} GR_{cr}, Gr_{dbh}, GR_{stem}	$m\ day^{-1}$ $cm\ day^{-1}$ $cm^2\ day^{-1}$
Height to top of tree	H_{top}	m
Height to a minimum over bark diameter of 0.07 m	$H_{0.07}$	m
Under bark diameter of the tree at 0.05 m above ground level	d_{base}	cm
Under bark diameter corresponding to an over bark diameter of 0.07 m	$d_{0.07}$	cm
Under bark diameters every 2.4 m along tree length	d_1, d_2 ..... d_n	cm
Length of the stem from $H_{0.07}$ to the top of the tree (of H_{top})	$l_{0.07}$	m
Under bark volume of each 2.4 m section of tree to a minimum over bark diameter of 0.07 m	V_{sec}	m^3
Under bark volume of the last section of the tree (from $H_{0.07}$ to the top of the tree H_{top})	V_{last}	m^3
Total volume of individual trees	V_{tot}	m^3
Total volume per hectare	V_{totha}	$m^3\ ha^{-1}$
Merchantable volume of individual trees (volume up to a minimum over bark diameter ≥0.07 m)	V_m	m^3
Merchantable volume per hectare	V_{mha}	$m^3\ ha^{-1}$
Taper		$m\ m^{-1}$

2.4 Statistical analyses of tree variates

2.4.1 Treatment comparisons between individual variates

The trial was laid out as a randomized complete blocks design. The nine treatments were randomized within each replicate, the randomization being carried out separately for each block. Each treatment occurred only once per block (Figure 2.2).

The blocks were arranged in such a way that the response of units within each block may be expected to be relatively homogenous, as compared to those of units taken from different blocks (HUNTSBERGER and BILLINGSLEY 1973). During analysis the variation for each property tested was separated into components and the statistical model used was:

$$\gamma_{ij} = \mu + \beta_j + \tau_i + \epsilon_{ij} \qquad (2.6)$$

Where μ is the overall mean, β_j is the effect of the j^{th} block (the deviation of the block mean from the overall mean), τ_i is the effect for the i^{th} treatment, and ϵ_{ij} is the deviation of the observed value, y_{ij} from its expected value (RAYNER 1967). It is assumed that μ, β_j and τ_i are unknown parameters and that the ϵ_{ij} are normally and independently distributed with mean zero and common variance. Before comparisons between individual treatment means were made, an overall *F*-test was carried out. The *F*-test is an overall test of the significance of the differences that have been observed between the means of all the treatments in the experiment and is calculated as in Equation 2.7 (MEAD and CURNOW 1983):

$$F = \frac{treatment\ mean\ square}{error\ mean\ square} \qquad (2.7)$$

Only if the *F*-value was significant were treatment differences further investigated using least significant differences (*lsd's*). The *lsd* is calculated from the product of the standard error of the of the difference of the means and the tabulated *t*-value for various degrees of freedom. The *t*-values are obtained from Student's *t*-distribution for various probability levels. This procedure provides for a value, at a prescribed level of significance, which serves as the boundary between significance and non-significant differences between any pair of treatment means (STEEL AND TORRIE, 1981). That is, two treatments are declared significantly different at a prescribed level of significance if their difference exceeds the computed *lsd*-value, otherwise they are not significantly different. Comparisons between the tree variates were analyzed as a randomized complete blocks design with the use of Genstat® for Windows™ (LANE and PAYNE 1996). In addition, Bartlett's test (SNEDCOR and COCHRAN 1956) was used to test the assumption of homogeneity of variance in order for a valid analysis of variance to be performed. Calculated x^2 (corrected) values for crown diameter, tree height, diameter at breast height as well as the variates determined when the trees were felled are shown in Appendices 2.3 and 2.4. Only the variate of tree height was significantly different (p<0.05) on certain measurement dates indicating the presence of heterogenous variance. The Fisher-Behrens test (CAMPBELL 1974) which uses separate variance estimates for the samples, was then used to determine differences between the means for the tree heights on those measurement dates.

CHAPTER 3

THE INFLUENCE OF COMPETING VEGETATION ON TREE GROWTH DURING ESTABLISHMENT

3.1 Introduction and objectives

As part of the vegetation management programme within South African forestry, various management techniques are sought whereby cost-effective and environmentally sound recommendations can be made. Part of this process involves the testing and application of these recommendations under field conditions. Until the implementation of this trial most of the weed control techniques centred around the use of minimum weeding with hoes. As the management of vegetation contributes a major portion to establishment costs, these minimum weeding practices needed to be tested together with alternatives in a statistical manner so as to determine their impact on tree performance. With this in mind the trial used in this study was established in 1990. The initial objectives were to determine the onset of early weed competition from several weed proximity treatments and to evaluate two leguminous cover-crops for cultural weed control. The weed control treatments selected for use in this trial reflected then current (at the time of trial initiation) methods of vegetation management. An outline of the treatments is given in Chapter 2, Table 2.4.

The influence of these various vegetation management treatments on initial tree performance (first two years growth) have been comprehensively documented and reported on by SCHUMANN (1992a) and SCHUMANN (1992b). In order to understand the long term effect of these various vegetation management treatments on tree performance, some of these initial growth trends need to be highlighted. This chapter will therefore look at some of these early growth trends.

3.2 Results and discussion

3.2.1 Initial weed growth and possible mode of competition

Relative to the manually weeded control, initial tree suppression was detected from the time the first measurements were taken (58 days after planting), for both the tree variates of height and crown diameter (Figures 3.3 and 3.4 and in Appendices 3.1 and 3.3 for additional detailed information). There is often a delay between the onset of weed induced stress in trees and the detection of this stress in the form of reduced growth for the tree variates measured. As the degree of suppression at this stage was already significant it indicates that suppression occurred at some stage earlier than that recorded. The early suppression of trees in this trial could be a result of the initial type of weed occurring on this site, that is yellow nutsedge (*Cyperus esculentus*). LITTLE and SCHUMANN (1996) detected weed (predominantly yellow nutsedge) induced tree suppression 30 days after planting in an *Eucalyptus* weeding trial, also on an ex-sugarcane field in Zululand.

The types of weeds occurring in ex-agricultural lands is often a reflection of the crop that was previously grown on the site, combined with the vegetation management techniques that were employed. As sugarcane (*Saccharum officinarum*) was grown on the site prior to the conversion to plantations, its management as the primary crop meant that all weeds were targeted for control by either manual hoeing or with either selective or non-selective herbicides. One of the weeds that proved to be resilient to most of the forms of weed control was yellow nutsedge. Yellow nutsedge is a weed characteristic of ex-agricultural lands and its competitiveness may be due to a number of factors. Although yellow nutsedge is able to propagate itself by seed, the main form of reproduction is by underground vegetative structures (corms and tubers) (THULLEN and KEELEY 1975; SCHIPPERS, TER BORG, VAN GROENENDAEL and HABEKOTTE 1993). This development from vegetative structures would provide a competitive advantage over those competitors that developed from seed, as it is able to develop almost immediately after conditions for growth become suitable. Initial development of the weed biomass in this trial was rapid, with an increase from 0.7 to 3.0 tons ha^{-1} being recorded for the first two months of growth (Figure 3.1). This rapid growth often coincides with the development of the young seedlings, the stage at which they are most vulnerable to competition from weeds. Another problem is the variability in the timing of the sprouting and resprouting habits of yellow nutsedge which makes control difficult. The herbicides used for the control of weeds as a pre-plant spray, in this case glyphosate spayed at 4 l ha^{-1}, did not provide effective yellow nutsedge control due to this variability in sprouting times. SCHIPPERS, TER BORG, VAN GROENENDAEL and HABEKOTTE (1993) found that yellow nutsedge is still able to grow even with 90 % herbicide efficacy. This means that although the growth of the yellow nutsedge plants may be delayed, rapid recovery and growth follows.

Initially it is unlikely that competition for light would have played a major role in limiting tree performance, as the height of the poorest performing treatment at 58 days after planting (inter-row weeding) was already 35.5 cm. Yellow nutsedge on these sites very seldom attains a height of over 30 cm. Relative to its proximity to trees, yellow nutsedge may have either restricted the initial above ground development of the trees through below-ground competition for moisture and nutrients limiting overall plant development, or alternatively by providing a physical barrier for the development of a larger tree crown. Thus the trees with the smallest crown diameters at 58 days after planting were those treatment plots in which the weeds were retained in the immediate proximity of the trees. These were the weedy control (26.56 cm), the inter-row weeding (23.94 cm) and the -ring weeding (30.39) treatments (Figure 3.3 and in Appendix 3.3 for additional detailed information).

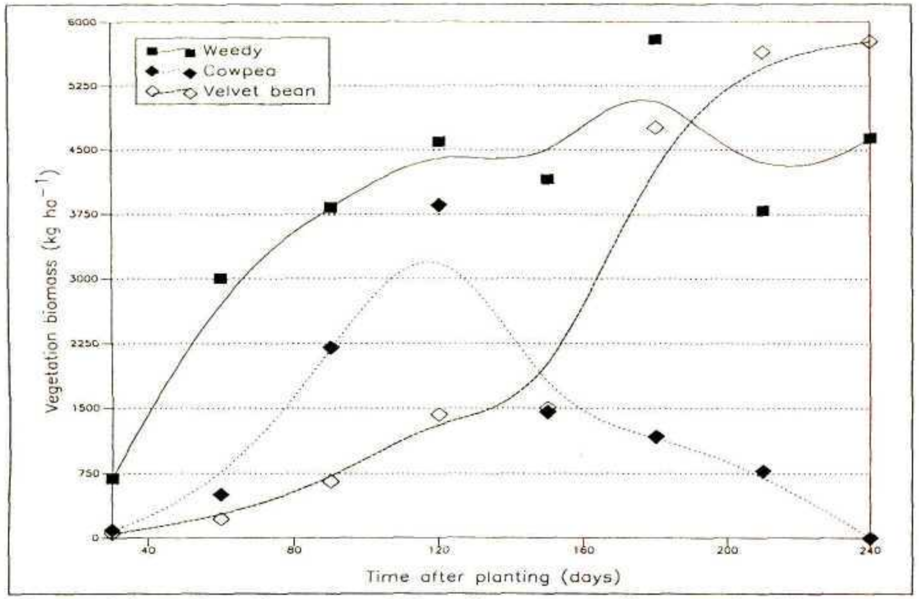


Figure 3.1: Development of 'dry above ground' vegetation biomass with time.

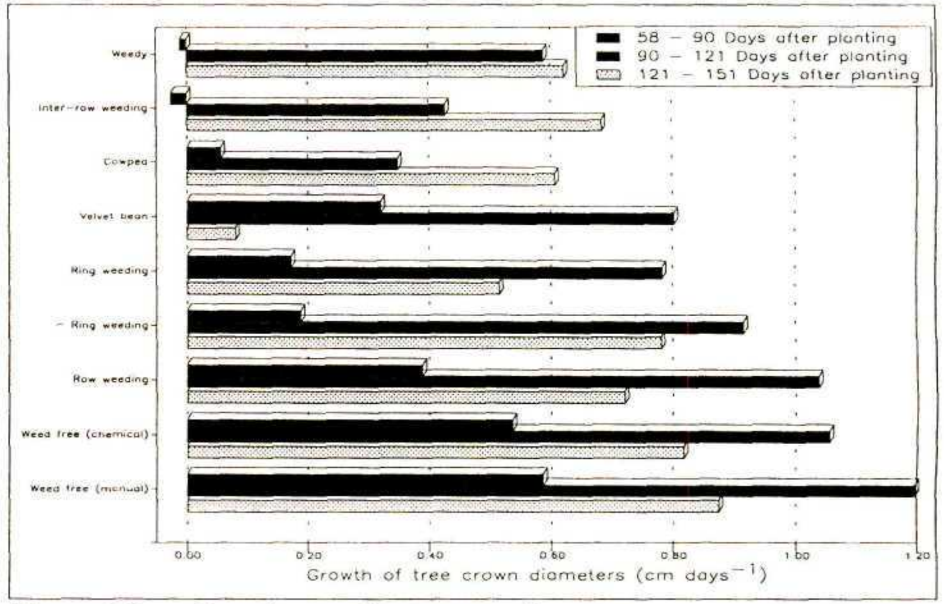


Figure 3.2: Growth rate of tree crown diameters.

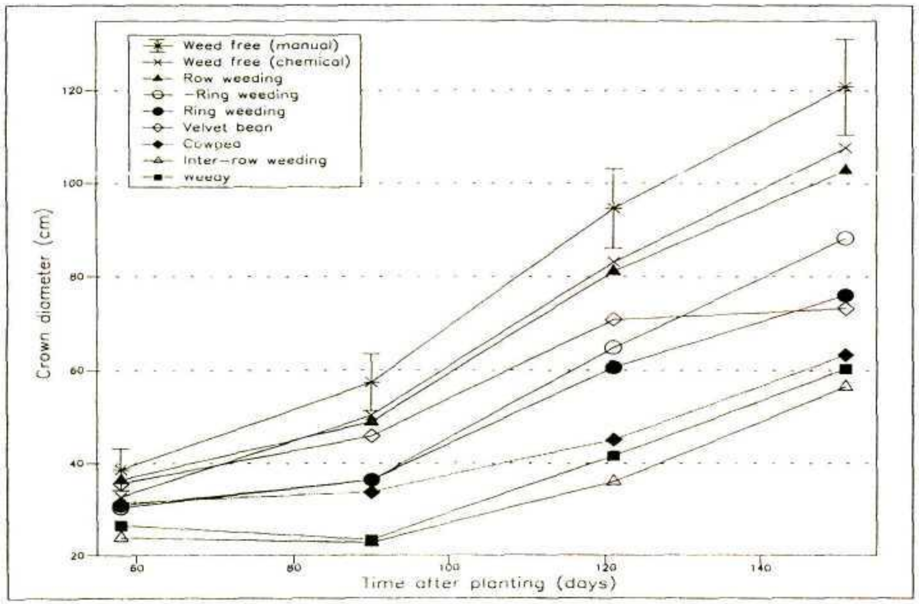


Figure 3.3: Initial development of tree crown diameter with time.

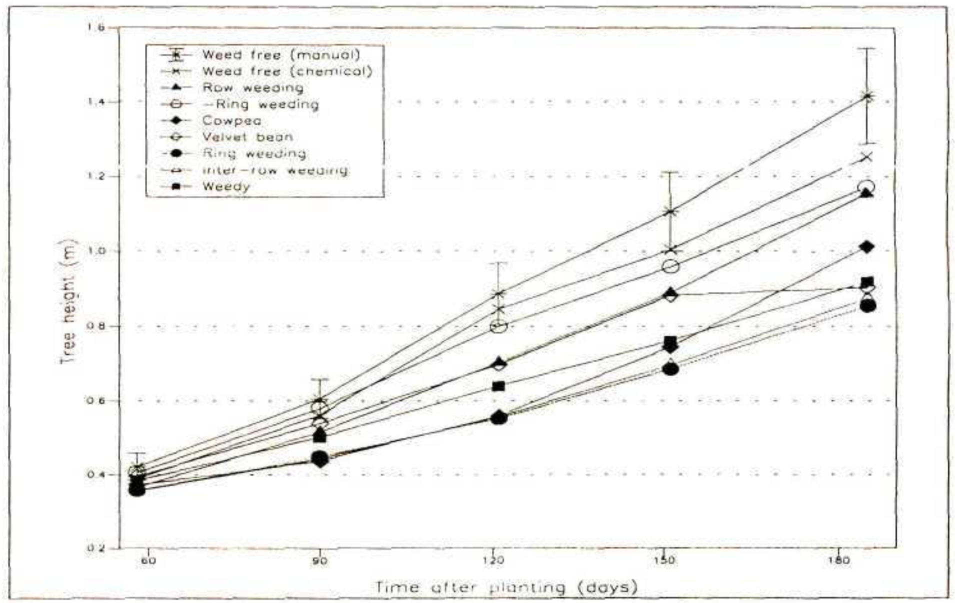


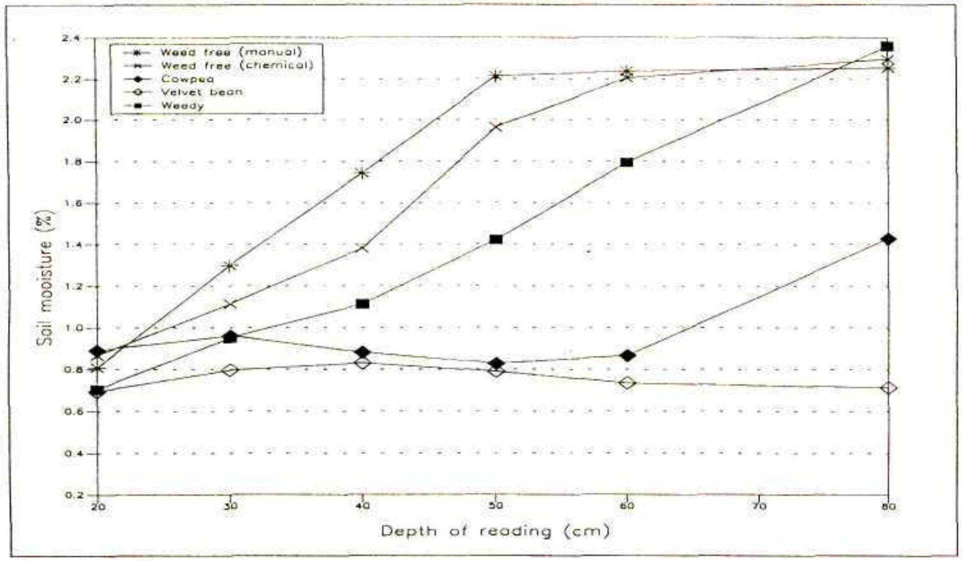
Figure 3.4 : Initial development of tree height with time.

The biomass of the weeds developed rapidly until 120 days after planting, after which the rate of development remained fairly constant (Figure 3.1). Although yellow nutsedge still remained on the site, it was succeeded by annual herbaceous broadleaved weeds and perennial grasses, of which *Panicum maximum* was the most abundant. Although taller than nutsedge, the delayed development of these weed species meant that competition would remain below-ground for resources, rather than for light, in all but the most suppressed trees. Evidence supporting competition for below-ground resources was provided by four sets of gravimetric soil moisture records that were measured at different depths with a Hydroprobe® from January 1991 to April 1991 (Figure 3.5). It is clearly visible that the plots in those treatments containing some form of vegetation cover have a lower soil water content. Similar results were reported by CHRISTIE (1994) and YEISER and BARNETT (1991). CHRISTIE (1994) found a decrease in soil moisture content with an increasing abundance of *Setaria megaphylla*. YEISER and BARNETT (1991) found that soil moisture was greatest and fascicle water potential was least negative for *Pinus echinata* trees which received complete control by herbicide compared with trees which received partial herbicide application or no weed control. Combined with this lower soil water content would be the reduced ability of the trees for nutrient uptake (GONCLAVES, BARROS, NAMBIAR and NOVAIS 1997). This would be further exacerbated, especially if some of the nutrients are taken up and retained within the weed biomass, thus not being freely available for tree growth. ELLIS, WEBB, GRALEY and ROUT (1985) reported that the removal of competing vegetation as opposed to it remaining alive on the site resulted in higher foliar concentrations of nitrogen in trees of *Eucalyptus delegatensis*. Foliar nutrient content of the different types of vegetation cover are presented in Table 3.1. Thirty days after planting, the weeds contained an approximate equivalent of 8 kg ha^{-1} of nitrogen. This level would continue to rise with increasing levels of weed biomass, although it only became available to the plants through decomposition after a weeding event or through natural mortality. As foliar nutrient samples were not taken from the trees it would be difficult to quantify the effect of this release of nutrients on tree performance.

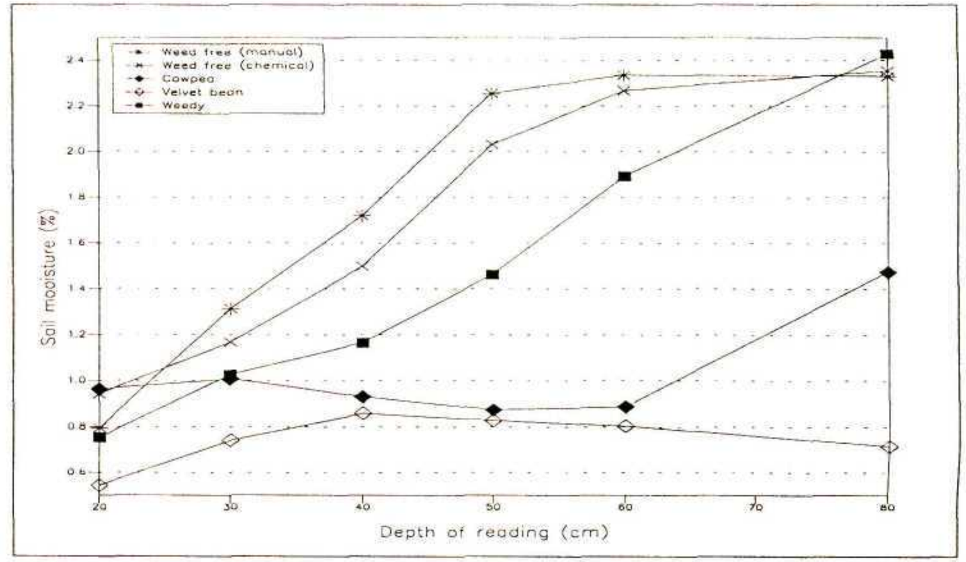
The continued development of weeds meant that competition for the site's resources would continue until the trees became dominant and thus more tolerant to interspecific competition. Increased growth rates for crown diameter from 90 days after planting in all but the velvet bean treatment indicates that trees were increasingly able to tolerate competition from weeds (Figure 3.2).

Table 3.1: Foliar nutrient contents contained in the biomass of the cover-crops and weeds.

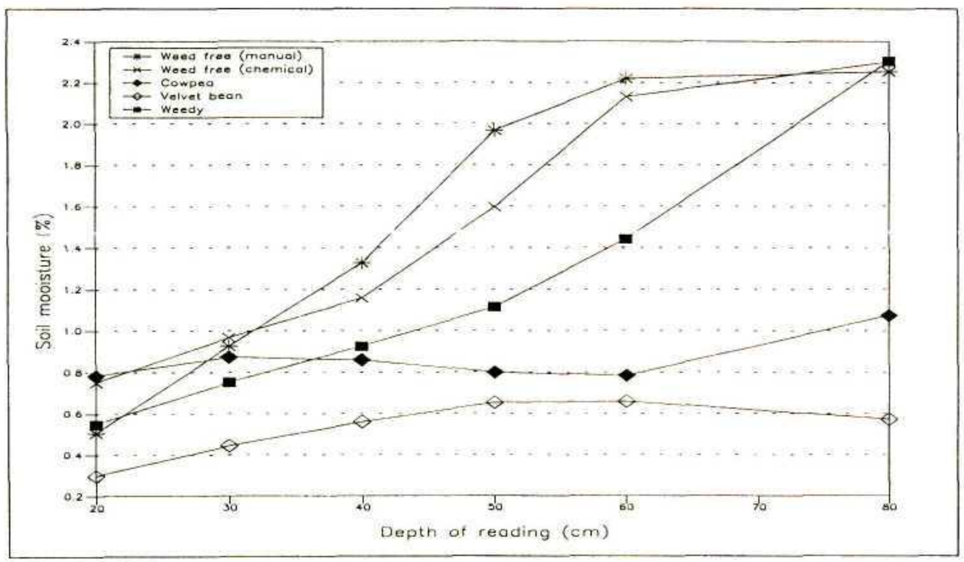
Element	Weeds (30 day biomass)	Velvet bean (120 day biomass)	Cowpea (120 day biomass)
Nitrogen (%)	1.2	3.12	3.17
Phosphorus (%)	0.46	0.93	0.72
Potassium (%)	1.17	2.66	2.05
Calcium (%)	0.42	1.83	1.49
Magnesium (%)	0.44	0.88	0.57
Sodium (%)	0.05	0.08	0.03
Iron (mg kg^{-1})	690	504	496
Zinc (mg kg^{-1})	21	80	72
Copper (mg kg^{-1})	4	7	7



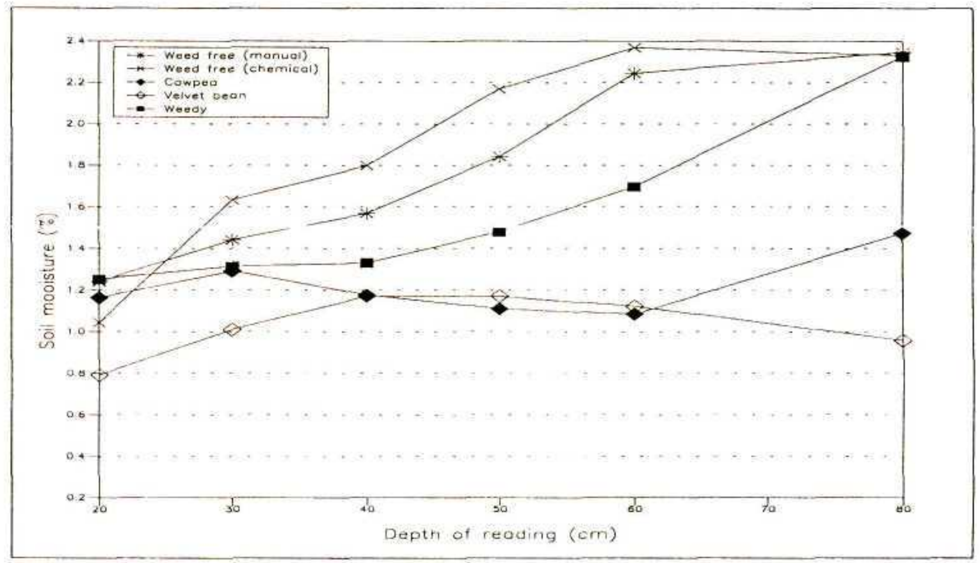
January 1991



February 1991



March 1991



April 1991

Figure 3.5: Changes in gravimetric soil moisture content with depth from four selected treatments.

3.2.2 Initial tree growth

3.2.2.1 Inter-row and complete weeding except within 0.5 m of the tree (- ring weeding)

The relative position of the weeds as reflected by their proximity to the trees, resulted in the continued divergence of the treatments over time (Figures 3.3 and 3.4).The inter-row weeding treatment was as poor in terms of performance, as the weedy control treatment for both height and crown diameter measurements. The removal of 40 % of the total vegetation between the tree rows did not result in any additional resources becoming available to the plant for improved growth due to its position relative to the tree. The development of a root system that could extend beyond the 0.9 m weed infested row was hampered by the small tree size. The growth rate of the crown diameters was negative for both the weedy and inter-row weeding treatments between the first two measurement dates (Figure 3.2). There was an improvement in the growth rate for the inter-row weeding treatment between 121 and 151 days after planting, resulting in a divergence in growth between the weedy and inter-row weeding treatments. This could possibly be associated with the development of the tree roots of the inter-row weeding treatment into the weed free zone. Although not significant, this difference was maintained through to felling.

Complete weeding except within a 0.5 m radius of the tree, resulted in the significant ($p<0.05$) initial suppression of the tree height and crown diameter growth in comparison to the manually weeded treatment. The weeds in the immediate proximity to the tree had a negative impact on growth. This is reflected in the low growth rate for crown diameter measurements between days 58 and 90 (Figure 3.2). Subsequent growth rates were much improved, indicating that the additional resources available for tree growth from the area beyond the 0.5 m radius were being utilised for growth.

3.2.2.2 Ring and row weeding

Compared to the manually weeded treatment, the 1 m ring weeding treatment resulted in the significant suppression of tree performance from the time of the first measurement. In this treatment 90 % of the weeds were retained on the site as opposed to the - ring weeding treatment where 90 % of the weeds were removed from the site. The difference in weed cover between these two treatments is reflected in the increase in the growth rates for crown diameter from 14.5 % (between 90 and 121 days after planting) to 34% (between 121 and 151 days after planting) (Figure 3.2). A 1 m ring weeding would only be expected to give some degree of benefit for tree growth up to 60 days on this site. Below, rather than above ground competition for the site's resources would have played a role in the restriction of growth in this treatment. SASSE and SANDS (1997) found in a comparison between the rooting of *Eucalyptus globulus* cuttings and seedlings, that cuttings had no tap root with the main structural components being adventitious roots formed during the propagation phase. The mean primary root length was 30 cm, eight weeks after planting, indicating a zone of influence of greater than 60 cm in diameter. If the root growth of the weeds is also taken into account, assuming a similar rate of growth and lateral spread, then the roots of the weeds and trees would be competing in the same zone within two months after planting. Due to the low soil strength properties associated with the sandy soils in this trial (Table 2.3) the growth of the roots of both the weeds and trees could be expected to be higher than average, resulting in larger zones of influence. MISRA and GIBBONS (1996) found a 71% and 31% reduction in the lengths of primary and lateral roots respectively with an increase in penetrometer resistance from 0.4 to 4.2 Mpa in 17 day old *Eucalyptus nitens* seedlings.

In a trial to determine the development of minimum row weeding requirements with time (also with eucalypts on ex-sugarcane land in Zululand), LITTLE and SCHUMANN (1996) found that the minimum row weeding requirements increased from a 1.5 m row weeding 59 days after planting to a 2.5 m row weeding 92 days after planting.

ENDO and WRIGHT (1992) compared the 22 month growth of *Eucalyptus grandis* under different levels of competing vegetation control in Columbia. Of the treatments imposed they found that the more intensive the weed control the better the performance, with the 1m row, 1m ring and low intensity weeding producing successively poorer growth. They attributed the response of these treatments to varying degrees of competition for moisture. Similar trials looking at the effect of increasing row or ring weeding areas on tree performance all indicate increase tree performance with an increase in the area that is kept free of weeds (TIARKS and HAYWOOD 1981; CONSTANTINI 1989; DOUGHERTY and LOWERY 1991; RICHARDSON, DAVENHILL, COKER, RAY, VANNER and KIMBERLEY 1995; LITTLE and SCHUMANN 1996).

The 1.2 m row weeding (60 cm weeded on either side of the tree) resulted in a 40 % removal of the weeds from this treatment. This increased removal of weeds when compared to the ring weeding treatment, benefited the development of tree height and crown diameter from the time that the first measurements were taken. As with the ring weeding treatment there was a significant reduction in tree height from 58 days after planting, and crown diameter from 91 days after planting when compared to the manually weeded treatment (Figures 3.3 and 3.4 and in Appendices 3.1 and 3.3 for additional detailed information). This suggests that although an improvement on the 50 cm ring weeding, the 1.2 row weeding would still need to be increased from between 58 and 91 days after planting in order for optimum growth to be maintained.

3.2.2.3 Cover-crops

Initial biomass accumulation for both the cowpeas and velvet beans was not as rapid as that for the naturally occurring weeds (Figure 3.1). The cowpeas and velvet beans had to develop from seeds, whereas the majority of yellow nutsedge development is from vegetative structures and this offered a far more rapid means of growth. The initial biomass development of the cowpea cover-crop was more rapid than that of the velvet bean cover-crop resulting in the suppression of tree growth from an earlier age. A reduction in the growth of the crown diameter occurred between 58 and 90 days after planting when the dry above ground biomass rose from 0.5 to 2.2 tons ha^{-1}. As the cowpeas were planted in the inter-row the reduction in initial tree performance could be attributed to competition for below-ground resources rather than for light.

The low gravimetric soil moisture content for cowpeas shown in Figure 3.5 indicates that competition is most likely to be for moisture. After maximum biomass accumulation at 120 days after planting, rapid senescence followed, resulting in no cowpea plants surviving at 180 days after planting. This resulted in an increase in the height growth rate, in comparison to the weedy control, from - 15.4 % between 90 and 121 days after planting to 34.4 % between 121 and 151 days after planting.

This could be attributed to a combination of a release from competition and the release of nutrients from decomposing plant matter. Foliar nutrient contents for cowpeas were determined 120 days after planting and are shown in Table 3.1. There would be a substantial release of nitrogen (approximately 122 kg ha^{-1}) following senescence which would have benefited tree growth on these nutrient deficient soils. A trial aimed at optimising tree and cowpea planting dates also showed the occurrence of tree suppression when planted at the same time as the cowpeas (LITTLE, SCHUMANN, ECCLES and SNELL 1994). A delay of three months in the planting of cowpeas resulted in the desirable qualities of weed suppression without adversely affecting tree growth.

Initial development of the velvet bean as a cover-crop was not as rapid as that of the cowpeas. The velvet bean biomass reached a competitive level only 121 days after planting. This coincided with a rapid increase in dry above ground biomass of the velvet beans from 0.6 to 1.4 tons ha^{-1} over the same period. Unlike the cowpeas, velvet bean biomass continued to increase over time providing sustained tree suppression late into the first season. This is visible in Figures 3.3 and 3.4 where the rate of tree growth after 120 days is negligible. The vining habit of the velvet bean also caused physical damage to the trees in the form of bent stems. Although these were removed from the trees, the effects were to be maintained through to harvest.

3.2.2.4 Chemically and manually weeded treatments

Tree height for the chemically weeded control was significantly different from the manually weeded control from 58 days after planting. This significance was maintained for tree height until 18 months after planting, after which no further significant differences between these two treatments for any of the measured tree variates were recorded. As extra care was taken to protect the trees from accidental spray drift during weeding operations it is unlikely that herbicide damage caused this suppression in tree growth. Rather the enhanced tree performance of the manually weed control could be attributed to increased nutrient mineralisation resulting from the manual weeding operations. Manual hoeing is not as effective in controlling weeds as chemical weed control, resulting in weed growth that was far more vigorous in these plots. Four manual weed control operations were required as opposed to the two for the chemically weeded control. Foliar nutrient contents for weeds that had grown over a 30 day period give an approximate indication of the nutrients that would be released into the soil in the manually weed plots if weeded on a monthly basis (Table 3.1). Although not as high in nutrient content as the cover-crops, the release of nutrients after manual weeding operations, especially on highly leached soils with a low organic carbon content, may have resulted in improved conditions for tree growth. SCHÖNAU (1983) found that the application of fertilizers high in nitrogen resulted in the beneficial growth of eucalypts on the sandy soils in South Africa highlighting the importance of this element on these highly leached soils. WOODS, NAMBIAR and SMETHURST (1992) demonstrated that the presence of weeds significantly enhanced the uptake of nitrogen from the site by plant biomass, thereby improving nitrogen retention on the site. By timing the weed control events such that tree suppression did not occur, these nutrients would be released into the soil. The use of manual hoeing would have also incorporated some of the weeds into the soil, increasing the rate of nutrient mineralization.

3.3 Conclusions

The different treatments applied during establishment resulted in the differential growth of the trees. This occurred from as early as 60 days after planting. The degree of competition could be directly related to the type of vegetation (cover-crops or naturally occurring weeds) and its proximity to the tree. The predominant weed on this site, yellow nutsedge, was able to colonise the site rapidly, causing severe and early competition. There were strong indications that this initial competition was mainly for moisture and possibly also for nutrients, rather than competition for light. Initially trees in those treatments that had weeds within their immediate vicinity were most affected (weedy control, inter-row weeding and - ring weeding). With time, tree performance was more closely related to an increase in the percentage of the area kept free of weeds. At 180 days after planting the ranking of the top five treatments in relation to the area kept free of weeds was: manually weeded treatment (100 % of area free of weeds) > chemically weeded treatment (100 % of area free of weeds) > - ring weeding (90 % of area free of weeds) > row weeding (40 % of area free of weeds) > ring weeding (10 % of area free of weeds).

The planting of cover-crops, although beneficial in terms of weed suppression, also caused significant tree suppression. This occurred despite the fact that their initial biomass accumulation was slower than that of the natural weed population. Of the two cover-crops, the use of a velvet bean cover-crop was not considered suitable due to its vigorous vining habit which affected the growth form of the trees. Subsequent work suggests that if the beneficial qualities of cowpeas are to be realised (that of weed suppression, erosion control and nitrogen fixation), a delay in their planting by three months after establishment of the trees should alleviate any negative impacts on tree growth.

CHAPTER 4

THE INFLUENCE OF WEED CONTROL ON POST-ESTABLISHMENT TREE GROWTH

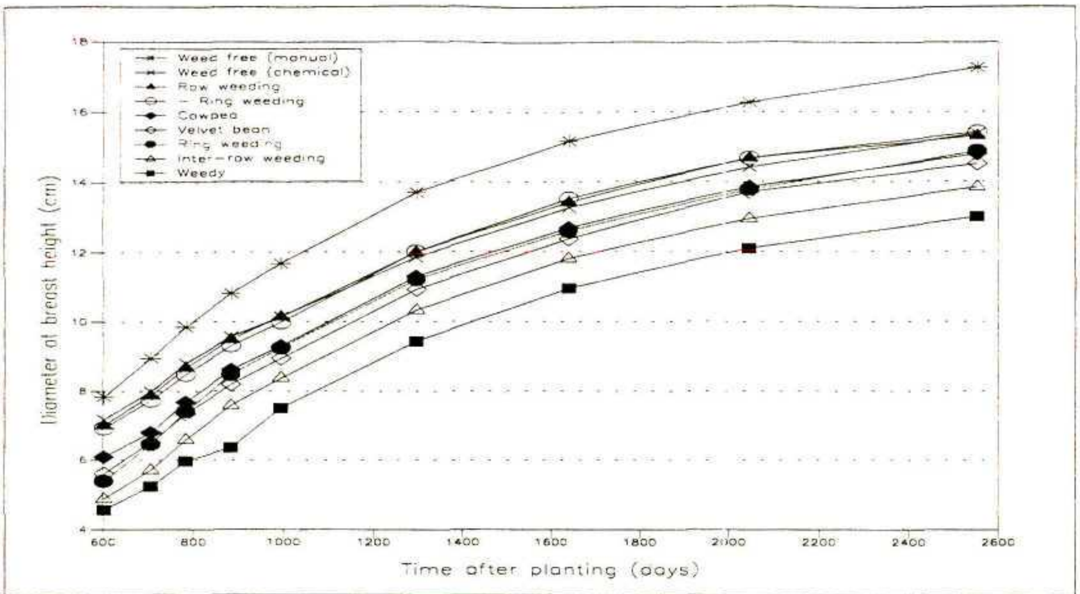
4.1 Introduction and objectives

Although the impact of vegetation management on early tree growth is fairly well documented, its importance relative to longer term tree growth is not well understood. The objective of this section was therefore to determine whether the initial treatment differences would be maintained through to felling, and whether they would still be significant. To answer these questions, various tree measurements were taken in order to monitor the development of the treatments over time. In addition to this, within treatment variability, as well as various competition indices, were tested to explain the presence or absence of inter- and intra- specific competition (as affected by weeding treatment) on individual tree growth.

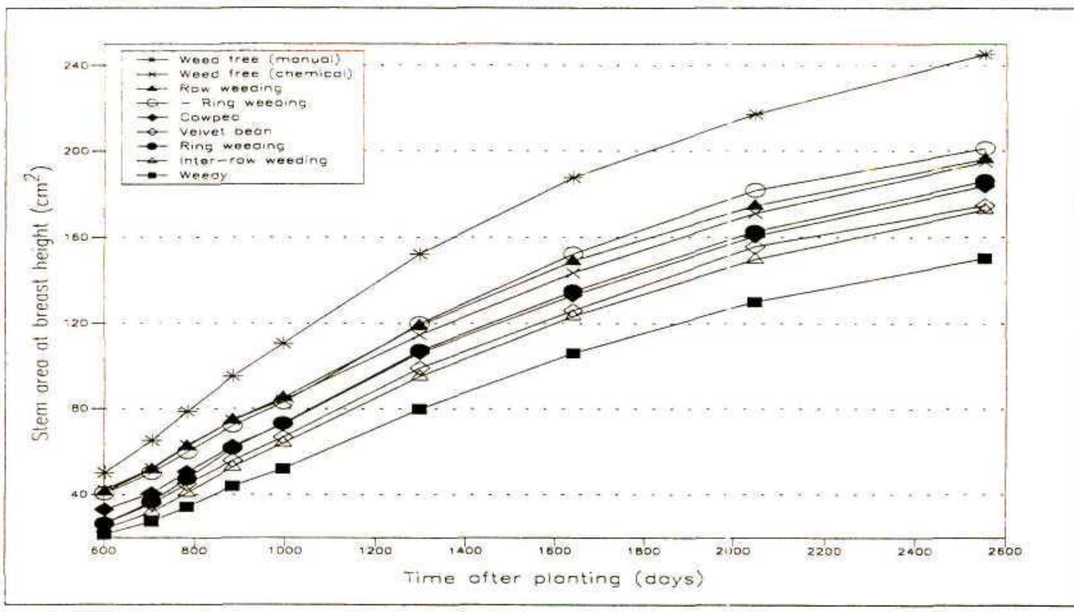
4.2 Results and discussion

4.2.1 The use of diameter at breast height, stem area and basal area as indicators of tree performance

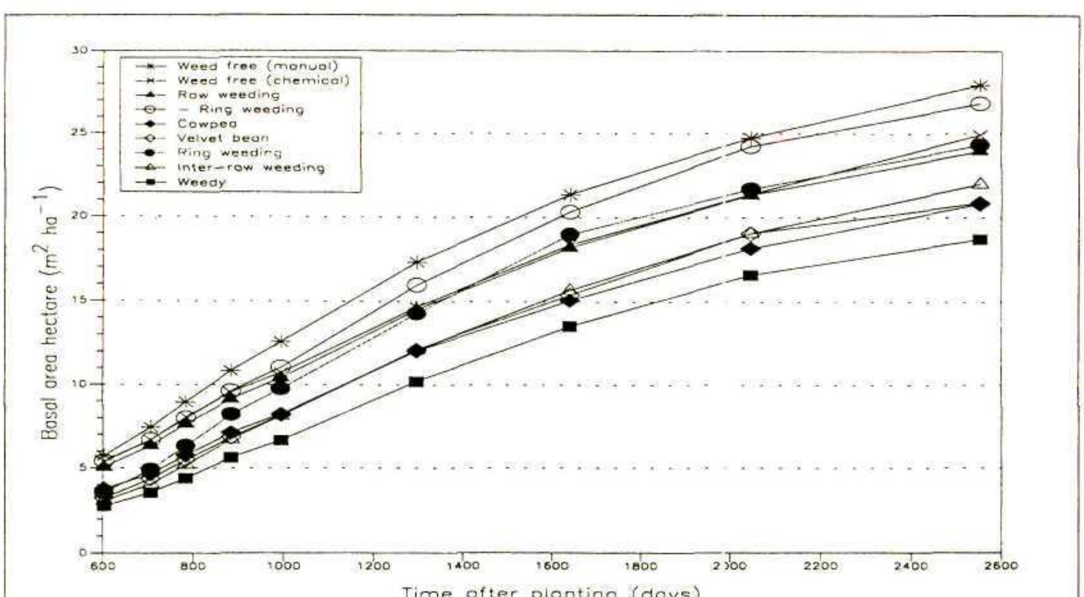
From 603 days after planting, measurements of diameter at breast height as opposed to height measurements were carried out until the trial was felled. Whilst the measurement of diameter at breast height on its own is not the most ideal measurement to be taken, it does provide a basis from which other measures can be derived (VAN LAAR and AKÇA 1997), namely stem area and basal area per hectare. Stem area is a two dimensional derivation of the diameter at breast height measurement and is reported in cm^2 or m^2. It provides a better estimate of the differences between diameter classes, and is more closely aligned to volume measurements (the ultimate measure of tree performance), than is the measure of diameter at breast height. For example, there was a 27.8 percentage difference in diameter at breast height between the weedy (10.95 cm) and manually weeded (15.17 cm) treatments at 1641 days after planting (Appendix 4.1). This difference increases to 43.5 percent when using stem area calculations for the same two treatments (Appendix 4.3). This difference between diameter and stem area measurements is visible in Figure 4.1, which compares the weedy control and the manually weeded treatments. The growth curves continue to diverge for stem area as opposed to diameter at breast height. The growth rates for diameter measurements remain fairly constant from 1641 days onwards after planting, with no significant differences occurring between any of the treatments even though there are significant differences between the diameter at breast height measurements (Appendix 4.2). The differences between the growth rates for stem area remain large, although they do tend to diminish towards the end of the rotation (Appendix 4.4).



Diameter at breast height



Stem area



Basal area

Figure 4.1: Development of diameter, stem area and basal area with time.

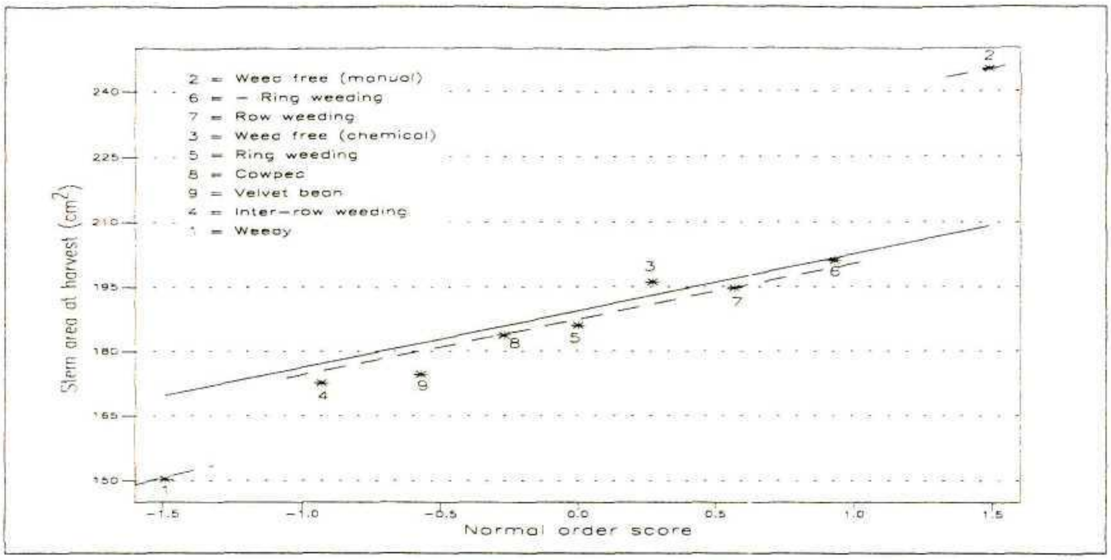


Figure 4.2: Stem area calculations when the trial was felled at 7 years. The solid line indicates the standard error of the grand mean, and the dashed lines indicate groups of means which are not significantly different.

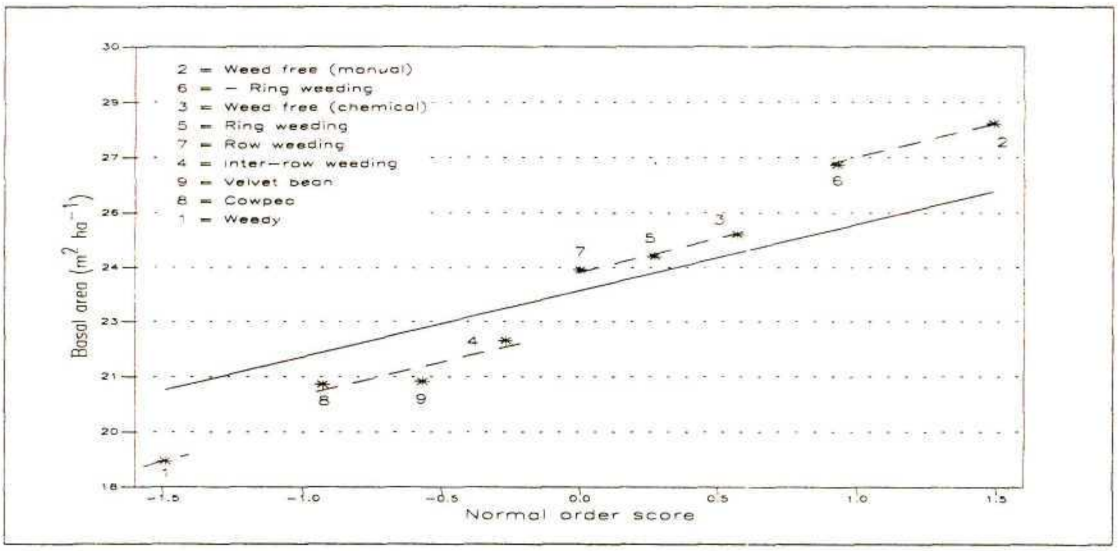


Figure 4.3: Basal area calculations when the trial was felled at 7 years. The solid line indicates the standard error of the grand mean, and the dashed lines indicate groups of means which are not significantly different.

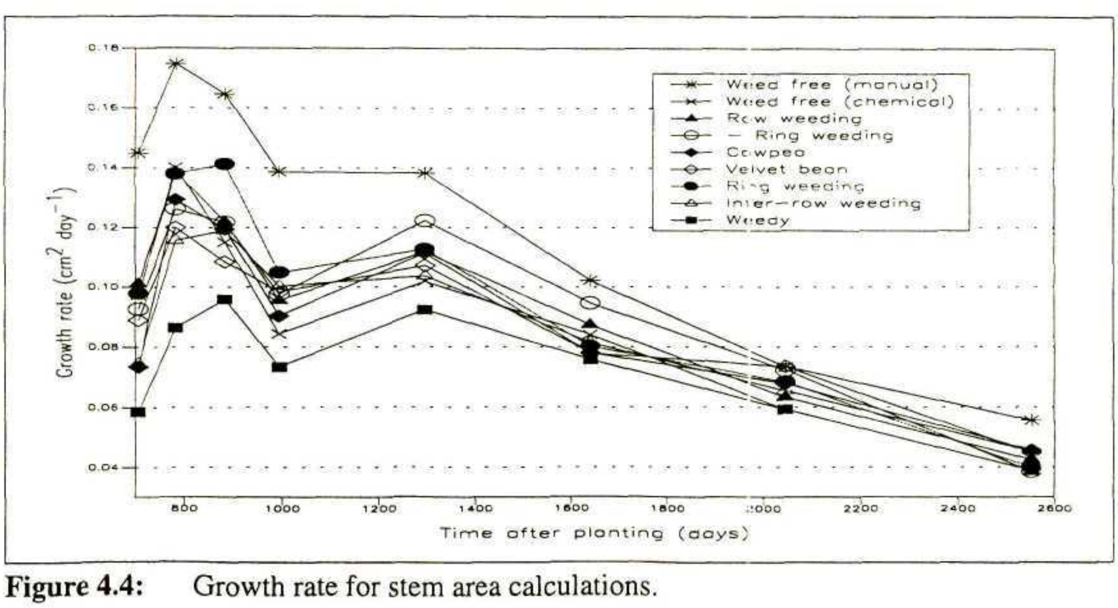


Figure 4.4: Growth rate for stem area calculations.

Basal area per hectare measurements take into account stem area as well as the stocking on a treatment plot basis, and provide an absolute rather than an estimated value, especially in the cases where there are missing trees. Although the treatments did not cause any significant mortality, there were differences between the different treatments (Appendix 4.5). These differences account for the change in the ranking and grouping of the different treatments. Normal order plots of the stem and basal area at felling were used to show the ranking and groupings of treatment means. The use of normal order scores as determined with the use of the standard error of the grand mean is described by PERRY (1986) and COUSENS (1988). This method is used as an alternative to multiple comparison procedures to search for patterns among groups of means. The normal order scores are presented in Appendix 4.6 and graphically displayed in Figures 4.2 and 4.3. In these figures the slope (solid line) equals the standard error of the grand mean and is the line on which the points would lie if there were no differences between the treatments. The full stocking (1333 stems ha^{-1}) of the -ring weeding treatment compared to the lower stocking (1139 stems ha^{-1}) for the manually weeded treatment, meant a reduction in the percentage difference between the two from 18 % for stem area to 4 % when using basal area. The poorer stocking of the cowpea treatment (1139 stems ha^{-1}) also accounted for a drop from 4^{th} to 2^{nd} worst.

4.2.2 Post-establishment tree performance

The development of tree diameter at breast height, stem area and basal area per hectare from 603 days after planting until felled, is shown in Figure 4.1. Treatment means, *F.* probabilities and *lsd's* are shown in Appendices 4.1 to 4.5. Significant differences between the treatment means, remained for the duration of the trial, with the weedy and weed free (manual) treatments continuing to produce the worst and best growth respectively. Tree performance during the latter stages of the trial were more affected by intraspecific competition (competition between the trees) for the resources of the site. As the resources available for tree growth on any given site will be finite, it is these resources that limit tree growth as the stand develops. By comparing the slopes for tree development over time (Figure 4.1), it is clear that the rate of increase for all the treatments is decreasing with time. The maximum growth rate for all the treatments except the weedy control, - ring weeding and inter-row weeding occurred between 707 and 784 days after planting (Figure 4.4). The maximum growth rate for the -ring weeding and inter-row weeding occurred between 784 and 884 days after planting, and between 884 and 995 days after planting for the weedy control. There was a positive seasonal effect on the growth rate between 995 and 1297 days after planting for all the treatments except the weedy and manually weeded control. This increase was not as great as previously experienced, due to the impact of the now larger trees competing more heavily for the site's resources. The manually weeded control, already having captured most of the site's resources, was unable to utilise the beneficial growing conditions for further growth. Although the growth rate of the larger trees within the weedy treatment did increase, the rate of growth for the majority of the trees within this treatment (which were smaller in diameter) meant that as a treatment, the relative growth was not positive.

4.2.3 Treatment variation and the determination of inter- and intra- specific competition

The cuttings used within this trial were the hybrid combination of *Eucalyptus grandis* and *E. camaldulensis.* The use of the various hybrid combinations on the more marginal sites in Zululand allow for the establishment of disease resistant plantations, together with potential production of timber volumes in excess of either of the original species when planted on the same site (DENISON and KIETZKA 1993b). Through the vegetative propagation of the desirable hybrid combinations on a commercial scale, much of the genetic variability that may be associated with the use of seedlings can also be negated (SAKAI, MUKAIDE and TOMITA 1968; ELDRIDGE, DAVIDSON, HARWOOD and VAN WYK 1993; LAMBETH, ENDO and WRIGHT 1994). The potential growth and performance of cloned hybrids in comparison to genetically variable seedlings is now only affected by the environment in which they are grown (DENISON and KIETZKA 1993b). This effect of the environment, as determined by four different sites in Zululand, on the growth of a *Eucalyptus grandis* clone (TAG 5) has been demonstrated by RETIEF, MALE, MALAN, DYER, CONRADIE, TURNER, HAVENGA and GAMA (1997). Site quality was found to have had a significant effect on the growth and pulp yield with a 62 % difference in volume per hectare between the best and poorest site.

Another manner by which the environment in which the cuttings are grown can be altered is through the use of different silvicultural practices. Examples would include fertilization, soil and site preparation or the manipulation of the vegetation as was practised in this trial. Possibly the greatest influence that these silvicultural practices would have, would be to increase tree growth and thus final yield. The use of cuttings together with optimum silvicultural practices should also increase the uniformity of the trees within a stand. Although the treatment means provide an insight as to the development of overall tree performance with time, they do not give an understanding of the variability of the trees relative to these means. More variable tree growth is likely to result where some vegetation is retained on the site. This would be due to the differential development and growth exhibited by different weeds or weed populations. This variability in tree performance is important, especially where the vegetation on a site is to be manipulated. Not only would one expect increased variability due to early interspecific competition, but the residual effect of this differential suppression would be expected to be manifested through intraspecific competition once the trees are more mature.

The use of genetically similar clones, as used in this trial, together with the selection of a site exhibiting no significant differences in terms of the soil properties tested (Appendices 2.1 and 2.2), provided an ideal opportunity to assess the variability of the different treatments in terms of inter- and intra- specific competition.

To quantify the effect of this treatment-related variability, various methods could be used. These include the use of the distribution of the individuals within each treatment to give an indication of skewness (TURNER and RABINOWITZ 1983), the use of measures of inequality, such as the coefficient of variation (WEINER 1985 and 1986; KNOX, PEET and CHRISTENSEN 1989; BOUVET 1997), or the use of relative growth rates (TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA 1994). All three of these methods were used to determine the presence or absence of inter- and or intra- specific competition, although only the initial two methods are discussed in this section (the use of the growth rate for different size classes to quantify intraspecific competition is dealt with in Section 4.2.4.2). With this in mind the following were calculated:

- The coefficient of variation on a treatment plot basis for each measurement date. The means are presented in Figure 4.5 for height (up to 20 months of age), and in Figure 4.6 for diameter at breast height (from 20 months until the trial was felled).
- To gain a more detailed understanding of the development of inter- and intra-specific competition on tree performance over time, only two of the nine treatments were selected for further presentation, the manually weeded treatment and the weedy control. For these two treatments, box and whisker diagrams were plotted against the coefficient of variation at each measurement date (Figures 4.7 and 4.8). The box and whisker diagrams provide an indication of the treatment mean, the upper and lower 95 % confidence limits and the extremes, thus giving an indication of the development of variation relative to tree size.
- Frequency diagrams were constructed and the degree of skewness (Table 4.1) calculated to illustrate the effect of this inter- and intra- specific competition on the distribution shape of the individual tree variates of height and diameter at breast height. Although only the manually weeded treatment and the weedy control are shown in Figure 4.10, the diameter at breast height (at age 20 months and 7 years) and height (at age 2 months and 7 years) frequency diagrams for all treatments are shown in Appendices 4.7 to 4.10.

4.2.3.1 Changes in treatment related tree variability with time

At the time that the first height measurement was taken (58 days after planting), there was already a treatment difference in terms of the coefficient of variation (Figure 4.5). From this date onwards there was a general increase, followed by a decrease in variation for all the treatments, although the magnitude and timing of this increase was treatment related. The treatments showed either relatively higher (weedy or inter-row weeding), or lower (manually or chemically weeded treatments) variability throughout, whereas some were initially high but then decreased with time (velvet bean, row weeding, -ring weeding and the cowpea treatment). As discussed in Chapter Three, the presence or absence of vegetation, the type of vegetation (cover-crops or weeds), the proximity of this vegetation to the tree (ring, row, -ring or inter-row weeding) and the rate of growth of this competing vegetation affected the growth of the trees. This in turn affected the onset, duration and degree of interspecific competition, which would in turn affect the variability (Figure 4.5).

A certain percentage of the variability detected during the initial stages of tree development, regardless of the treatment, could possibly be attributed to factors other than that of interspecific competition. This becomes apparent when the variability in relation to tree growth is assessed in the manually weeded control as shown in Figure 4.7. Although there was an initial increase in cutting variability for the manually weeded treatment (from 18 % at 58 days to 23 % at 151 days) this was not as great as in the weedy control, and did tend to stabilise, before decreasing from 9 months

(276 days) after planting. As this increase in variation could not be attributed to either interspecific competition or genetic variability (no competing vegetation, together with the use of genetically similar cuttings), other possible explanations were sought. This variability could have been the result of one or a combination of the following factors:

- Variability may have been introduced at the nursery due to factors such as cutting size, time that the cuttings were taken, the handling of the cuttings, nutrition, medium used, as well differences in the rooting environment (HOAD and LEAKEY 1992; THOMPSON 1992; WIGNALL, BROWN and PURSE 1992; ELDRIDGE, DAVIDSON, HARWOOD and VAN WYK, 1993). All of these have been shown to have an effect on the rooting potential of different cuttings, resulting in some exhibiting greater vigour than others;
- Variability may have resulted from differences when the cuttings were planted in the field, as not all would have been planted at the same depth or by the same labourer. MORRIS (1994) was able to demonstrate that different labourers planting *Pinus patula* at Usutu Pulp Company in Swaziland resulted in different rates of growth and survival. TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA (1994) attributed a similar increase in variability in *Eucalyptus globulus* seedlings, shortly after planting, to the response of different seedlings to transplanting;
- The increase in variability may also be attributed to the small differences that occur in the topsoil into which the cuttings were planted as well as to micro-climate differences occurring due to slight topographical changes.

From 9 months (276 days) onwards there was a decline in the coefficient of variation for height measurements until 17 months (512 days), although canopy closure had already occurred in the manually weeded treatment by this stage. In contrast to the manually weeded treatment, the coefficient of variation for the weedy control was already higher at the first measurement date (27 %), rising to 30 % and only showing signs of decreasing from 17 months (512 days) after planting (Figure 4.7). The effect of interspecific competition on the trees would have had an additive effect over and above any of the "natural variability" that was exhibited in the manually weeded treatment.

By comparing the box and whisker diagrams for these two treatments on different measurement dates, there is an increase in the mean height, 95 % confidence limits and in the extremes (Figure 4.7). The 95 % confidence limits and extremes for the weedy control were greater than that for the manually weeded treatment for any one measurement date, this, despite the fact that the weedy control had smaller trees. The extremes, with a bias towards the smaller trees, as shown by the box and whisker diagrams, also indicated that the range of trees in terms of height distribution was skew.

After canopy closure, interspecific competition would be negligible due to either suppressed weed growth or the absence of any vegetation. Figure 4.6 provides an indication of the change in the coefficient of variation for diameter at breast height measurements during the latter stages of tree growth. For all treatments in general, there was an initial decrease in the coefficient of variation followed by an increase. The release of trees from competition in those treatments that initially contained some form of vegetation resulted in a more rapid decline in variability. This decrease in variability in terms of height and diameter at breast height measurements, would possibly indicate that the smaller trees were now able to grow at their optimum, with the growth of the larger trees slowing down.

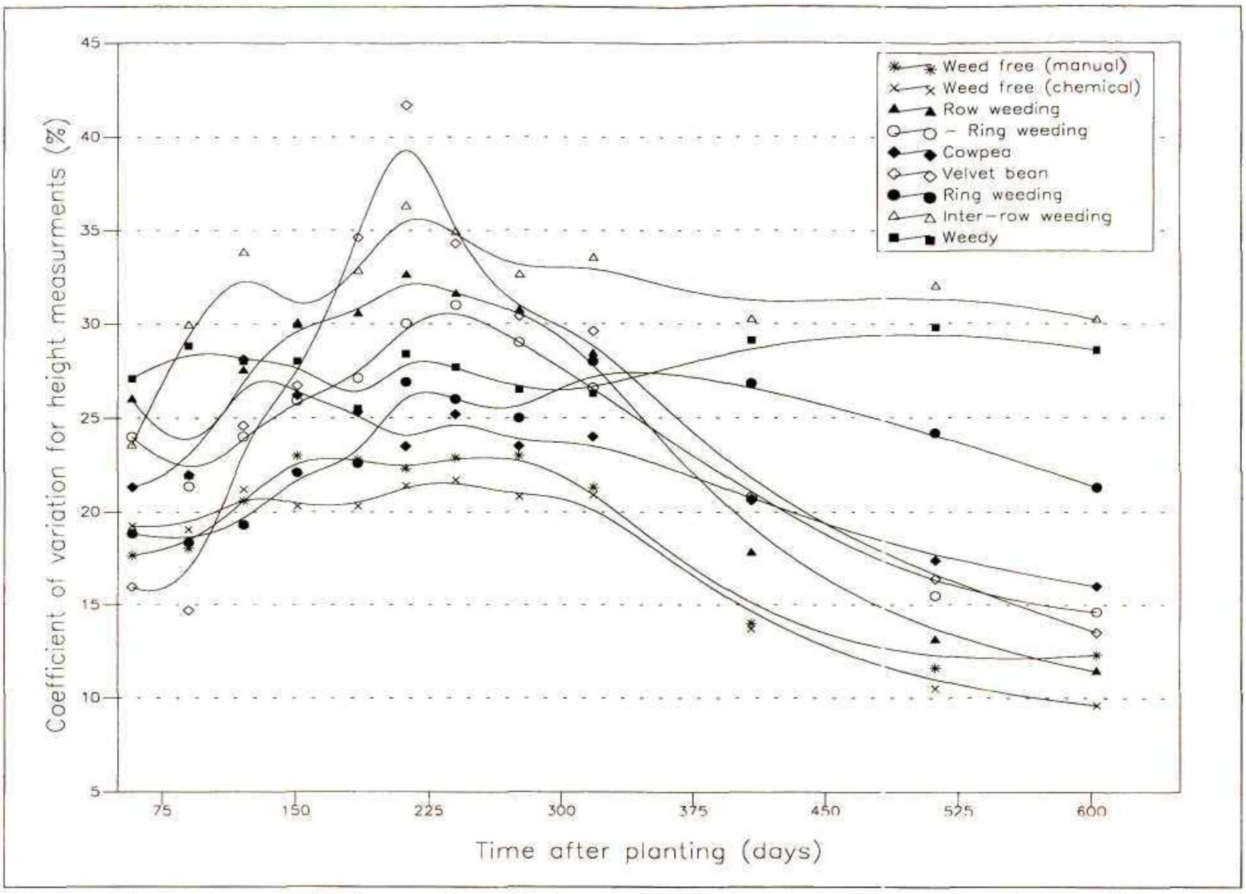


Figure 4.5: Changes in the coefficient of variation for height measurements for the different treatments with time.

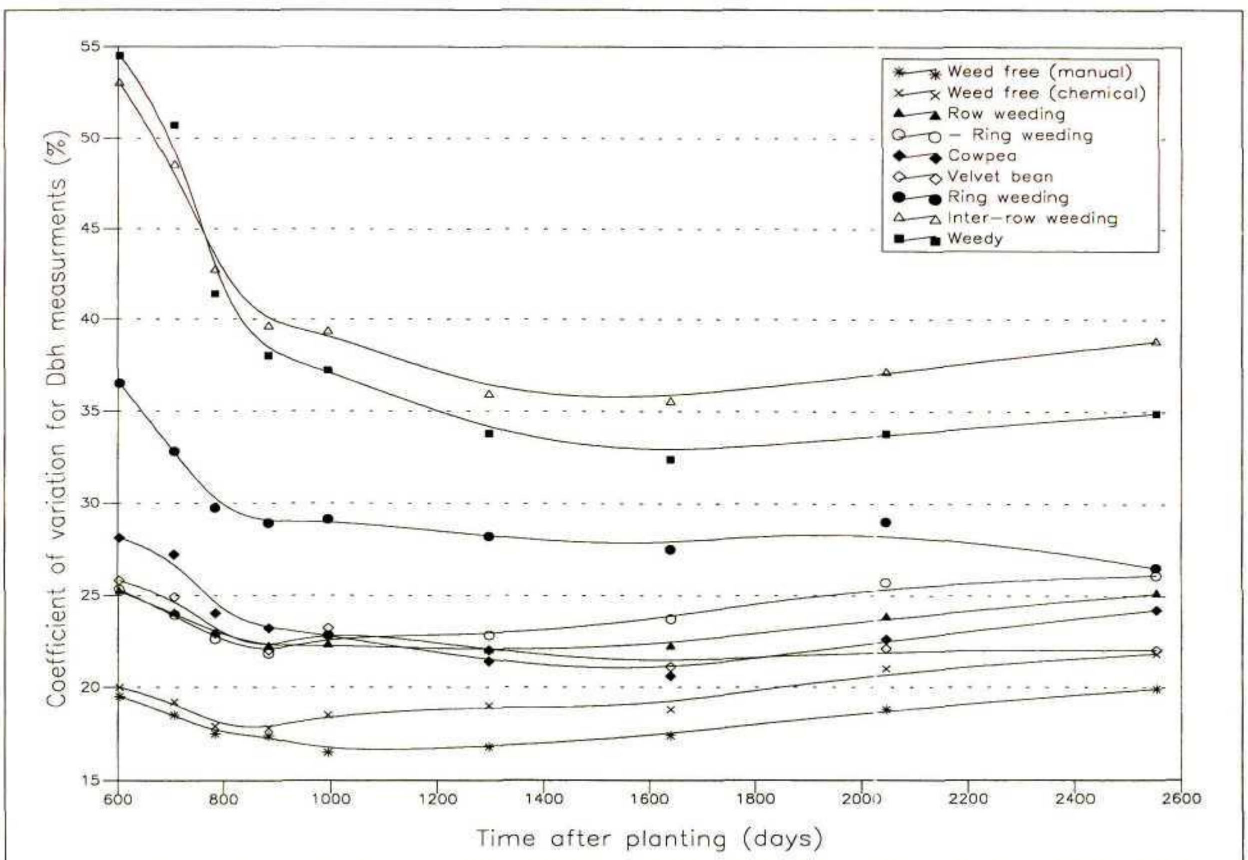


Figure 4.6: Changes in the coefficient of variation for diameter at breast height measurements for the different treatments with time.

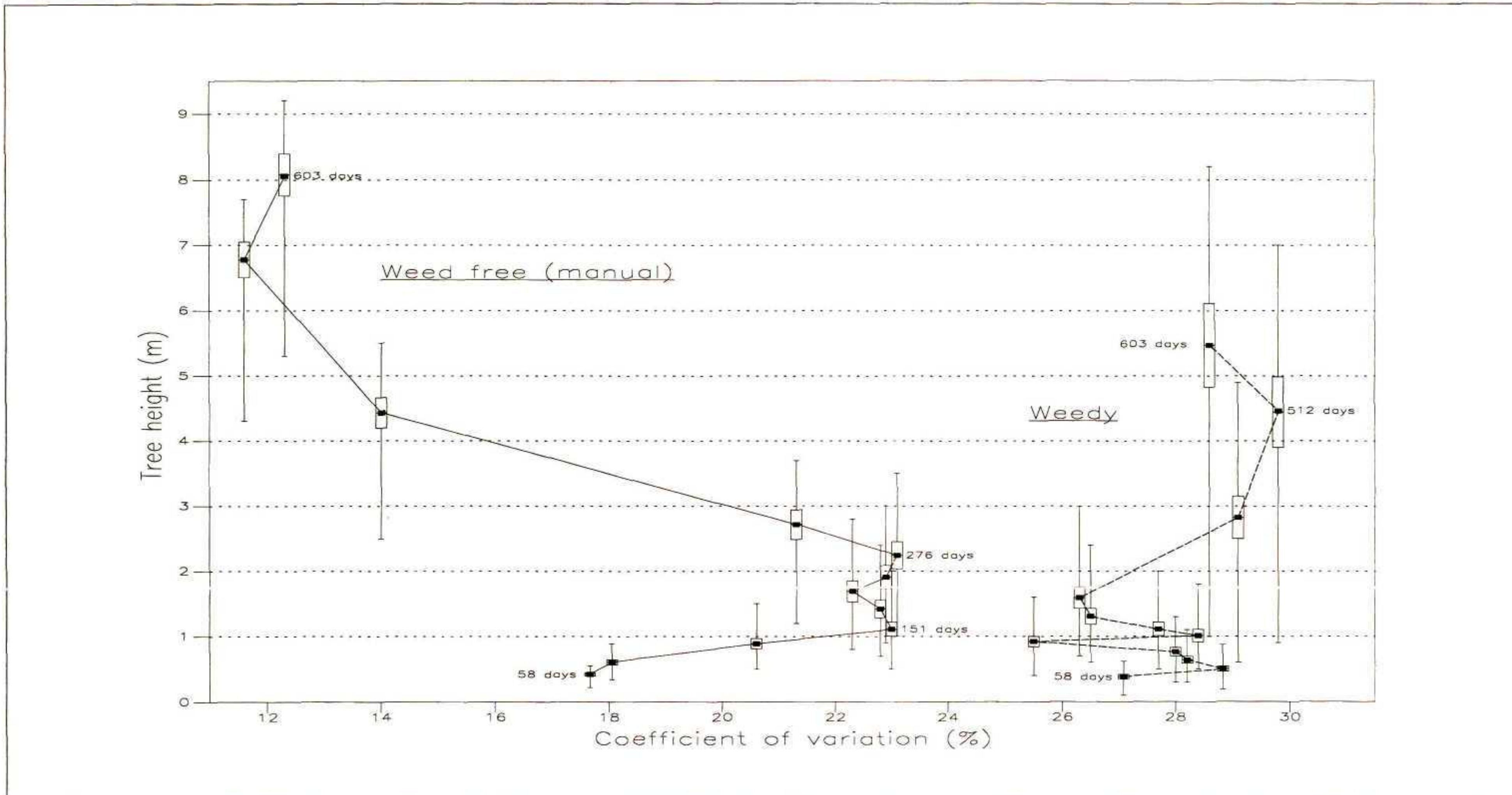


Figure 4.7: Changes in the coefficient of variation relative to height for the weedy control and manually weeded treatment. Box and whisker diagrams for each treatment date give an indication of the treatment mean, the upper and lower 95 % confidence limits and the extremes.

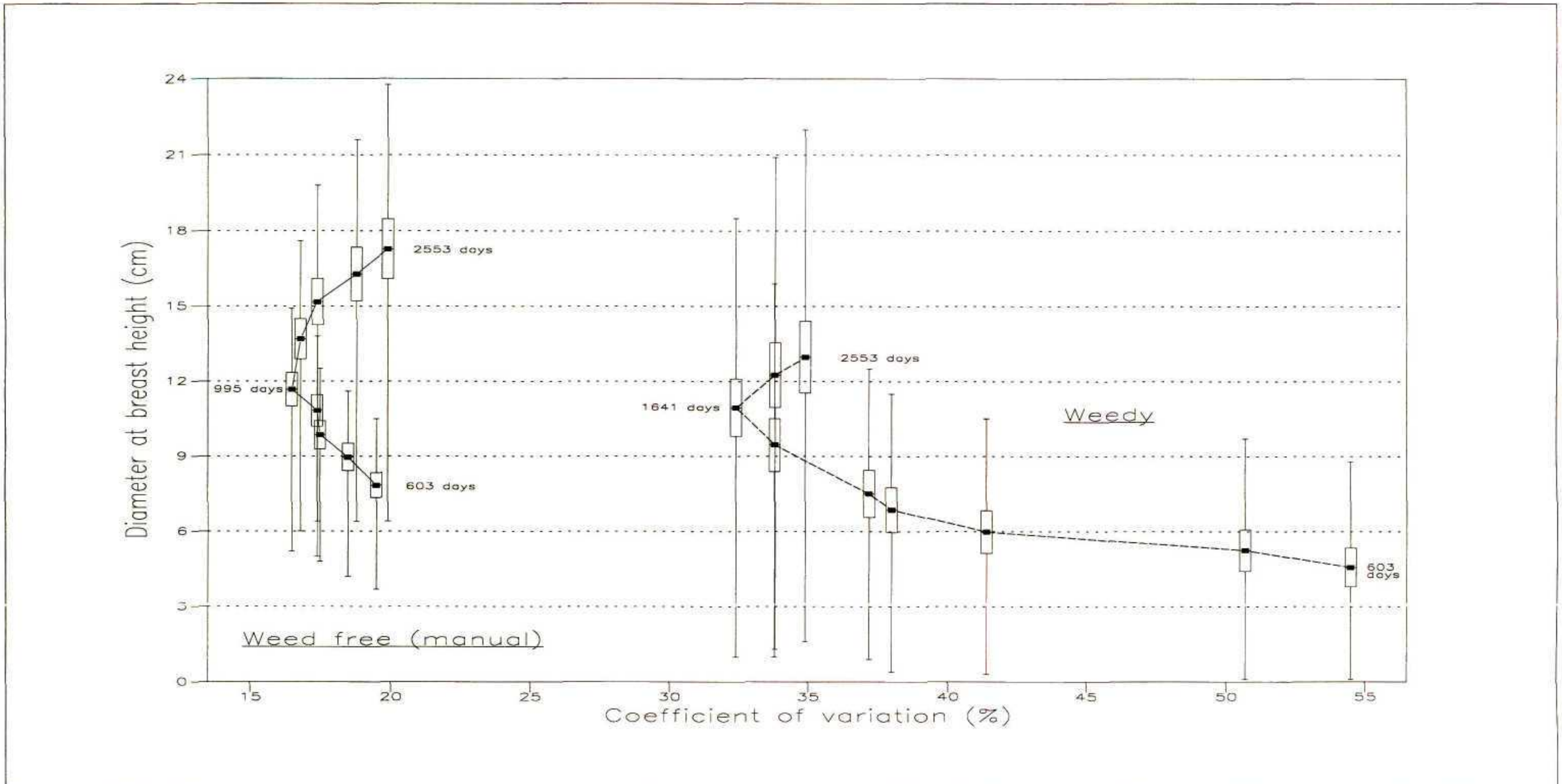


Figure 4.8: Changes in the coefficient of variation relative to diameter at breast height for the weedy control and manually weeded treatment. Box and whisker diagrams for each treatment date give an indication of the treatment mean, the upper and lower 95 % confidence limits and the extremes.

TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA (1994) and BOUVET (1997) in two separate studies using eucalypts found a similar decline in the coefficient of variation after planting. BOUVET (1997) related this decline in the coefficient of variation for various *Eucalyptus* clones to their growth stage. He explained that after a stage of free growth, the most vigorous cuttings came into competition and their growth is slowed. Less vigorous or initially suppressed cuttings then catch up coming more progressively into competition. The result is a reduction in differences among individual clones and thus a smaller coefficient of variation. Another possible explanation could be related to the physiological age of the individual trees, with a natural decrease in active growth on attaining a certain size. TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA (1994) attributed a similar decrease in variability from 0.8 years to 1.8 years in *Eucalyptus globulus* seedlings, to the recovery of different seedlings from transplanting stress. If competition was not present or if it is in its early stages, small trees would have greater growth efficiency than larger ones which would generate greater maintenance costs. If this was indeed the case, then the difference between the rates of growth for the larger and smaller trees should decrease just prior to or at the time that the coefficient of variation decreased.

To assess this, the growth rates for height were calculated for both the manually weeded treatment and the weedy control. The means for the larger 50 % of the trees and the smaller 50 % of the trees were determined, with the differences between the two plotted in Figure 4.9. An increase in the slope of the line would indicate divergence in the growth rate between the top half and bottom half of the trees in terms of performance. In a similar manner a horizontal line would indicate no divergence, and a decrease in the slope, convergence. For the manually weeded treatment, this decrease in the difference between the "better and poorer performers" was determined to occur between 240 and 276 days, and between 512 and 603 days for the weedy control. These dates do seem to be related to the onset of a decrease in the coefficient of variation, indicating that the differences in rates of growth between the "better and poorer performers" may be the cause of this response.

The onset of intraspecific competition was detected by an increase in the coefficient of variation for the diameter at breast height measurements (Figure 4.6). This onset of intraspecific competition between the trees in any one treatment plot would be related to the time after planting that resources available for growth would become limiting. The differential growth rates caused by interspecific competition on some of the treatments during the establishment phase, delayed the growth of trees, and thus the onset of this intraspecific competition. For the manually weeded treatment this occurred at 2 years and 9 months (995 days), and at 4 years and 6 months (1641 days) for the weedy control (Figure 4.8). The mean diameter at breast height was similar for these two treatments on those two dates (11.67 cm for the manually weeded treatment and 10.95 cm for the weedy control). Assuming there would be a delay in tree growth response between the onset of competition and the manifestation of this in any measurements, this onset of intraspecific competition should be related to a decline in the growth rate for the different treatments. This decline in the rate of growth was detected between 787 and 884 days for the manually weeded treatment and between 995 and 1297 days for the weedy control (Figure 4.4).

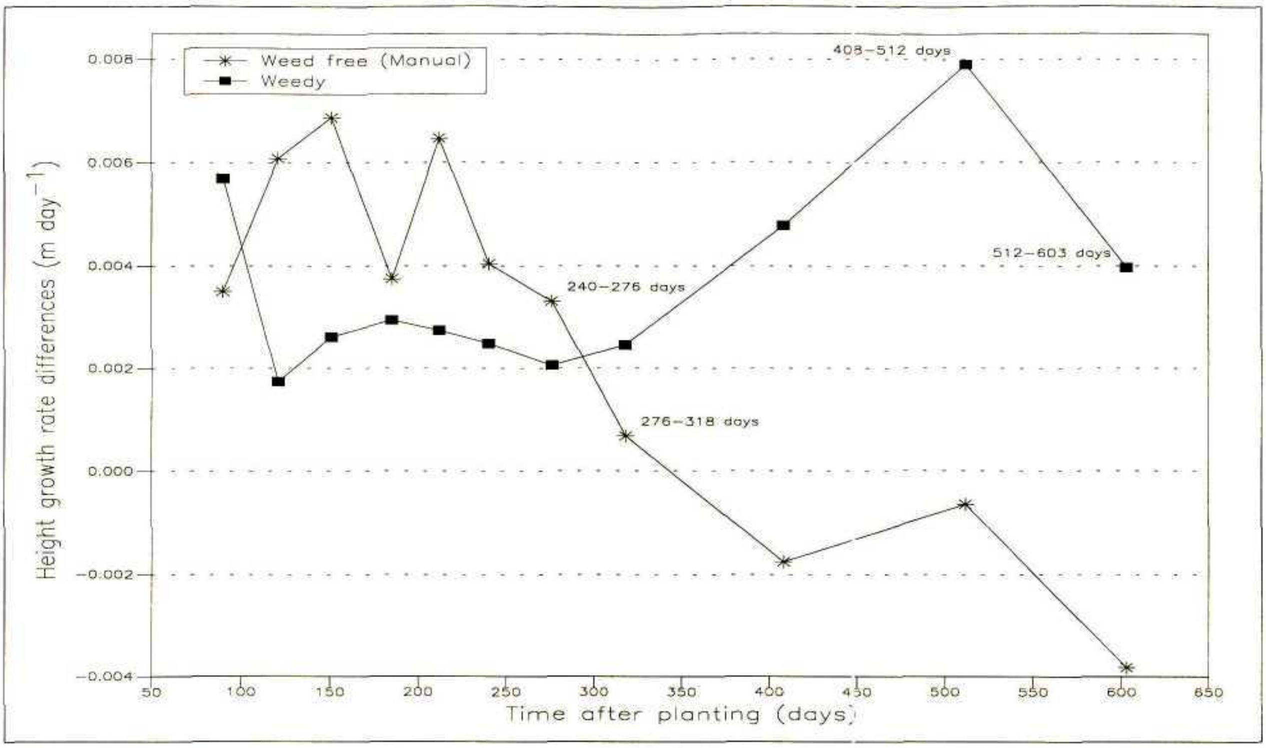


Figure 4.9: The difference between the rates of height growth for the weedy control and the manually weeded treatment. The line for each treatment represents the difference between top and lower 50 % of the trees in terms of performance.

Table 4.1: The measure of skewness of the distribution for the variates of height and diameter at breast height.

Tree height			Diameter at breast height		
Time after planting (days)	Weedy control	Weed free (manual)	Time after planting (days)	Weedy control	Weed free (manual)
58	-0.2125	-0.6413	603	-0.3545	-1.0872
90	0.4001	0.1272	707	-0.4463	-1.1482
121	0.4192	0.7633	784	-0.3832	-1.0559
151	0.3252	0.5655	884	-0.4377	-1.0451
185	0.3378	0.3988	995	-0.443	-1.1733
212	0.3557	0.2828	1297	-0.5779	-1.1452
240	0.2885	0.0558	1641	-0.6751	-1.1685
276	0.1864	-0.1844	2046	-0.6566	-1.1217
318	0.2381	-0.6665	2553	-0.7572	-1.105
408	-0.5168	-1.0493			
512	-0.5893	-1.3084			
603	-0.5579	-1.5215			
2553	-1.7981	-2.8984			

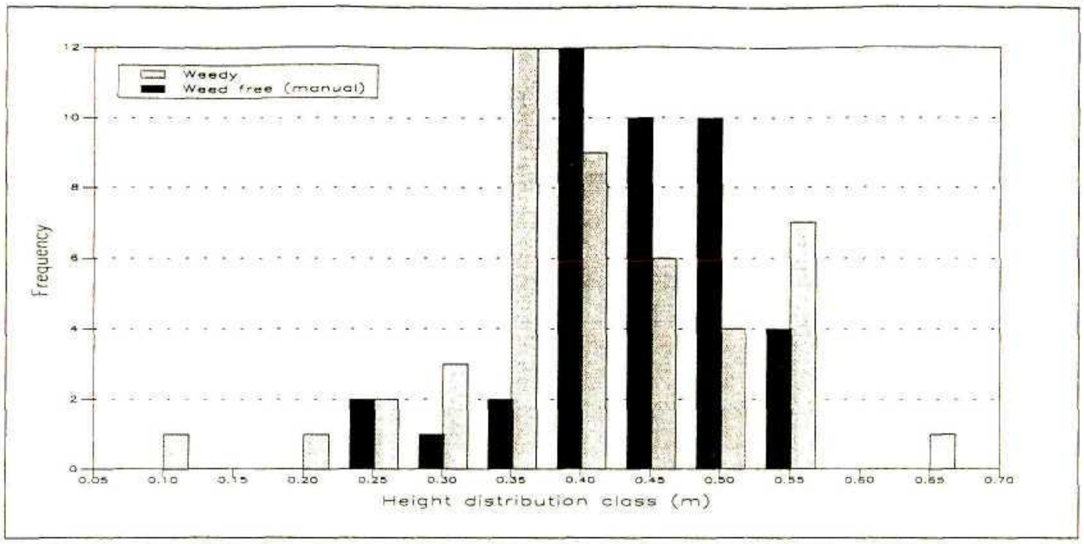
The box and whisker diagrams for the diameters at breast height serve to illustrate the differences between these two treatments (Figure 4.8). For both treatments, there is an increase in the 95 % confidence limits and extremes with an increase in growth, although this was more pronounced in the weedy control. As with tree height, the extremes, with a bias towards the smaller trees, indicate that the range of trees in terms of diameter at breast height distribution might be skew.

4.2.3.2 Changes in the distribution and shape of this distribution with time

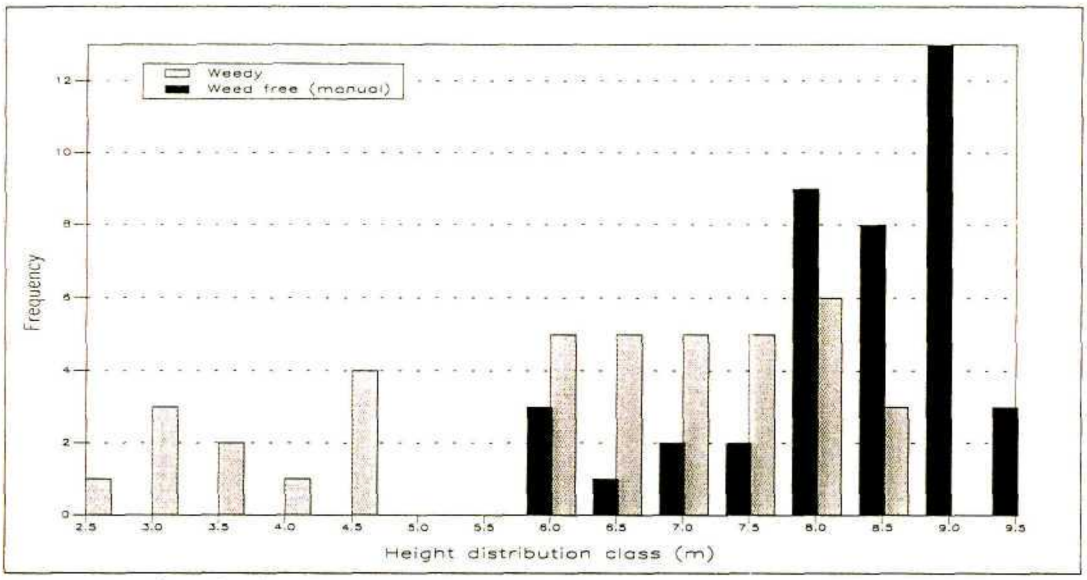
To further illustrate the effect of this inter- and intra- specific competition on the distribution of tree growth variates, frequency diagrams were constructed using tree height at three time intervals for the manually weeded treatment and the control (Figure 4.10). According to TURNER and RABINOWITZ (1983), a change in the distribution shape could provide a basis for detecting the effects of competition. Although these frequency diagrams contain class intervals that were arbitrarily chosen, they do provide a visual image of the skewness of the distribution. The time intervals were chosen to represent the onset of interspecific competition (2 months), post-canopy closure (20 months) and when the trees were felled (7 years). In addition the degree of asymmetry of these distributions (skewness) was calculated for all the height and diameter at breast height data for these two treatments (Table 4.1).

Initial tree growth was affected either directly or indirectly by the presence or absence of competing vegetation and this had an effect on the distribution and skewness of height classes (Table 4.1 and Figure 4.10). TURNER and RABINOWITZ (1983) and WEINER (1985) attribute the possible causes of this size inequality (skewness) to: differences in age; genetic variation; heterogeneity of resources or other environmental factors; the effects of herbivores or pathogens; mortality or competition. As genetically similar cuttings of the same age were used, together with the lack of treatment related mortality, browsing or pathogens, the initial size inequality found in the height data for the manually weeded treatment must be attributed to other "non-treatment" related factors (as discussed in Section 4.2.3.1.). The combination of these "non-treatment" related factors together with interspecific competition caused an even greater size inequality in the weedy control. The weedy control had 10 height distribution classes as opposed to 7 for the manually weeded treatment at 2 months of age.

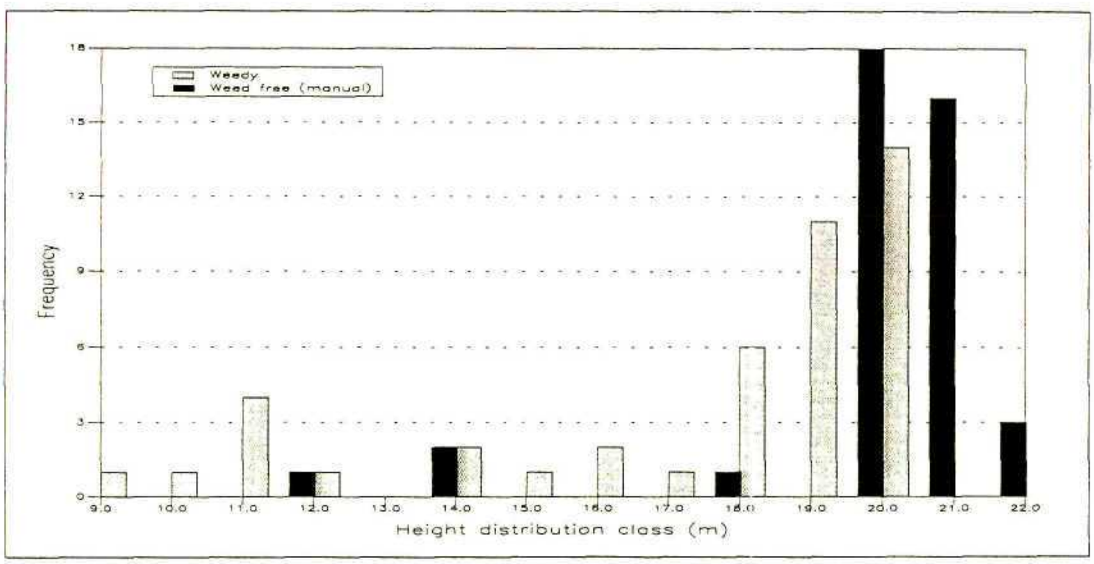
Although the data were negatively skewed on the first measurement date, by three months of age there was a positive skew in terms of the distribution of the height measurements for both the manually weeded treatment (0.1272) and the weedy control (0.4010) (Table 4.1). This pattern of distribution was to change progressively for both treatments from a positive to a negative skew over time. The time at which this change took place coincided with a decrease in the coefficient of variation (276 days for the manually weeded treatment and 408 days for the weedy control) as well as with the time that there was a reduction in differences between the rates of growth (Figure 4.9). Similar changes in asymmetry from positive to negative were noted by TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA (1994) for *Eucalyptus globulus* and PERRY (1985) for *Pseudotsuga menziesii.*



2 months after planting (58 days).



20 months after planting.



7 years after planting.

Figure 4.10: Height frequency distributions for the weedy control and manually weeded treatment when measured at the onset of competition (58 days), post-canopy closure (603 days) and when felled (2553 days).

For the manually weeded treatment, this increase in negative skew was as a result of most of the trees falling into fewer and the larger of the height distribution classes, to such an extent that by the time that the trees were felled, 83 % of the trees were in only two classes (Figure 4.10). A lack of interspecific competition in the manually weeded treatment meant that most of the trees were of a similar size at the onset of intraspecific competition, resulting in the equal sharing of the sites resources (TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA 1994). This is known as two-sided intraspecific competition where resources are shared equally (BRAND and MAGNUSSEN 1988).

The presence of interspecific competition in the weedy control resulted in differential suppression being exerted on different trees even within the same treatment plot. This meant that not only would the time taken to canopy closure be delayed, but some trees would be larger than others. The effect of this differential suppression on tree performance can be seen in Figure 4.10 when height distribution is compared at 20 months (603 days) after planting. The impact of this interspecific competition resulted in a wide spread of tree heights with a bimodal distribution. This variability caused by interspecific competition would be further enhanced by intraspecific competition. Intraspecific competition between the trees for the site's resources would be unequal, resulting in the continued and enhanced development of trees of different size classes until felling at seven years of age (Figure 4.10). This type of competition is known as asymmetric competition whereby the smaller trees lose vigour at the expense of the larger trees (BRAND and MAGNUSSEN 1988).

Although the presence of intraspecific competition was detected, there was a need to quantify the actual impact of this type of competition on individual tree performance. Two methods were used, the calculation of nearest neighbour indices, and the development of stem area class with time, both of which are discussed in Section 4.2.4.

4.2.4 The influence of the nearest neighbours on individual tree performance

4.2.4.1 Determination with competition indices

When an analysis of variance was carried out for the tree variate of diameter at breast height at felling, the presence or absence of the four nearest neighbours was used as a co-variate. The presence or absence of missing trees was just not significant at $p<0.05$ (*F.* probability = 0.065) indicating that there was some influence of missing neighbours on the measured tree. As a form of analysis, the use of missing neighbours would not be valid, especially for those treatments where trees suppressed by weeds could be considered as missing trees because they were not competitive. Competition indices were therefore sought and tested whereby the presence or absence of missing as well as the size of the nearest neighbours were taken into consideration. Of the competition indices that were available, only those that used diameter at breast height could be used as this was the only tree variate that was measured for all the trees in the whole trial (measured trees as well as border trees). An additional problem was that the border trees were only measured at felling and therefore the development of individual tree diameter over time in relation to its nearest neighbours could not be determined.

Various competition indices as well as comparisons between different competition indices have been used successfully for the determination of competitive stress on individual trees in a stand (LORIMER 1983; DANIELS, BURKHART and CLASON 1986). According to LORIMER (1983) most of the competition indices that take the spatial pattern of individual trees into account can be grouped into the following categories: indices that measure the amount of overlap of hypothetical "zones of influence" among neighbouring trees; growing space polygons that measure the area potentially available to each tree; and indices incorporating relative diameters and distances between subject tree and competitors. Of the competition indices that were available for use, a distance-dependent index (Equation 4.1) and a distance-independent index (Equation 4.2) were selected for use. The distance-dependent index relies on the principle that the size of the subject tree is thought to be proportional to its growing space and therefore takes into account the distance to and size of the surrounding trees (VAN LAAR and AKÇA 1997). The distance-independent index predicts the growth of the individual tree and is not based on over-lapping zones of influence (VAN LAAR and AKÇA 1997).

The three competition indices used on the data set were :

$$CI_1 = \sum_{j=1}^{n} \frac{D_j \ / \ D_i}{DIST_{ij}} \qquad (4.1)$$

$$CI_2 = \frac{\sum_{j=1}^{n} D_j}{D_i} \qquad (4.2)$$

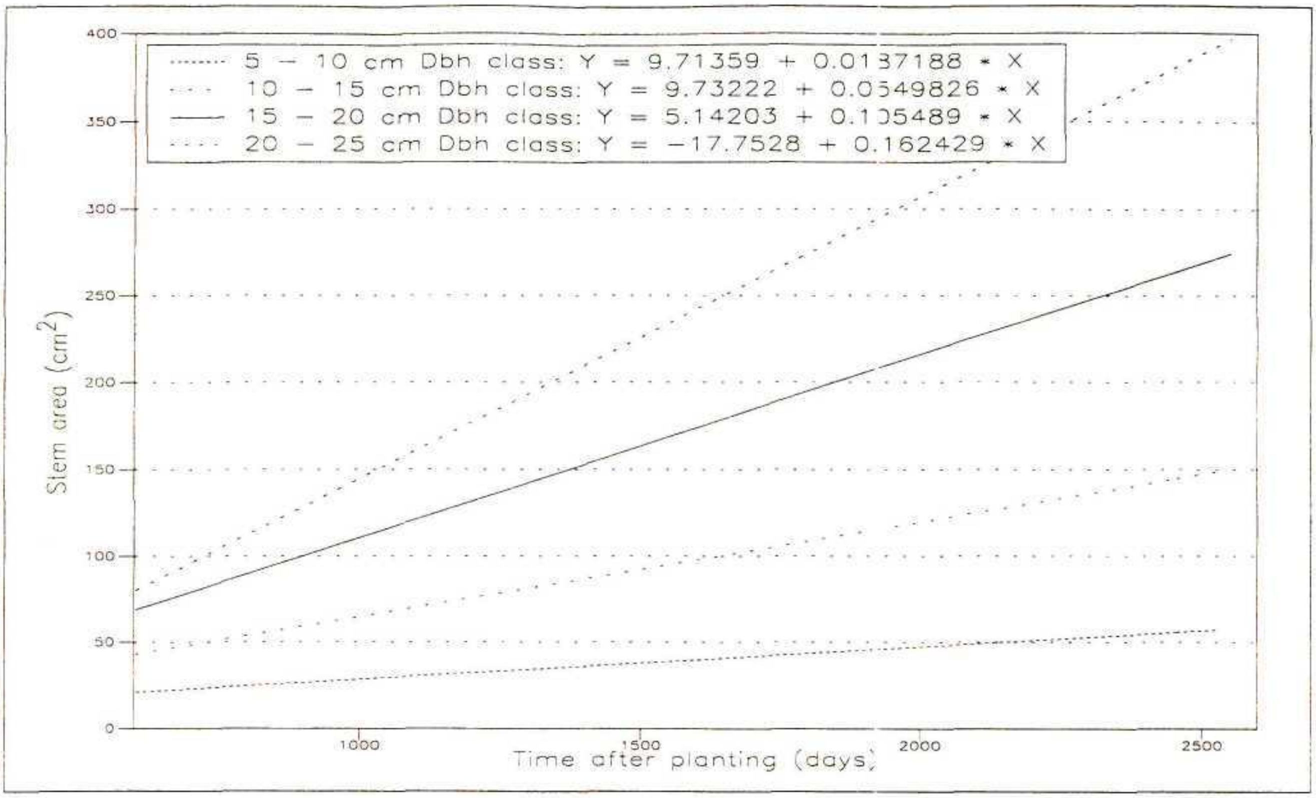
$$CI_3 = \sum_{j=1}^{n} \frac{D_j}{DIST_{ij}} \qquad (4.3)$$

where CI is the competition index, D_j is the diameter at breast height of the competitor tree j, D_i is the diameter of the subject tree i, $DIST_{ij}$ is the distance between trees i and j and n is the total number of competitors. In order to test the effect of distance from the subject tree, these competition indices were calculated for the nearest two neighbours (2.5 m radius), the nearest four neighbours (3 m radius) and the nearest eight neighbours (4 m radius). Simple linear and exponential regression with the treatments as groups was performed with the competition indices against the subject tree. The summary of the regression analyses is presented in Appendix 4.11. Although the competition indices CI_1 and CI_2 were not used in the final analysis as a similar term (subject tree diameter) was used in both the response and explanatory variables (CLARKE personal communication). The competition index CI_3 was determined as being more suitable for this type of exercise as the diameter of the subject tree only occurs as the response variate (CLARKE personal communication). No significant relationship between CI_3 and the tree diameters was detected at felling. This inability to account for any relationship between the subject tree and its nearest neighbours was attributed to one or a combination of the following factors. There were insufficient measured trees per treatment (maximum of 48 trees) available for use in this type of exercise. There was the lack of a suitable competition index which was sensitive enough to detect any relationship. The absence of growth data over time for the border trees meant that data from this source were lacking. An additional problem may have been that the initial impact of some of the weed proximity treatments and cover-crops may have had a greater and longer residual effect on individual tree growth, than did intraspecific competition.

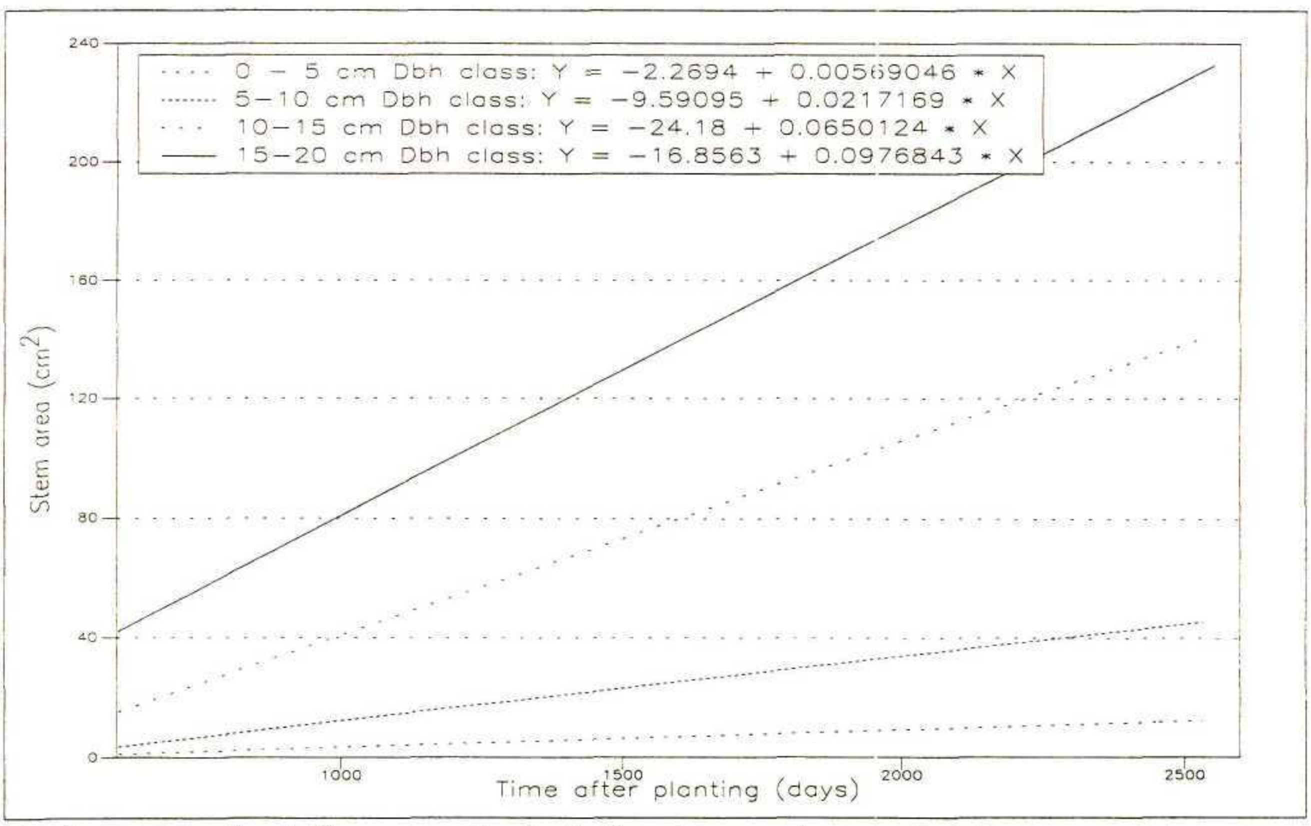
4.2.4.2 Determination of intraspecific competition using the slopes of stem area class development with time

Despite the unsuccessful attempt to find a suitable competition index to explain differential growth, the results from Section 4.2.3 indicated the presences of this intraspecific competition occurring between trees of different size classes. To try and illustrate this relationship in terms of individual tree performance, the weedy control and the manually weeded treatment were selected. As there was no proximity effect related to the management of the weeds around the trees in the weedy treatment, any suppression that did occur was the result of the natural distribution of weeds. The manually weeded treatment was selected due to the lack of interspecific competition, and the weedy control due to a relatively high degree of variability caused by interspecific competition. The stem areas for the trees in each treatment were ranked and sorted into five stem area classes. Each stem area class equating to a diameter class of 0 - 5 cm, 5 - 10 cm, 10 - 15 cm, 15 - 20 cm and 20 - 25 cm. To determine if there were any differences in the rates of growth between the five stem area classes, simple linear regression was performed on the development of stem area over time for each individual tree and the slope recorded. This approach is suggested by TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA (1994) as a suitable alternative to measures of skewness as an indication of intraspecific competition. An analysis of variance for unequal group sizes was then carried for the weedy and manually weeded control separately to determine if there were any significant differences between the slope classes (Table 4.2).

The analysis of variance for both treatments was highly significant, indicating that there were differences between the slopes and therefore rates of growth for the different stem area classes. Only once significance had been detected were differences between the different stem area classes tested, using the Student's *t*-test for samples of unequal size. The results of these tests are shown in Appendices 4.12 to 4.14. The slopes for all the stem area classes were significantly different ($p<0.05$) for each treatment, indicating differences in the rates of growth. This is clearly visible in Figure 4.11 where the rate of growth in stem area of the larger trees is greater than for the smaller trees. The diverging slopes of the different stem area classes indicates that the larger trees are growing at the expense of the smaller trees and this type of competition is known as asymmetric intraspecific competition (TOMÉ, TOMÉ, CLARA ARAÚJO and PEREIRA 1994). In addition, a comparison was made between the slopes for the weedy and weedfree treatments for the three similar diameter classes. No significant difference was detected, indicating that similar size classes in these two treatments grew at similar rates.



Weed free (manual). Simple linear regression for the four stem area classes against time.



Weedy treatment. Simple linear regression for the four stem area classes against time.

Figure 4.11: Linear regression for the slopes of the stem area classes (as determined by diameter class) over time, for the weedy control and the manually weeded treatment.

Table 4.2: Summary of analysis of variance (for unequal group sizes) for the slopes of stem area growth as determined by simple linear regression.

	Weedy control				Weed free (manual)			
Source of variation	DF	SS	MS	*F*. prob	DF	SS	MS	*F*. prob
Among groups	3	0.0488	0.016	123.99***	3	0.0583	0.0193	72.44***
Within groups	41	0.0054	0		37	0.01	0	
Total	44	0.0542			40	0.0679		

Means for slopes of the different stem area classes

Slopes of the stem area class as determined by diameter class	Mean	Slopes of the stem area class as determined by diameter class	Mean
0 - 5 cm	0.0056[a]	0 - 5 cm	-
5 - 10 cm	0.0215[b]	5 - 10 cm	0.0185[a]
10 - 15 cm	0.0645[c]	10 - 15 cm	0.0545[b]
15 - 20 cm	0.0977[d]	15 - 20 cm	0.1055[c]
20 - 25 cm	-	20 - 25 cm	0.1624[d]

Note: Within each column, values followed by the same letter are not significantly different; $p<0.05$ according to Student's *t*-test.

4.3 Conclusions

The differences in tree performance that were recorded during tree establishment, were still significant at felling. As there was no vegetation cover after canopy closure, these differences could be attributed to the negative impact of the vegetation on tree performance during the first seasons growth. This highlights the need for some degree of vegetation management in young plantations due to the susceptibility of these trees to competition during this stage. The development of stem area with time indicated that there was a continued divergence in growth between the manually weeded treatment and the weedy control. This occurred despite a more rapid decline in the growth rate and a lower stocking (although not significantly different) for the manually weeded treatment. This was attributed to the larger number of suppressed trees in the weedy control which did not contribute significantly to the treatment means.

Two forms of competition (interspecific and intraspecific competition) were evident in the weedy control at different stages of tree development in contrast to the one (intraspecific competition) in the manually weeded treatment. Interspecific competition resulted in greater variability between the trees in the weedy control by the time canopy closure had occurred. This differentiation in tree size was further enhanced by asymmetric intraspecific competition once the trees had become established. The onset of intraspecific competition was first detected at 995 days after planting for the manually weeded treatment and at 1641 days after planting for the weedy control. Of the various competition indices that were tested in order to try and explain this differential growth in terms of individual tree performance, none were able to do so to complete satisfaction. The growth rates of different tree size classes were therefore compared for the weedy control and manually weeded treatment. The diverging slopes of the different stem area classes indicated that the larger trees were growing at the expense of the smaller trees. This type of competition is known as asymmetric intraspecific competition. In addition, a comparison was made between the slopes for the weedy and weedfree treatments for similar stem area classes. No significant difference was detected, indicating that similar size classes in these two treatments grew at similar rates.

CHAPTER 5

VOLUME, STEM FORM AND ASSOCIATED TREATMENT COSTS AS A FUNCTION OF VOLUME WHEN TREES FELLED

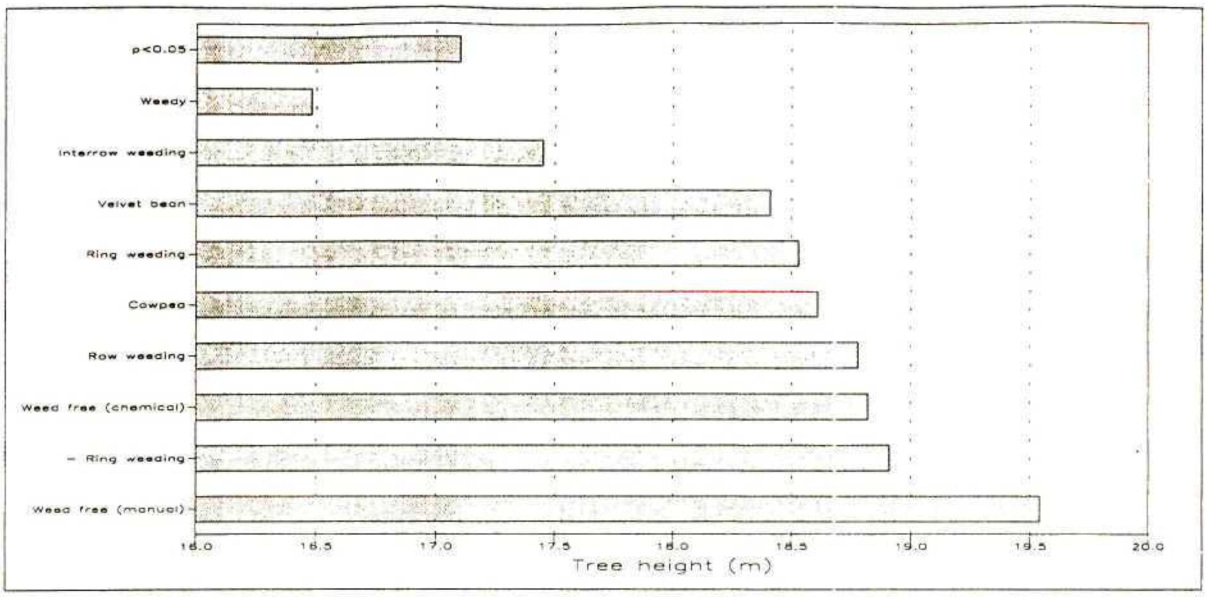
5.1 Introduction and objectives

When the trees were felled, various measurements were taken in order to determine the total and merchantable volume. The whole tree was used to determine the total volume whereas the merchantable volume excludes those trees that have an overbark diameter of less than 7 cm, or that section of the tree that is less than 7 cm in diameter. This 7 cm overbark equates to an under bark diameter of between 5 and 6 cm, the minimum diameter that can be utilized for pulp in a cost efficient manner. The determination of volume at felling is important as it provides a three dimensional measure and incorporates both stem area and height, both of which may have different levels of significance relative to the different treatments. As with the basal area calculations, the volume per hectare may also be determined by taking the stocking of the various treatments into account, thus providing one of the most important measures of tree performance (VAN LAAR and AKÇA 1997). The method by which this variates is obtained is presented in Chapter 2. This information was combined with the weed control costs of the different treatments to provide information as to the most cost-effective method of weed control. In addition to the determination of volume, additional information was derived such as bark thickness and stem form.

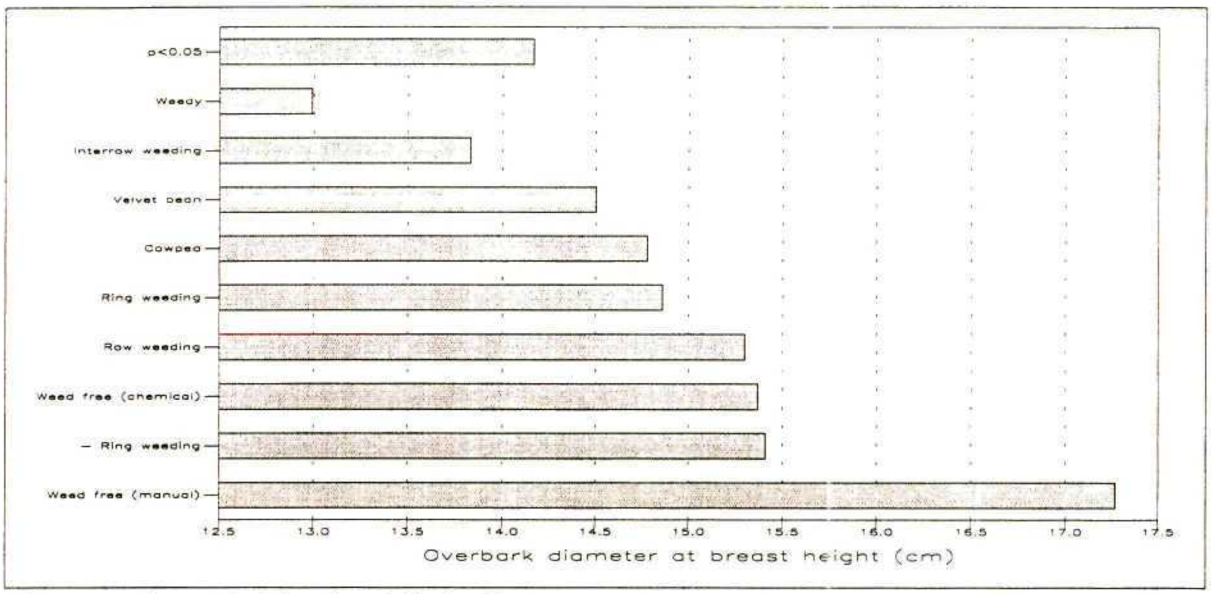
5.2 Results and discussion

5.2.1 Tree form and volume determination at felling

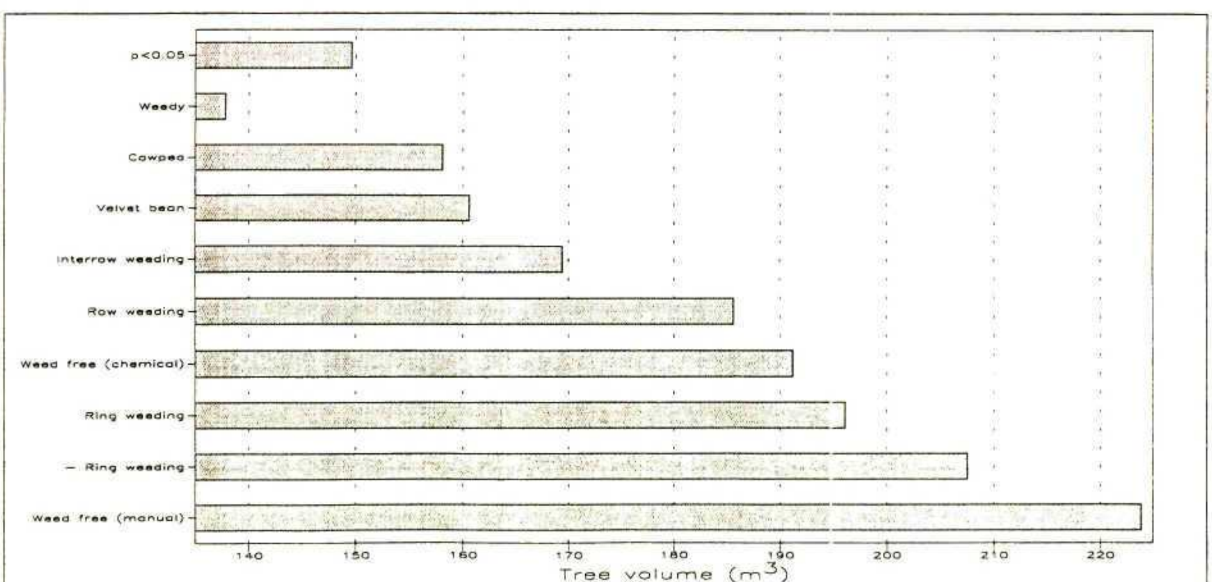
The type, duration and proximity of competing vegetation on trees during establishment had a long lasting effect on tree performance. As no weed vegetation was present on the site during the post-establishment phase it is assumed that it was the initial treatment responses that affected tree performance later in the rotation. Diameter at breast height and height measurements were significantly different when the trees were felled, as were the variates of volume and merchantable volume per hectare (Figure 5.1 and Table 5.1). Being a derived value, the merchantable volume per hectare is influenced by tree height, stem area, as well as the stocking. The effect of height does not have as much influence as that of diameter at breast height on volume. Relative to the manually weeded treatment, only the heights of the weedy control, the inter-row weeding and the velvet bean cover-crop were significantly different ($p<0.05$). In comparison, all the treatments were significantly different to the manually weeded trees for diameter at breast height (Figure 5.1). There was a 24 % reduction in diameter at breast height between the manually weeded treatment and the weedy control with only a 15 % reduction for height. This may be due to intraspecific competition amongst the trees for light, where height growth occurs at the expense of diameter growth especially in those treatments where initial suppression occurred.



Tree height when felled at 7 years.



Diameter at breast height when felled at 7 years.



Tree volume when felled at 7 years.

Figure 5.1: Tree height, diameter at breast height and volume for the different treatments when felled.

Table 5.1: Treatment means, standard errors and *F*. probabilities for the variates measured when the trees were felled.

	Variates measured and determined when trees felled									
	Height	Dbh_{ob}	Stocking (all trees)	Merchantable Stocking*	Total volume	Merchantable volume	Merchantable volume per hectare	Bark thickness at 1.3 m	Under bark diameter at 7 cm overbark	Taper
Treatments	(m)	(cm)	(stems ha^{-1})	(stems ha^{-1})	(m^3)	(m^3)	(m^3 ha^{-1})	(cm)	(cm)	(m m^{-1})
Weedfree (manual)	19.54^{a}	17.27^{a}	1139	1111	0.2004^{a}	0.201^{a}	223.9^{a}	1.654^{a}	6.046	0.842^{a}
Weed free (chemical)	18.82^{ab}	15.37^{b}	1278	1278	0.1531^{b}	0.1492^{b}	191.4^{ab}	1.474^{ab}	5.807	0.746^{b}
- Ring weeding	18.91^{ab}	15.41^{b}	1333	1278	0.1602^{b}	0.1631^{b}	207.5^{ab}	1.506^{ab}	5.9	0.762^{b}
Row weeding	18.78^{ab}	15.3^{bc}	1222	1167	0.1558^{b}	0.1604^{b}	185.6^{abc}	1.486^{ab}	5.874	0.754^{b}
Ring weeding	18.53^{abc}	14.86^{bc}	1305	1250	0.1542^{b}	0.1572^{b}	196.1^{ab}	1.437^{bc}	5.787	0.778^{ab}
Cowpea	18.61^{abc}	14.78^{bc}	1139	1083	0.1444^{bc}	0.1481^{b}	158.1^{bc}	1.429^{bc}	6.018	0.731^{bc}
Velvet bean	18.41^{bc}	14.5^{cd}	1194	1139	0.1382^{bc}	0.1408^{b}	160.6^{bc}	1.393^{bc}	5.829	0.729^{bc}
Inter-row weeding	17.45^{cd}	13.83^{cd}	1278	1139	0.1376^{bc}	0.1504^{b}	169.4^{bc}	1.362^{bc}	5.746	0.722^{bc}
Weedy	16.48^{d}	12.99^{d}	1250	1028	0.1152^{c}	0.1383^{b}	137.8^{c}	1.284^{c}	5.632	0.672^{c}
Mean	18.39	14.92	1238	1163	0.151	0.1565	181.1	1.447	5.849	0.748
s.e.d.	0.559	0.848	79.8	113.9	0.0158	0.0145	24.06	0.095	0.247	0.033
F. prob	<0.001	<0.001	0.2	0.339	<0.001	0.001	0.0388	0.016	0.819	<0.001

*Merchantable stocking excludes those trees whose diameters are less than 7 cm overbark at breast height.

Note: Within each column, values followed by the same letter are not significantly different; $p<0.05$ according to Students *t*-test, except for Height where significant differences ($p<0.05$) were calculated using the Fisher-Behrens test.

CANNELL and GRACE (1993) indicate that one of the ways a plant may respond to shading is by an increase in extension of growth through an increase in their allocation of assimilates to the shoot. As tree height in this trial was not measured between 603 days after planting until the trees were felled, the resource allocation in terms of height and diameter growth over time could not be quantified from the data set available. However, height and diameter data available from two mensuration trials on *Eucalyptus grandis* suggest that under weed free conditions, diameter growth is favoured over that of height growth at two years of age. In the first trial situated in Zululand near Kwambonambi (using data from the treatment that had a stocking of 1300 stems ha^{-1}), the diameter at two years of age was already 60.4 % of the diameter measured at seven years of age, whereas the height was only 47.7 % of the height at seven years of age (COETZEE, CHISWELL, STOREY and ARBUTHNOT 1996). In the second trial situated in the KwaZulu-Natal Midlands at Kia-Ora (using data from the treatment that had a stocking of 1333 stems ha^{-1}), the diameter and height again expressed as a percentage of the final diameter and height was 63 % and 49.5 % (COETZEE and NAIKER 1998). If one assumes that a similar pattern of growth would apply to *Eucalyptus* hybrids grown under weed free conditions in Zululand, then these trees would have a larger taper than those trees which are competing for light. Most of the trees fell into the 18 to 20 m height classes except for the manually weeded control where the majority of the trees were in the 20 to 22 m height class (Appendix 4.8). In direct contrast, not only was there much greater distribution in terms of diameter at breast height between the different treatments but there were differences between the treatments in the manner in which they were distributed (Appendix 4.10). This differentiation between the distribution of height and diameter at breast height was assessed with the use of a taper equation (Equation 2.5) (CLARKE, GARBUTT and PEARCE 1997). The use of this equation gives an indication of the decrease in diameter with increasing tree height. The treatment with the smallest taper was the weedy control, and that with the greatest was the manually weeded treatment (Table 5.1). In other words, the trees in the weedy treatment were taller in relation to their diameter than were the trees from the manually weeded treatment. There was no significant difference between the weedy control, the inter-row weeding, and the cowpea and velvet bean cover-crops, supporting the fact that growth in terms of height was partially in response to competition for light. This is especially the case in those treatments where initial tree growth was delayed due to interspecific competition. Whether a similar response would be achieved if the treatment plots were much larger is a question that cannot be answered by this trial.

5.2.2 The influence of competing vegetation on site index as determined by top height.

The suitability of land for forestry plantations may be defined, in part, by a measure of "site index" that infers potential productivity from tree height at a particular age (BREDENKAMP 1993; BATTAGLIA and SANDS 1997). For example, a site index of 25 with five years as the reference age means that the top height at age five years will be 25 m. Site index curves are constructed so that the determined top height at any age will provide an estimated indication of the site index of the stand. When linked to stand density, top height will enable the forester to estimate the predicted yield for a specified future age (COETZEE 1994). Implicit in this concept are the assumptions that forests follow a predictable course of growth over time, that is determined by a single measure of site quality, and that specific relationships exist between stocking, height, diameter and volume (BATTAGLIA and SANDS 1998). The definition of top height as used to determine site index in South Africa is calculated as the mean height of the 20 % of the trees per hectare with the largest diameter at breast height (BREDENKAMP 1993). According to GOULDING (1994), the concept of site index may fail if silvicultural practices or environmental conditions change so that the established growth relationships no longer apply. This may be even more evident for short rotation tree crops since the measured site-index could vary due to temporal changes in yield variation (BATTAGLIA and SANDS 1998).

To assess if site index, as determined by top height, was affected by the different vegetation management treatments, the dominant 25 % of the trees per treatment plot were compared to each other using height, diameter at breast height, volume and taper as well as to the mean when using all the data. As each treatment plot consisted of twelve measured trees, it would be impossible to determine the largest 20 % of the trees as advocated by the Mensuration and Modelling Group (BREDENKAMP 1993). Instead the dominant three trees per plot were used as equates to the top 25 % of the trees, the results of which are shown in Table 5.2.

Although significant differences were detected for all the variates when using the data for all the measured trees, no significant differences were detected for tree height, diameter at breast height and volume when using the top 25 % of the performing trees. The difference between the heights for the manually weeded treatment and the weedy control was reduced from 15.66 % to 6.49 % with the use of the dominant trees. At present there are no data available for the determination of top height for *Eucalyptus* hybrids grown in Zululand. However, based on available site index curves calculated for *Eucalyptus grandis* grown in KwaZulu-Natal (COETZEE, 1994), the manually weeded treatment would have had a site index of 16 when using the mean height of all the trees and 17 when using top height. In contrast the weedy control would have been assigned a site index of 14 if the mean height of all the trees was used and 16 for top height. The rest of the treatments (except for the velvet bean cover-crop) would also have been assigned a site index of 17 with the use of top height. Thus in terms of predicting the potential of the yield of the site, the use of top height would give a satisfactory estimate, provided adequate weed control is carried out. If a compartment is left in an untended (no weed control) state, the ability to accurately predict the future volume of the trees with the use of top height alone would be difficult due to the suppressed trees having a smaller diameter in relation to the height. This is evident by the 16.8 % reduction in tree diameter at breast height and the 32.6 % reduction in volume per tree in the absence of any weed control, despite the use of only the top 25 % of the trees. This height to diameter relationship (taper) still remains significant ($p<0.023$) even with the use of only the top performing trees. The weedy control was the only treatment to have a significantly different taper from the manually weeded treatment. As treatment induced mortality was not significant (Table 5.3), the indications are that the established growth relationships as required by site index were only affected in the weedy control. As part of the standard weed control operations, some form of minimal weed control is implemented during

Table 5.2: Treatment means calculated by using either all the trees per treatment plot or the largest three trees per treatment plot.

	Tree height		Diameter at breast height		Volume			Taper	
	Mean tree height as determined by the:		Mean Dbh_{ob} as determined by the:		Mean volume per tree as determined by the:		Percentage of total volume accounted for by the top 25 % performers	Mean taper per tree as determined by the:	
	Mean of all the trees[a]	Mean of the top 25 % of the trees per plot[a]	Mean of all the trees[a]	Mean of the top 25 % of the trees per plot[a]	Mean of all the trees[a]	Mean of the top 25 % of the trees per plot[a]		Mean of all the trees	Mean of the top 25 % of the trees per plot
Treatments	(m)	(m)	(cm)	(cm)	(m^3)	(m^3)	(%)	($m\ m^{-1}$)	($m\ m^{-1}$)
Weed free (manual)	19.54	20.17	17.27	20.34	0.2004	0.2612	32.6	0.842	0.985
Weed free (chemical)	18.82 (3.68 %)	20.12 (0.25 %)	15.37 (11.00 %)	18.68 (8.16 %)	0.1531 (23.60 %)	0.2136 (18.22 %)	34.9	0.746	0.888
- Ring weeding	18.91 (3.22 %)	20.42 (-1.24 %)	15.41 (10.77 %)	19.68 (3.24 %)	0.1602 (20.06 %)	0.2393 (8.38 %)	37.3	0.762	0.959
Row weeding	18.78 (3.89 %)	20.14 (0.14 %)	15.30 (11.41 %)	19.48 (4.23 %)	0.1558 (22.26 %)	0.2432 (6.89 %)	39	0.754	0.92
Ring weeding	18.53 (5.17 %)	20.05 (0.59 %)	14.86 (13.95 %)	19.08 (6.19 %)	0.1542 (23.05 %)	0.2372 (9.19 %)	38.5	0.778	0.949
Cowpea	18.61 (4.76 %)	20.48 (-1.54 %)	14.78 (14.42 %)	19.08 (6.19 %)	0.1444 (27.94 %)	0.2356 (9.80 %)	40.8	0.731	0.903
Velvet bean	18.41 (5.78 %)	19.68 (2.43 %)	14.5 (16.04 %)	18.20 (10.52 %)	0.1382 (31.04 %)	0.2110 (19.22 %)	38.2	0.729	0.886
Inter-row weeding	17.45 (10.69 %)	20.59 (-2.08 %)	13.83 (19.92 %)	19.96 (1.87 %)	0.1376 (31.34 %)	0.2565 (1.80 %)	46.6	0.722	0.943
Weedy	16.48 (15.66 %)	18.86 (6.49 %)	12.99 (24.78 %)	16.91 (16.86 %)	0.1152 (42.55 %)	0.1760 (32.62 %)	38.2	0.672	0.786
Mean	18.39	20.06	14.92	19.04	0.151	0.2304		0.748	0.913
s.e.d.	0.559	0.757	0.848	1.091	0.0158	0.0325		0.033	0.049
F. prob	<0.001	0.493	<0.001	0.129	<0.001	0.282		<0.001	0.023
$lsd_{(0.05)}$	1.099	-	1.667	-	0.031	-		0.065	0.101

[a] The figures in brackets indicate the percentage reduction in height, Dbh_{ob} and volume relative to the manually weeded treatment.

the establishment of commercial eucalypt plantations. This means that it will become increasingly unlikely that situations will arise where the lack of any weed control will affect the form of the trees. For compartments where this does occur, special care will have to be taken such that the site-index model takes into account the actual rather than the predicted potential.

5.2.3 Bark thickness

Two additional tree variates were derived from the measurements taken at felling, both of them relating to bark thickness. The first was the determination of bark thickness at breast height and was calculated as the difference between the over bark and under bark measurements taken when the trees were felled. A comparison was then made between the different treatments, the means of which are shown in Table 5.1. There were significant treatment differences ($p<0.001$) for bark thickness. Those treatments with the largest diameter had the thickest bark. To determine whether this relationship was either treatment related or as a function of tree size, simple linear regression with treatments as groups was performed. There was no differentiation between the treatments indicating that bark thickness is a function of tree size (as indirectly affected by treatment), rather than a direct result of the treatment. This relationship between diameter and bark thickness is shown in Figure 5.2, with a summary of the analysis given in Appendix 5.1. Similar results have been obtained by GRANT, KOCH, BELL and LONERAGAN (1997) in a trial to assess the relationship between bark thickness and tolerance to burning in five eucalypt species. They found that within individual species and across all species, bark thickness was significantly correlated with diameter at breast height.

The second was the determination of the under bark diameter in relation to that part of the tree where the over bark diameter was measured at 7 cm. The exact location of the stem diameter at 7 cm was difficult to determine especially for those trees where this occurred within the crown. A comparison between the treatments indicated that there were no significant differences (Table 5.1) and that the mean under bark diameter was 5.849 cm. This lack of significance was important as it meant that the determination of the merchantable volume would not be affected by any inaccuracies in the determination of precisely where 7 cm overbark occurred.

5.2.4 Weeding costs as a function of final yield

One month after the initial pre-plant spray, all the treatments except for the weedy control were weeded. In addition to this, three more manual weed control operations were carried out in all the treatments except for the cover-crops and chemically weeded treatment, each of which received only one further weeding (Table 5.3). In terms of the number of weed control events, the use of the cover-crops or herbicides for the control of competing vegetation being far more effective than manual hoeing. The herbicide used in this trial (glyphosate) is translocated to the actively growing regions of the weed ensuring an effective kill. With manual hoeing the weeds are often either only topped leaving the root system intact, or the weeds (especially those that reproduce by vegetative means) are able to regrow albeit in a different

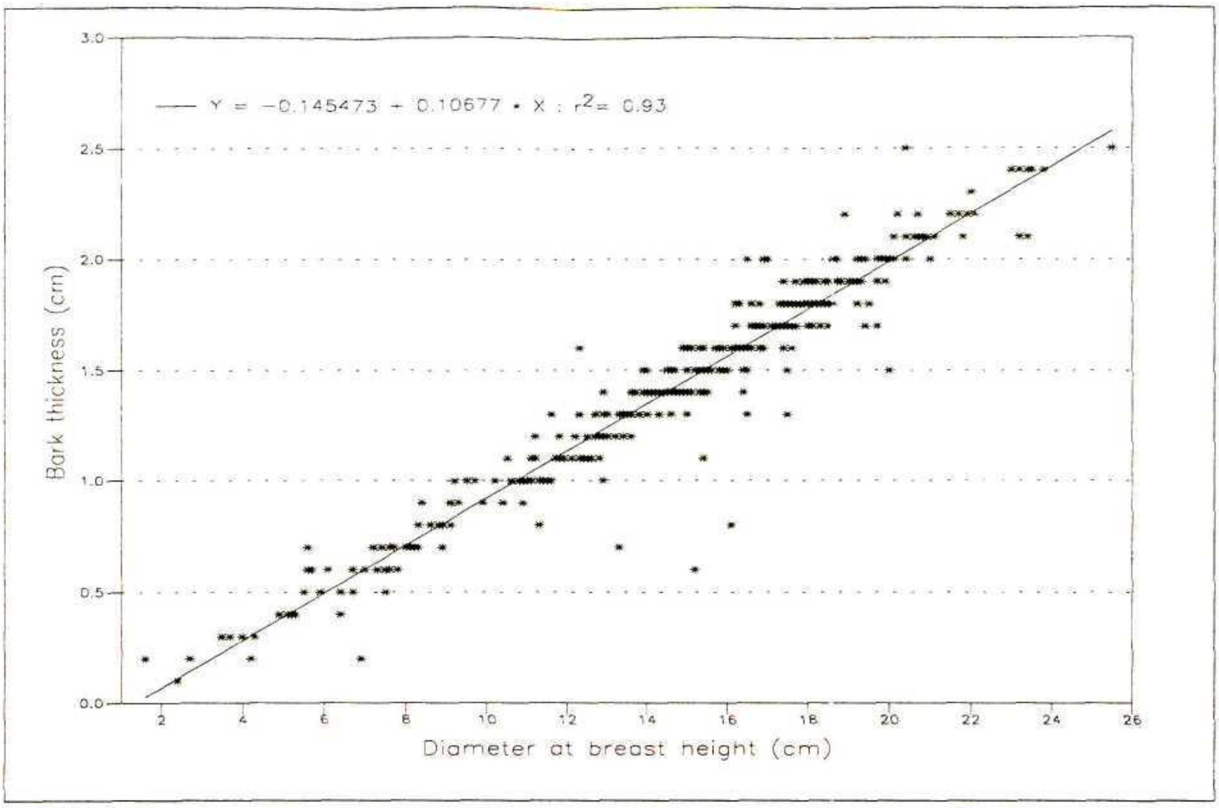


Figure 5.2: Simple linear regression showing the relationship between increasing diameter at breast height and bark thickness when the trees were felled at 7 years.

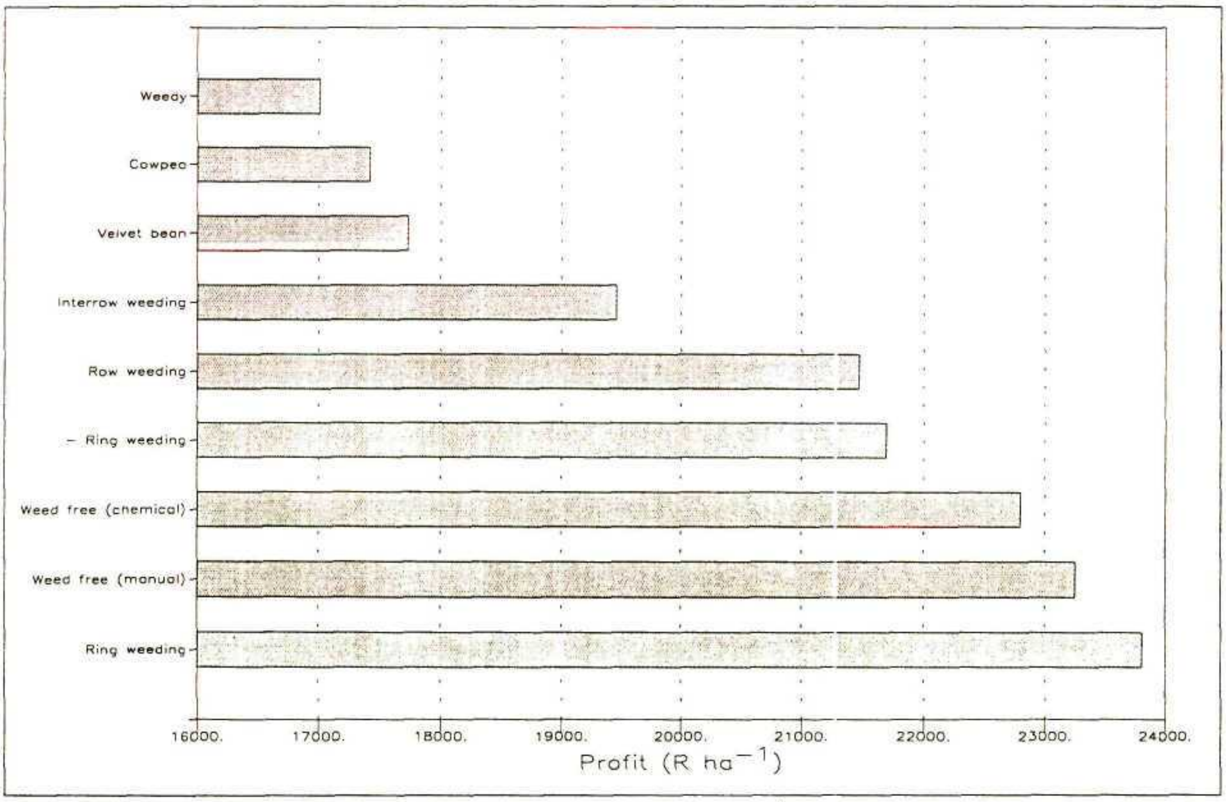


Figure 5.3: Profit that would be realized relative to the tons ha^{-1} of timber obtained at harvest for the different of weeding treatments. The figures in this graph reflect deductions in relation to tree performance and weed control costs only. No other establishment costs have been deducted.

Table 5.3: Estimated effect of establishment weeding costs on final prices received for timber.

Type of weeding operation	Method	Cost of each operation in 1990\1	Number of weed control operations	Total weed control costs incurred during establishment (1990/1)	Total establishment weed control costs adjusted for financial charges[1]	Merchantable volume	Rand per volume	Merchantable volume converted tons per hectare	Price that would have been received for the timber at the 1997 price of R175 per ton.	Price of timber after deduction of establishment weeding costs
		(Rands ha^{-1})	-	(Rands ha^{-1})	(Rands ha^{-1})	(m^3 ha^{-1})	(Rands m^{-3})	(tons ha^{-1})	(Rands ha^{-1})	(Rands ha^{-1})
Pre-plant spray		143	1	143						
Complete weeding	manual	750	4	3143	4737	223.9	21.57	159.93	27987.5	23251
Complete weeding	chemical using cones	302	2	747	1126	191.4	5.88	136.71	23925	22799
Ring weeding (1m diameter)	manual	82	4	471	710	196.1	3.62	140.07	24512.5	23803
Row weeding (1.2 m)	manual	250	4	1143	1723	185.6	9.28	132.57	23200	21477
Inter-row weeding (1.2 m)	manual	250	4	1143	1723	169.4	10.17	121	21175	19452
- Ring weeding (1 m diameter)	manual	668	4	2815	4243	207.5	20.45	148.21	25937.5	21695
Cowpea cover-crop with weeding to establish	seed + fert. + planting costs	160	1	1553	2341	158.1	14.81	112.93	19762.5	17422
	manual	750 + 500	2							
Velvet bean cover-crop with weeding to establish	seed + fert. + planting costs	160	1	1553	2341	160.6	14.58	114.71	20075	17734
	manual	750 + 500	2							
Weedy	-	-	-	143	216	137.8	1.57	98.43	17225	17009

[1]Interest capitalisation has been based on Mondi Forest Afforestation Accountancy Policy using actual interest over the period from October 1991 to October 1997.

position. In addition, continual topsoil disturbance renders conditions more favourable for seed germination and growth. Because chemical weeding results in all the weeds coming into contact with some herbicide, all the weeds are killed, whereas often with manual hoeing the smaller weeds are left.

The estimated costs for the different weeding operations are displayed in Table 5.3. As all the treatments received a pre-plant spray at a cost of R 143 ha^{-1}, these have been added to the total establishment weed control costs. The weeding costs for 1997 (time that the trial was felled) were very similar to those incurred in 1990/1. For example a pre-plant spray cost R 163 ha^{-1} in 1997 as opposed to R 143 ha^{-1} in 1991 and a coning operation cost R 233 ha^{-1} as opposed to R 302 ha^{-1}. The reason for this difference could be related to the price of glyphosate being very much cheaper in 1997 than when the trial was established. This decrease in price was brought about through the patent for the manufacture of glyphosate expiring. This resulted in the availability of many different brand names at drastically reduced prices (R 35 - R 40 per litre in 1990/1 as opposed to R 12 - R 18 per litre in 1997). Manual weeding costs have also remained fairly constant due to the companies no longer carrying out the weed control operations themselves. All the weed control operations are now being carried out by weed control contractors. This lack of "big company" overheads and the competitive nature associated with submitting tenders for work has resulted in the maintenance of a similar price. For example a complete manual weeding in 1990 would have cost R 750 ha^{-1} as opposed to R 640 ha^{-1} in 1997 and a ring weeding R 82 ha^{-1} as opposed to R 80 ha^{-1}. For this reason it was decided to use the 1990/1 costs for establishment weeding control. These weed control costs have been adjusted to take into account interest capitalisation, and has been based on Mondi Forests Afforestation Accountancy Policy using actual interests over the period from October 1991 to October 1997.

To obtain an understanding of the costs per unit growth obtained, the price per hectare (R ha^{-1}) was divided by the merchantable volume per hectare (m^3 ha^{-1}), yielding the amount spent in obtaining a m^3 of timber (Table 5.3). The two best performing treatments, also with the largest areas kept manually weeded (manual weed free and -ring weeded treatments) cost the most at approximately R 21 m^{-3}. In terms of keeping the entire area free of weeds then the chemically weeded treatment was the most cost-effective, whilst the ring weeding and the weedy control were the least costly albeit at the expense of reduced tree growth.

As the prices paid at the paper mills are determined on a mass basis R 175 per ton in 1997), it was necessary first to convert the volume per hectare (m^3 ha^{-1}) into tonnes per hectare (tonnes ha^{-1}). This was performed by the dividing the volume per hectare by the standard conversion factor used by Mondi of 1.4 (SWAINE personal communication). After determining the price that would have been received for the timber at the 1997 price of R 175 per ton, the costs of establishment weed control were deducted. No other establishment costs (marking, pitting, planting and fertilization) have been deducted. All these values are shown in Table 5.3, with the profit expressed as R ha^{-1} shown in Figure 5.3.

The profit to be gained from establishment weed control is affected both directly and indirectly by the method of weed control, as any improvement in yield needs to be taken into consideration together with any monetary input in terms of weed control expenditure. For example the manually weeded treatment not only had the highest merchantable volume of 223.9 m^3 ha^{-1}, but also the highest weed control input costs of R 4737 ha^{-1}. In comparison, the chemically weeded treatment produced 191.4 m^3 ha^{-1} at a cost of only R 1126 ha^{-1}. By taking the weed control costs into consideration the profit difference between these two treatments was reduced from R 4062.50 ha^{-1} to R 452 ha^{-1}, indicating the importance of taking all factors into account.

In order to make a comparison between the different treatments, they were first ranked according to their timber volume and weed control costs. Treatments within these two factors were then further separated into low, medium and high classes and tabulated as shown in Table 5.4.

Provided long term sustainability is not jeopardised, the ideal scenario in terms of any form of silvicultural management would be to obtain the maximum return from minimum input. Higher input costs would have to be justified in terms of significant growth benefits, and profit, before they could be considered a viable option. If this were not the case, or where significantly improved growth could not be guaranteed, there would be an increased risk associated with the carrying of these higher weed control costs over a full rotation. Although the manually weeded treatment produced the second highest returns (after weed control input costs were deducted) it was not significantly different from the row, - ring, chemically and ring weeded treatments. This would place it in the high risk category as the high weed control input costs could not be statistically guaranteed to result in improved yield.

The chemically and ring weeded treatment are examples of low input/high output treatments. Although the volume obtained from these treatments was not as high as the manually weeded treatment, the lower cost of applying herbicides and the small area that was manually ring weeded contributed to a higher profit. These low input costs also carry a lower risk as is shown by the amount of money spent to obtain a m^3 of timber (Table 5.4). If the size of the ring weeding was to be increased, then the additional costs of this operation would have to be justified in terms of profit obtained from a significantly improved volume.

The competitive nature of the cover-crops when planted at the same time as the trees resulted in a low timber output. If these cover-crops could be planted in such a manner so as to minimise tree suppression and maximise weed suppression, a medium input/high output scenario could be achieved.

The -ring and inter-row weeding treatments would not normally be considered as a viable option due to the high risk of mortality associated with the retention of weeds in the immediate vicinity of the tree when small. Although mortality was not significant in this trial, resulting in higher than expected volumes obtained for these treatments, there is a considerable body of evidence to suggest that these are high risk treatments.

The weedy control fell into the low weed control input/low volume output class, confirming that on this site some form of vegetation management would be needed due to the severity of weed competition.

Table 5.4: Ranking of treatments in terms of timber volume output and weed control input costs.

		Timber volume output		
		High	Medium	Low
Weed control input costs	High	Manual weeding (R 21.57 m^{-3})[1] -Ring weeding (R 20.45 m^{-3})	-	-
	Medium	-	Row weeding (R 9.28 m^{-3}) Inter-row weeding (R 10.17 m^{-3})	Cowpea cover-crop (R 14.81 m^{-3}) Velvet bean cover-crop (R 14.58 m^{-3})
	Low	Chemical weeding (R 5.88 m^{-3}) Ring weeding (R 3.62 m^{-3})	-	Weedy control (R 1.57 m^{-3})

[1]The figure enclosed in brackets is the total weed control costs incurred during establishment expressed as a function of merchantable volume (amount spent on weed control to obtain a m^3 of timber).

5.3 Conclusions

When the trees were felled, various measurements were taken in order to calculate absolute rather than estimated parameters. There was a larger difference between the treatments in terms of diameter at breast height than in top height. This was further demonstrated by comparing the taper for the different treatments. Trees in those treatments which experienced interspecific competition during establishment (weedy control, inter-row weeding and the cover-crops), were taller in relation to their diameters (lower taper). This may be due to intraspecific competition amongst the trees for light, where height growth occurs at the expense of diameter growth, especially in those treatments with initial suppression.

The use of top height rather than mean height would provide a satisfactory estimate in terms of predicting the potential yield of the site, provided weed control is carried out. If a compartment is left in an untended state (no weed control), the ability to accurately predict the future volume of the trees with the use of top height alone would be difficult due to the suppressed trees having a smaller diameter in relation to their height.

Bark thickness, determined at breast height, was found to be related to tree size rather than as a direct result of the treatment, with a positively linear relation between tree size and bark thickness. The underbark diameter of the stem where the overbark diameter was 7 cm was also determined, and was found to be 5.8 cm. The exact location of this position on the tree is important, especially if an accurate assessment of merchantable volume is to be made. No significant differences were detected between the different treatments.

The initial impact of interspecific competition on the trees was carried through to felling, resulting in significant differences between the different treatments. The best performing treatment, the manually weeded treatment, produced 38.5 % more merchantable timber than the weedy control, at an increased profit of 27 %. This highlights the large potential gains that can be had through vegetation management.

When deciding on a weed control strategy, numerous factors need to be taken into account. Firstly, the effect of input costs needs to be considered together with final volume to determine the most profitable scenario. Secondly, the degree of risk associated with the carrying of high weed control costs through to felling needs to be considered. Weed control operations with high input costs may not always guarantee a significantly improved yield, putting them into a high risk category. Thirdly, the physical characteristics of the site need to be considered when choosing a viable weed control system. For example the larger the area weeded, especially as in the manually weeded treatments, the higher the risk of soil loss from the site. The degree of erosion would be further enhanced as the gradient becomes steeper. On sites sensitive to erosion, weed control options should be aimed at the retention of some weed biomass on the site. This biomass should be retained in the area between the trees, as is practised for a ring and row weeding, or alternatively a cowpea cover-crop could be planted in the inter-row. Whatever minimum weeding option is selected, care will need to be taken to reduce any negative impact on tree growth. The retention of post-harvest residues, as is being increasingly practised in the Zululand region, will also limit the degree of manual weeding that can be carried out in the area immediately around the seedling.

CHAPTER 6

THE RELATIONSHIP BETWEEN VEGETATION MANAGEMENT AND WOOD AND PULPING PROPERTIES

6.1 Introduction and objectives

Wood (for use as pulpwood and saw or veneer logs) is one of man's most important resources, with its importance in a world of limited resources increasing (BROWN and HILLIS 1984). 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. The composition of the wood has changed; non-coniferous species now contribute nearly 30 %, and an increasing fraction of this is made up of eucalypts, much grown in the subtropics and tropics (BROWN, NAMBIAR and COSSALTER 1997). An increased pulpwood supply from plantations need not require a corresponding increase in area. An improvement in the management of existing resources may well result in an improvement in timber yield. The factors influencing an increase in yield and pulpwood from an existing land base can be achieved by different means. According to CLARK (1991) genetic, site and silvicultural variability may be important factors that may influence pulpwood quality and yield.

Very little information was found relating the silvicultural practice of vegetation management with that of pulpwood quality and yield, with no data found for eucalypts grown in South Africa. Data from three selected treatments in this study were therefore used to quantify if there were indeed any negative or positive impacts on pulpwood quality and yield resulting from different methods of weed control.

6.2 Measurements

6.2.1 Selection of sample trees

Cost and time restraints combined with the limited facilities available for the testing of pulp and wood properties in South Africa limited the number of samples that could be assessed from this trial. For these reasons selected tees from only three of the nine treatments were selected for further analysis. The weed free control (best tree performance), 1.2 metre row weeding (average tree performance) and the no weed control (worst tree performance) were chosen as they represented a diverse range in terms of tree growth and performance, the factors most likely to affect wood and pulping properties. Of the twelve measured trees per plot, five were randomly selected in a stratified manner using the diameter at breast height measurements taken prior to felling. Using these data, the trees in each treatment plot were ranked, then divided into the top three performers, the middle six performers (further divided into three groups of two) and the lower three performers. One tree was selected from each of the top and bottom levels of stratification and the remaining three trees from the middle level. This represented twenty trees per treatment and sixty for the whole trial.

6.2.2 Tree growth

Prior to felling, the over bark diameters at breast height (Dbh_{ob}) were measured and marked on the selected trees. The trees were felled as close as possible to the ground (≤0.05 m). Once felled the height to the top of each tree (H_{top}) and height to a minimum over bark stem diameter of 0.07 m ($H_{0.07}$) was measured. Under bark diameter measurements were taken 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 (CAILLIEZ 1980) as follows (Equation 6.1):

$$V_{sec} = \frac{\pi}{12} (d_1^2 + d_1 d_2 + d_2^2) \times l \qquad (6.1)$$

where d_1 and d_2 are the under bark diameters of the lower and upper ends of each section and l is the length of each section. The merchantable volume for each individual tree ($V_{0.07}$) was then calculated from the sum of the volumes of each section. From this, the total merchantable volume per hectare (V_{mha}) was calculated with the use of the stocking obtained for the respective treatments. Tree growth properties and the units used are shown in Table 6.1.

Table 6.1: Growth properties of the selected trees used for wood and pulp tests.

Property measured	Variable	Unit
Over bark diameter at breast height (1.3 m)	Dbh_{ob}	cm
Height to top of tree	H_{top}	m
Under bark diameters every 1 m along tree length	$d_1, d_2 \ldots\ldots d_n$	m
Merchantable height of tree (height to minimum over bark diameter ≥0.07 m)	$H_{0.07}$	m
Under bark volume of each 1 m section of tree	V_{sec}	m^3
Merchantable volume of individual trees (volume up to a minimum over bark diameter ≥0.07 m)	$V_{0.07}$	m^3
Merchantable volume per hectare	V_{mha}	$m^3\ ha^{-1}$

6.2.3 Wood properties

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. These discs were marked and stored in order to determine the wood properties of individual trees at the CSIR Forestry and Forest Product Programme laboratories in Pretoria.

6.2.3.1 Density

Density is the ratio of the mass of a quantity of a substance to its volume and is expressed in terms of mass per unit volume (kg m^{-3}). Wedges were cut from the discs at breast height and the discs from 5 %, 15 %, 35 % and 65 % of the total tree height. The volume of each sample was determined by water displacement and the mass from oven dried wedges according to the TAPPI test method T258 om-89. Due to differences in height between the sample trees, the weighted mean density of each tree was determined relative to the diameter of each disc. 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})(Equation 6.2).

$$Timber\ yield = \frac{V_{mha} \times Density}{1000} \qquad (6.2)$$

6.2.3.2 Fibre length and coarseness

A single sub-sample was taken from the pulp of each individual tree for the determination of the fibre length and fibre coarseness. A Kajaani FS-200 optical fibre length analyser situated at the Mondi Pulp Mill in Richards Bay was used for fibre assessment. 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}).

6.2.3.3 Extractable content of wood

From each tree a wedge was cut from the 5 %, 15 %, 35 % and 65 % discs. The individual wedges were chipped and Wiley milled in order to obtain a sample of air dried sawdust to pass through a 0.40 mm screen in accordance to the TAPPI test method T 257 cm-85. The ground wood from the four 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.

Table 6.2: Wood properties of the selected trees used for wood and pulp tests.

Property measured	Units	Method
Density	kg m^{-3}	TAPPI test method T258 om-89
Density (weighted mean)	kg m^{-3}	
Density at breast height	kg m^{-3}	
Timber yield per hectare	tons ha^{-1}	
Fibre length (arithmetic mean)	mm	Kajaani FS-200 optical fibre length analyser
Fibre length (weighted mean)	mm	
Fibre coarseness	mg m^{-1}	
Solvent extractable content	%	TAPPI test method T204 om-88
Hot water extractable content	%	TAPPI test method T207 om-88

6.2.4 Pulping and pulping properties

The wood of various species of the genus *Eucalyptus* has become an important source of papermaking fibre. By far the largest number of cells are made up of vessels, parenchyma and fibres, of which fibres are used in the manufacture of pulp and paper. The fibre walls are made up of cellulose microfibrils encased in hemicellulose sheaths. These sheaths are bonded together to form the various wall components into a fairly rigid unit as well as bonding the various fibre units to form compact wood by the secretion of lignin in the middle lamella zone (BAMBER 1985). The organic materials which make up 99 % of eucalypt wood may be divided into structural and non-structural (extraneous material) components. The composition of extractive free eucalypt woods consists of roughly half cellulose, one quarter hemicellulose and one quarter lignin (BLAND 1985). Pulping, the separation of the wood into its constituents requires the breaking of the bonds between the cells. During pulping this is achieved under pressure and temperature with the use of chemicals to penetrate the various cell constituents and break down the lignin and remove the extractives to leave individual fibres consisting mainly of cellulose.

Individual tree samples were made up by combining the 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. The moisture content was determined and the chips were then stored in sealed plastic bags at $4^{0}C$.

Samples were then pulped in an electrically heated, batch type, rotating digester using the kraft process. The kraft process, a well defined process, is tolerant to variation in woodchip dimension and quality, and produces pulp whose quality is acceptable on world markets (CLARK 1991) This kraft process is summarised by SMOOK (1989) as: "White liquor containing the active cooking chemicals, sodium hydroxide (NaOH) and sodium sulfide (Na_2S), is used for cooking the chips. The residual black liquor containing the reaction products of lignin solubilization is concentrated and burned in the recovery furnace to yield an inorganic smelt of sodium carbonate (Na_2CO_3) and sodium sulfide. The smelt is dissolved to form green liquor, which is reacted with quick lime (CaO) to convert Na_2CO_3 into NaOH and regenerate the original white liquor". The Kappa number test is used to determine the degree of delignification occurring during cooking and is used as a control test for cooking. The pulping conditions used in this study were selected to achieve a Kappa number of between 20 and 22.

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 minutes
	Time at 170°C	50 minutes
• 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 minutes

6.2.4.1 Active alkali content

A spent (black) liquor sample was taken through a coil condenser at the end of the cook but prior to blowdown. This was analyzed for residual alkali content according to TAPPI test method T625 om-85. The active alkali content gives an indication of the degree of delignification.

6.2.4.2 Kappa number

The Kappa number is an index related to the lignin content after pulping. After the chips from each tree had been pulped the Kappa number was determined according to TAPPI test method T236 cm-85. The Kappa number is the volume (ml) of 0,1N potassium permanganate solution consumed by one gram of moisture-free pulp. The results are corrected to 50 % consumption of the permanganate added.

6.2.4.3 Screened pulp yield and total pulp yield

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}) can be calculated as in Equation 6.3:

$$Pulp\ yield\ per\ hectare = Timber\ yield \times \frac{Pulp\ yield}{100} \qquad (6.3)$$

Table 6.3: Pulping properties calculated or tested.

Property tested/calculated	Units	Test method (where applicable)
Active alkali content	%	TAPPI test method T625 om-85
Kapppa number		TAPPI test method T236 om-85
Screened and Total pulp yield	%	
Pulp yield per hectare	tons ha^{-1}	

6.3 Statistical analyses

6.3.1 Treatment comparisons between individual variates

Variation for each property tested was separated into components and the statistical model was as follows:

$$Y_{ij} = \mu + \beta_j + \tau_i + \epsilon_{ij} \qquad (6.4)$$

Where y_{ij} is the property tested for the i^{th} treatment and j^{th} block, μ is a component common to all plots, β_i are the block effects for the j^{th} block, τ_i are the treatment effects for the i^{th} treatment and ϵ_{ij} is the uncontrolled error. Bartlett's test (SNEDCOR and COCHRAN 1956) was used to test the assumption of homogeneity of variance in order for a valid analysis of variance to be performed. This was carried out on all the tree and wood property variates used in this section. Calculated x^2 (corrected) values are shown in Appendix 6.4. Only the tree variate of height (which was not used in any derived calculations) and the pulping properties of active alkali consumption and fibre coarseness were significantly different ($p<0.05$) indicating the presence of heterogenous variance. The Fisher-Behrens test (CAMPBELL 1974) where separate variance estimates for the samples, was used to determine differences of means for these three variates. Results for this test are presented in Appendices 6.5 to 6.7. All the rest of the variates were analyzed using Genstat® for Windows™ (LANE and PAYNE 1996) with analysis of variance. Where significant differences were detected, treatment differences were further investigated using least significant differences (*lsd*'s) (STEEL AND TORRIE 1981).

6.3.2 Comparison 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 (TER BRAAK and ŠMILAUER 1998). Results for the CVA are presented in Appendices 6.8 to 6.11 and displayed graphically in Figure 6.1. In addition a permutation test (Monte Carlo test) was used to determine whether the differences between the clusters were significant.

6.4 Results and discussion

6.4.1 Tree performance

A summary of the analysis of variance and treatment means for tree growth properties is shown in Table 6.4. Individual data for all the sampled trees as well as the various wood and pulping properties is shown in Appendices 6.1 to 6.3.

The variates of height and over bark diameter at breast height were just not significant at $p<0.05$ with *F.* probability values of 0.056 and 0.057 respectively. The manually weeded treatment was superior in performance in both cases. In order to determine the merchantable volume of each individual tree, the height to an overbark diameter of 0.07 m was measured. The assumption was that this would equate to an under bark diameter of between 0.05 and 0.06 m in diameter. When this value was analyzed no significant differences were detected between the different treatments, indicating that the volume calculations would not be influenced by erroneous values.

Table 6.4: Summary of analyses of variance and data for growth properties of the selected trees used for wood and pulp tests.

Summary of analysis of variance						
		Mean squares				
Source of variation	DF	Height (m)	Dbh_{ob} (cm)	Diam. of last disc (cm)	Merchantable volume per tree (m^3)	Merchantable volume per hectare (m^3 ha^{-1})
Replications	3	2.060^{ns}	11.19^{ns}	0.0296^{ns}	0.006795^{ns}	8458^{ns}
Treatments	2	21.669^{ns}	64.08^{ns}	0.074^{ns}	0.030250^{ns}	43450*
Trees (residual)	6	4.496	13.39	0.067	0.006508	7770
Total	11					
Summary of data						
Manual weeding		20.07^{a}	18.05	5.745	0.2067	230^{a}
1.2 m Row weeding		18.78^{b}	15.23	5.7	0.1469	171^{b}
Weedy control		18.01^{b}	14.73	5.625	0.1338	138^{b}
Mean		18.95	16	5.69	0.1625	180
Standard error		0.671	1.157	0.259	0.02551	27.87
Coeff. of var. (trees)		9.2	21	10.5	42	42.6

Note: Within each column, values followed by the same letter are not significantly different; $p<0.05$ according to Students *t*-test, except for Height where significant differences ($p<0.05$) were calculated using the Fisher-Behrens test.

The stocking for the three treatments was used together with the merchantable volume in order to calculate merchantable volume per hectare. The merchantable volume per hectare calculations (based on the diameters of underbark discs taken at various heights), were significant ($p<0.05$), with the manually weeded treatment the best performer. Greater variability occurred between diameter at breast height measurements than with the height measurements (Table 6.4) with the greatest variability occurring in the weedy control and 1.2 m row weeding. The volume data exhibited a greater degree of variation, with the diameter data contributing more to this increase than the height in variation due to the readings being squared during the calculation of the volume (Equation 1).

6.4.2 Wood properties

A summary of the analysis of variance and treatment means for wood properties is shown in Tables 6.5 and 6.6. Individual data for all the sampled trees as well as the various wood and pulping properties is shown in Appendices 6.1 to 6.3.

6.4.2.1 Fibre length and coarseness

No significant differences were detected for the variate of fibre coarseness. However the manually weeded control produced fibres that were significantly longer ($p<0.05$) than the other two treatments (Table 6.5 and Figure 6.1). Anatomical differences in fibres differ with species, within species, with height, as well as from pith outwards (BAMBER 1985). In a study linking various wood to pulpwood properties for *Eucalyptus grandis* grown in South Africa, Du PLOOY (1980) found that cell wall thickness was the one property that appeared most frequently in the multiple regression equations. 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, DINWOODIE (1965) concluded that 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. The manually weeded treatment with the longest fibres indicated a beneficial trait in terms of paper making. HANS and BURLEY (1972) carried out studies on wood density and fibre length on *Eucalyptus grandis* (Hill) Maiden after application of NPK and boron fertilizers in Zambia. The experiment revealed a non-significant effect of fertilizer on fibre length.

6.4.2.2 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 and or time to cook 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 and the weedy control the least.

HILLIS (1969) indicates that 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. Extractives are the non-structural or secondary constituents of plants which include ellagic acid, gallica acid, allagatinnins, gallotannins, flavonoids and their polymers (CLARK 1991).

Table 6.5: Summary of analyses of variance and data for wood properties of the selected trees.

Summary of analysis of variance					
		Mean Squares			
Source of variation	DF	Fibre length (weighted mean) (mm)	Fibre coarseness (mg m^{-1})	Extractable content: Hot water (%)	Extractable content: Ethanol Benzene (%)
Replications	3	0.0009111^{ns}	0.00003095^{ns}	0.6974^{ns}	0.09241^{ns}
Treatments	2	0.0036317*	0.00002240^{ns}	1.0642^{ns}	0.91764*
Trees (residual)	6	0.000563	0.0000103	0.2965	0.09918
Total	11				
Summary of data					
Manual weed control		0.7720^{a}	0.06495	2.85	1.766^{a}
1.2 m Row weeding		0.7545^{b}	0.06335	2.84	1.522^{ab}
Weedy control		0.7455^{b}	0.06535	2.44	1.339^{b}
Mean		0.7573	0.06455	2.711	1.542
Standard error		0.0075	0.001761	0.1722	0.0996
Coeff. of var. (trees)		3	5	16.9	17.8

Note: 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 where the Fisher-Behrens test was used to detect for any significant differences ($p<0.05$). None were found for Fibre coarseness.

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 (HIGGINS 1984). 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 (BATCHELOR, PRENTICE and TURNER 1971). In general, extractive content increases with the age of the tree and with slowness of growth as well as from the pith outwards within the tree. HILLIS (1972) found that faster growing trees had lower extractive levels. 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 pulpwoods requiring less active alkali to cook to a given degree of delignification will have a processing-cost advantage (CLARK 1991). CLARK (1990) in 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. He linked alkali requirements to pulp yield, with high alkali requirements associated with lower pulp yields. According to DADSWELL and WARDROP (1959) the properties most desirable for paper manufacture include a higher than average fibre length, higher proportion of thin walled cells, a percentage of late wood, low extractive content and high cellulose content.

6.4.2.3 Density

Of the wood properties measured relating tree growth to pulp yield, measures of wood density are of great importance. Due to the variation in density occurring within trees (over height as well as from the centre outwards), the density was determined in two ways: at breast height and as a weighted estimate from discs taken at 5 %, 15 %, 35 % and 65 % of the total tree height. Both methods of density determination gave very similar results in terms of the means obtained (Table 6.6), with both the manually weeded and 1.2 m row weeding treatments producing wood of a higher density than the weedy control. There was a significant response ($p<0.05$) to both replication and the differences between the treatments with the use of the weighted mean density. A t-test $_{(0.05)}$ was used to determine if any differences occurred between the three treatments for the two methods of density determination. As no significant differences were detected between the methods of determination for the different treatments, the weighted mean density with the lower treatment variation (Appendices 6.1 to 6.3) was selected for use in comparisons and any derived calculations. The fact that the weighted mean density provides a measure over the whole tree, whereas the density at breast height only provides a point measure may influence the interpretation.

ZOBEL (1981) suggests that the two characteristics most affecting pulp properties of different eucalypts are their density and the presence of extractives. 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} (HILLIS 1984).

Basic wood density is a complex characteristic because it is dependent on numerous other factors (MALAN 1989) and is thus an important indicator of pulpwood quality (CLARK 1991). 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 (HIGGINS 1984) . 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 (HILLIS 1972) of which the relationship between fibre wall thickness to the lumen or whole cell diameter is most important (DADSWELL and WARDROP 1959; BAMBER 1985). As wood density rises above 300 kg m^{-3} there is a decline in the strength properties of paper. This is related to ratio of fibre diameter to wall thickness. The thicker the walls the weaker the paper. TAYLOR

(1972b) has shown that 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. BAMBER and HUMPHREYS (1963) also found that within trees the basic density and fibre length increased from the pith outwards.

Table 6.6: Summary of analyses of variance and data for the density of the selected trees.

Summary of analysis of variance				
			Mean squares	
Source of variation	DF	Weighted mean density (kg m^{-3})	Density at breast height (kg m^{-3})	Timber yield (tons ha^{-1})
Replications	3	1702.1*	1869^{ns}	3099^{ns}
Treatments	2	1376.5*	3614^{ns}	11805*
Trees (residual)	6	263.2	1295	2014
Total	11			
Summary of data				
Manual weeding		519.6^{ab}	521.7	119.6^{a}
1.2 m Row weeding		526^{a}	522.9	92.3^{ab}
Weedy control		509.6^{b}	499	71.1^{b}
Mean		518.4	514.5	94.3
Standard error		5.13	11.38	14.19
Coeff. of var. (trees)		4.7	6.3	47.4

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

6.4.2.4 Literature related to density as affected by rate of growth, tree age and silvicultural treatment

Density and rate of growth:
According to HILLIS (1984), there appears to be no general correlation between tree growth rate and wood density, although exceptions have been noted. Similarly BAMBER and HUMPHREYS (1963) and BAMBER, HORNE and GRAHAM-HIGGS (1982) assessed the effect of fast growth on the wood properties of *Eucalyptus grandis* and found no effect on fibre length and density, both important properties for paper manufacture. *Eucalyptus globulus* and *Eucalyptus nitens* were grown on four sites across an altitudinal gradient resulting in significant growth rate responses. Although there was a significant pulp yield response there were no significant differences in weighted density between the sites (BEADLE, TURNBULL and DEAN 1996). According to HIGGINS (1984), it seems generally accepted that 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. DADSWELL and WARDROP (1959) 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.

Tree age and density:
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, superior black liquors leading to easier chemical recovery, minimal extractives and higher bonding strength (HIGGINS 1984). CLARK (1990) in 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. He concluded that the effect of age on pulpwood quality is species dependent. HALL, HANSEN and RUDRA (1973) in a study of eleven eucalypts grown in Victoria in Australia, found that species and age were the best indicators of pulpwood quality, with the younger species being favoured in terms of lower basic density and extractive content.

Silviculture and density:
Many factors which affect 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 (FARRINGTON 1980). 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*, WILKINS (1990) recorded an increase in wood density with increased growth rate. HANS and BURLEY (1972) carried out studies on wood density and fibre length on *Eucalyptus grandis* (Hill) Maiden after application of NPK and boron fertilizers in Zambia. 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. They concluded that the study of wood properties was secondary to an improvement of growth. FARRINGTON, HANSEN and NELSON (1977) examined the effect of improved growth through fertilization on 2-, 4-, and 6- year old *Eucalyptus globulus*. They found that the use of fertilizer produced a significant increase in wood yield per hectare without having a detrimental effect on pulp strength properties. CROMER, BALODIS, CAMERON, GARLAND, RANCE and RYAN (1998) studied the effect of fertilizer application on the growth and wood properties of 5.6 year old *Eucalyptus grandis*. Fertilization resulted in increased rates of growth together with an associated increase in pulp yield and wood basic density. They concluded that the combined effect of these substantially improved the productivity of pulpwood from fertilized trees which would considerable enhance the economic viability of a pulp mill utilising wood from fast growing *Eucalyptus grandis* plantations.

6.4.2.5 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 (Appendix 6.12). This decrease in stem area for each treatment is highlighted in Figure 6.2, 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, the close espacement of these trees meant that resources would become increasingly limited, and thus unable to maintain sustained 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 (Appendix 6.13), indicating that irrespective of treatment the faster 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 (Appendix 6.14), indicating that irrespective of the treatments the faster the rate of growth the lower the extractable content.

6.4.3 Pulping properties

The different treatments had an influence on both the Kappa number and the active alkali content. The Kappa number was higher for the manually weeded and 1.2 m row weeding treatment than the weedy control. There was greater variability between the replications than between the treatments, for the screened pulp yield, with no significant differences being recorded.

Table 6.7: Summary of analyses of variance and data for pulping properties for the selected trees.

Summary of analyses of variance					
		Mean Squares			
Source of variation	DF	Active alkali (%)	Kappa number	Screened pulp yield (%)	Pulp yield per hectare (tons ha^{-1})
Replications	3	6.291^{ns}	1.5424^{ns}	2.0382^{ns}	785.6^{ns}
Treatments	2	18.930^{ns}	15.2667*	0.2907^{ns}	3167.1*
Trees (residual)	6	5.727	0.8446	0.2016	524.8
Total	11				
Summary of data					
Manual weed control		92.31^{a}	21.59^{a}	51.52	61.5^{a}
1.2 m Row weeding		90.37^{b}	21.09^{a}	51.66	47.6^{ab}
Weedy control		91.39^{ab}	19.89^{b}	51.42	36.4^{b}
Mean		91.36	20.86	51.533	48.5
Standard error		0.757	0.276	0.2114	7.26
Coeff. of var. (trees)		2	4.4	0.9	47.2

Note: Within each column, values followed by the same letter are not significantly different; $p<0.05$ according to Students *t*-test., except for Active alkali where significant differences ($p<0.05$) were calculated using the Fisher-Behrens test.

Screened pulp yield, expressed as a percentage, is the ratio of oven-dry pulp produced from oven-dry wood (BEADLE, TURNBULL AND DEAN 1996). 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 (Table 6.7).

Pulp yield has an important influence on the profit realised from timber grown for pulp and paper manufacture. CLARKE (1990) calculated that a one percent increase in pulp yield for *E. grandis* with a mean annual increment of 37.5 t/ha/annum would result in an eleven percent increase in profit per hectare at no extra cost. Pulp yield is the most important indicator of pulpwood quality (CLARK 1990).

6.4.4 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 (TER BRAAK and ŠMILAUER

1998). 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 (TER BRAAK and ŠMILAUER 1998), a program for canonical community ordination. Results for the CVA are presented in Appendices 6.8 to 6.11 and displayed graphically in Figure 6.1. The first two eigenvectors are given in Appendix 6.9. The first eigenvalue corresponds to 64 % of the variation and is apparently most heavily influenced by the alcohol extractable content and fibre length (Figure 6.1 and Appendices 6.8 and 6.9). 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 (Appendix 6.11). These differences are illustrated in Figure 6.1 by the cluster means which are separated along the x-axis.

6.5 Conclusions

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 both the wood volume (and therefore pulp yield) and pulp quality were influenced by different vegetation management techniques. The graphical presentation of the output from this Canonical Variate Analysis showed an increasing trend of higher density, extractable content and active alkali consumption with improved weed control. There was a corresponding increase in fibre length with improved weeding.

There is a considerable body of literature linking wood and pulping properties with tree age and rate of tree growth. As the effects of silviculture impact on the rate of tree growth, attempts were made to quantify the rates of growth for the different treatments and to link this to the wood and pulping properties. There was a significant difference in terms of the growth rates for the different treatments (as indicated by the slope of the stem areas over time) during the latter phase of tree development. The weedy control and 1.2 m row weeding experienced a lower rate of decline than did the manually weeded treatment. This could be a result of increasing intraspecific competition between the trees for the sites resources, especially between the larger trees in the manually weeded treatment. Although there was no significant difference between the weighted density for the different treatments, there was a significantly negative response related to increasing rates of growth. A similar response was found when comparing the extractable content with the rate of growth. Lower extractive contents were associated with more rapid growth. There was also a significant difference between the length of fibres, a beneficial property, with the manually weeded treatment having the longest fibres. Any negative impacts associated with the manually weeded control in terms of the wood and pulping properties (higher density, extractable content and active alkali consumption) would be minor in comparison to the significantly improved pulp yield per hectare. 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.

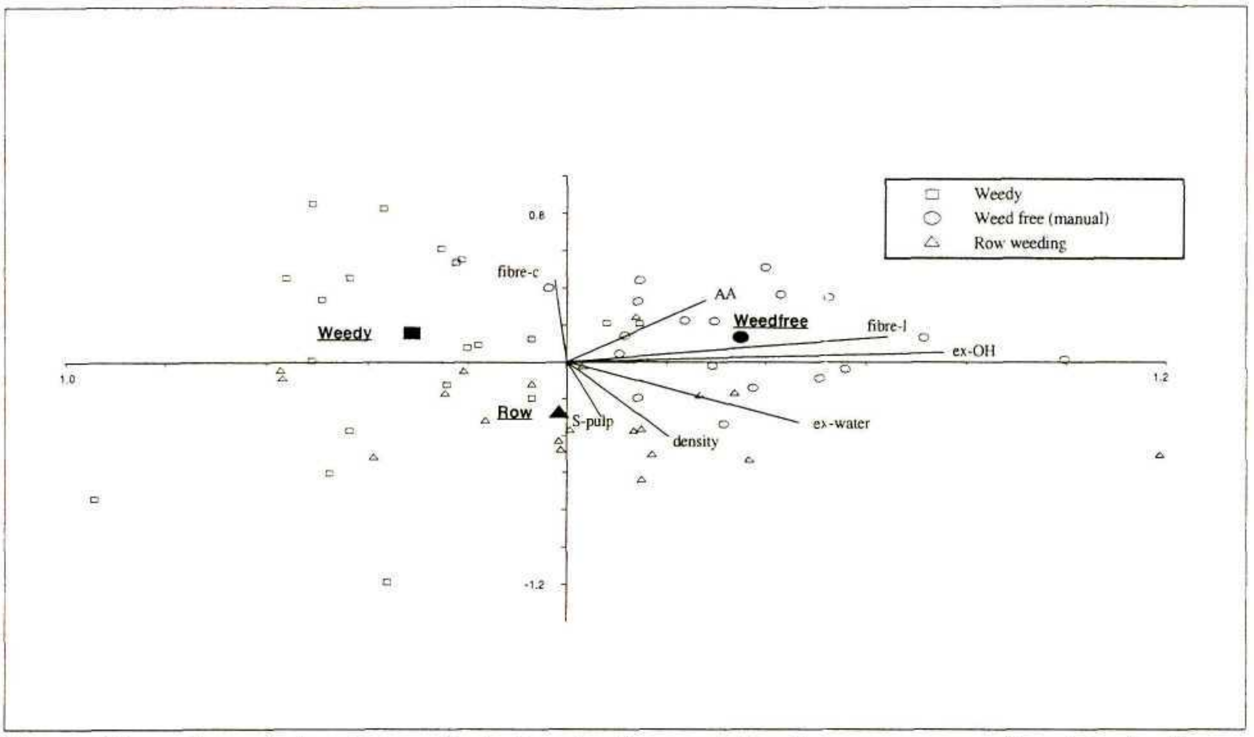


Figure 6.1: Canonical variate analysis showing the correlation between groups of variates for the three treatments. The unfilled symbols indicate individual trees in relation to the measured variates (lines) with the filled symbols indicate the treatment centroid. The vectors (lines) apply to the variates active alkali (AA), fibre length (fibre-l), alcohol extractive content (ex-OH), water extractive content (ex-water), 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.

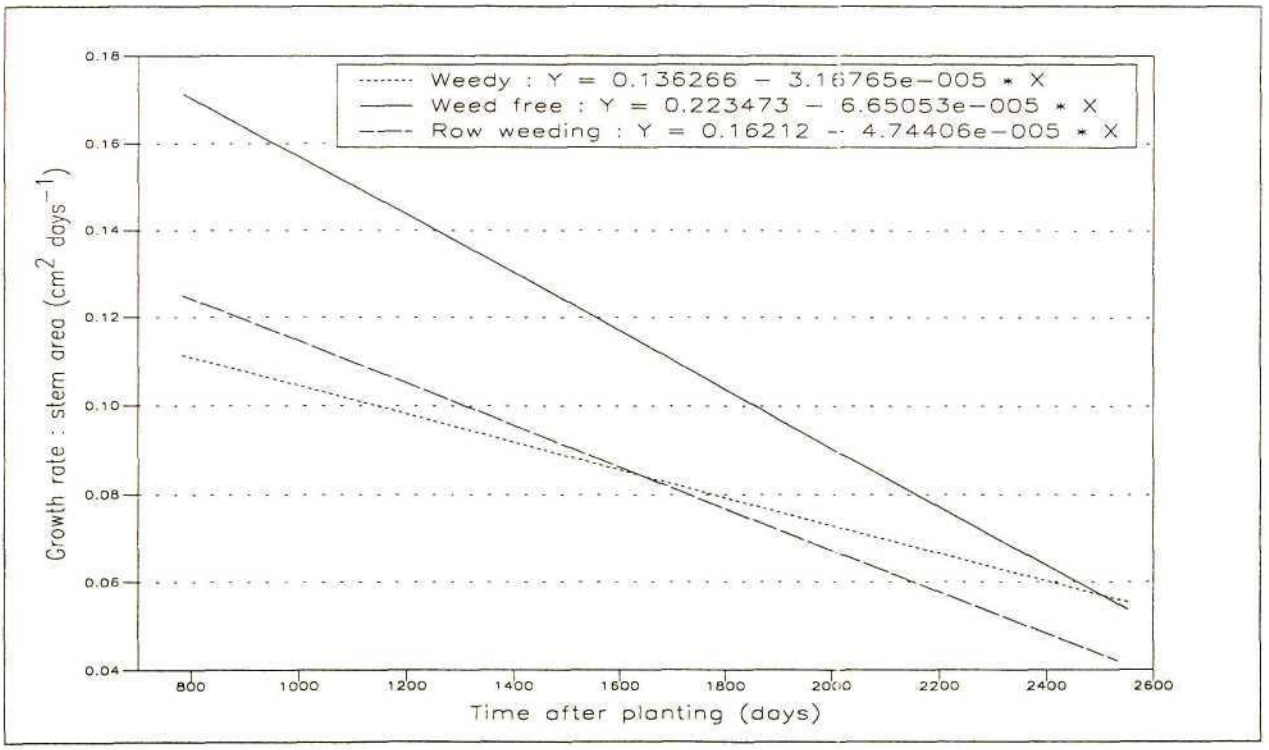


Figure 6.2: Linear regression performed on growth rates for the different stem area calculations.

CHAPTER 7

OVERALL CONCLUSIONS

In order to determine if 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, a *Eucalyptus* hybrid clone (GC304) was planted in a field trial initiated in 1990. The trial was situated in the coastal Zululand region near the KwaZulu-Natal town of Mtunzini. Nine different vegetation management treatments were imposed from establishment. These included a weedy control, a manually and chemically weeded treatment, a 1.2 m row and 1.2 m inter-row weeding, a 0.5 m radius ring weeding, a complete weeding except for a 0.5 m radius around the tree, and the use of two legume cover-crops, *Mucuna puriens* (cowpea) and *Vigna sinensis* (velvet bean).

Initial improvement in tree performance from these competition control treatments were detected from 60 days after planting, resulting in the differential growth of the trees. The degree of competition could be directly related to the type of vegetation (cover-crops or naturally occurring weeds) and its proximity to the tree. The predominant weed on this site, yellow nutsedge, was able to colonise the site rapidly, causing severe and early competition. There were strong indications that this initial competition was mainly for moisture and possibly also for nutrients, rather than competition for light. Initially trees in those treatments that had weeds within their immediate vicinity were most affected (weedy control, inter-row weeding and - ring weeding). With time, tree performance was more closely related to an increase in the percentage of the area kept free of weeds. At 180 days after planting the ranking of the five best performing treatments in relation to the area kept free of weeds was: manually weeded treatment (100 % of area free of weeds) > chemically weeded treatment (100 % of area free of weeds) > - ring weeding (90 % of area free of weeds) > row weeding (40 % of area free of weeds) > ring weeding (10 % of area free of weeds).

Two forms of competition (interspecific and intraspecific competition) were evident in the weedy control at different stages of tree development in contrast to the one (intraspecific competition) in the manually weeded treatment. Interspecific competition resulted in greater variability between the trees in the weedy control by the time canopy closure had occurred. This differentiation in tree size was further enhanced by asymmetric intraspecific competition once the trees had become established. The onset of intraspecific competition was first detected at 995 days after planting for the manually weeded treatment and at 1641 days after planting for the weedy control. Of the various competition indices that were tested in order to try and explain this differential growth in terms of individual tree performance, none were able to do so to complete satisfaction. The growth rates of different tree size classes were therefore compared for the weedy control and manually weeded treatment. The diverging slopes of the different stem area classes indicated that the larger trees were growing at the expense of the smaller trees. This type of competition is known as asymmetric intraspecific competition. In addition, a comparison was made between the slopes for the weedy and weedfree treatments for similar stem area classes. No significant difference was detected, indicating that similar size classes in these two treatments grew at similar rates.

When the trees were felled, various measurements were taken in order to calculate absolute rather than estimated parameters. There was a larger difference between the treatments in terms of diameter at breast height than in height. This was further demonstrated by comparing the taper for the different treatments. Trees in those treatments which experienced interspecific competition during establishment (weedy control, inter-row weeding and the cover-crops), were taller in relation to their diameters (lower taper). This may be due to intraspecific competition amongst the trees for light, where height growth occurs at the expense of diameter growth especially in those treatments with initial suppression. The differences in tree performance that were recorded during tree establishment were still significant when the trees were felled after seven years of growth. This occurred despite the absence of competition vegetation after the first growing season due to reduced light following crown canopy closure. This highlights the importance of vegetation management in young plantations due to the susceptibility of these trees to competition during this stage. The best performing treatment at felling, the manually weeded control, produced 17.1 % and 38.5 % more merchantable timber than the 1.2 m row weeding and the weedy control, at an increased profit of 8 % and 27 %, respectively.

Three selected treatments (manually weeded treatment, 1.2 m row weeding treatment and the weedy control) were tested for the wood and pulping properties of density, active alkali consumption, extractable content, screened pulp yield, pulp yield ha^{-1} and fibre length and coarseness. The use of Canonical Variate Analysis to determine if there were differences between the three treatments for the variates measured, indicated that they were significantly different. There was a significantly positive trend of an increase in density and alcohol extractable content with improved weed control. A possible explanation for this could be that the larger trees of the manually weeded treatment were under more stress (from increased intraspecific competition) during the latter phase of their growth. This was demonstrated by comparing the growth rates of these three treatments with the smaller trees of the 1.2 m row weeding treatment and the weedy control exhibiting a lower rate of decline. As no significant difference was detected between the screened pulp yield, any differences in the pulp yield per hectare values could be attributed to differences in the merchantable 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 the weedy control.

When deciding on a weed control strategy, numerous factors need to be taken into account. Firstly, the effects of input costs need to be considered together with final volume to determine the most profitable scenario. Secondly, the degree of risk associated with the carrying of high weed control costs through to felling needs to be considered. Weed control operations with high input costs may not always guarantee a significantly improved yield, putting them into a high risk category. Thirdly, the physical characteristics of the site need to be considered when choosing a viable weed control system. For example the larger the area weeded, especially as in the manually weeded treatments, the higher the risk of soil loss from the site. The degree of erosion would be further enhanced, as the gradient becomes steeper. On sites sensitive to erosion, weed control options should be aimed at the retention of some weed biomass on the site. This biomass should be retained in the area between the trees, as is practised for a ring and row weeding, or alternatively a cowpea cover-crop could be planted in the inter-row. Whatever minimum weeding option is selected, care will need to be taken to reduce any negative impact on tree growth. The retention of post-harvest residues, as is being increasingly practised in the Zululand region, will also limit the degree of manual weeding that can be carried out to that area immediately around the seedling. The planting of cover-crops, although beneficial in terms of weed suppression, caused significant tree suppression. This occurred despite the fact that their initial biomass accumulation was slower than that of the natural weed population. Of the two cover-crops, the use of a velvet bean cover-crop was not considered suitable due to its vigorous vining habit which affected the growth form of the trees. Subsequent work suggests that if the beneficial qualities of cowpeas are to be realised (that of weed suppression, erosion control and nitrogen fixation), a delay in their planting by three months should alleviate any negative impacts on trees.

This trial has been invaluable in terms of providing an understanding about the impacts of different methods of establishment vegetation management on longer term tree growth and performance, as no other data of this nature exist for *Eucalyptus* plantations grown in South Africa. This trial has also highlighted future research requirements, such as the determination of minimum row weeding distances and the optimization of tree and cover-crop planting dates to gain the maximum benefits of cover-crops without adversely affecting tree performance. Future research should include: the studying of the mechanisms responsible for any responses gained as this will allow the extrapolation of results to cover larger areas; the integration of the different methods of vegetation management to address long term site sustainability as well as other ecological issues; and the development of a comprehensive vegetation management programme of the most effective treatments at different phases of growth, taking both the costs as well as improved yields into account.

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INDEX OF APPENDICES

Appendix 1

Appendix 1.1: Treatment numbers associated with the weeding and cover-cropping treatments used in the appendices.

Number	Treatment	Method/species
1	Weedy	None
2	Weed free	Manual
3	Weed free	Chemical
4	Inter-row weeding (1.2 m width)	Manual
5	Ring weeding (0.5 m radius)	Manual
6	Complete weeding except ring[1] (0.5 m radius)	Manual
7	Row weeding (1.2 m width)	Manual
8	Cover-crop with weeding to establish	Cowpea
9	Cover-crop with weeding to establish	Velvet bean

[1] This treatment is described in the text and tables as a "- Ring weeding"

Appendix 2

Appendix 2.1: Treatment means for soil chemical and physical properties.

	Property measured	Sample depth	1	2	3	4	5	6	7	8	9
Soil physical properties	Sand (%)	0 - 15 cm	91.5	91	91	90.75	92.5	89.75	91.75	90.25	91.75
		50 - 65 cm	86.5	86	89	87	90.75	78.75	89	82.25	83
	Silt (%)	0 - 15 cm	4.75	4.75	5	5	4.25	5.5	5	5.75	5.25
		50 - 65 cm	4.5	4.5	4	4.25	3.25	4.25	4.25	4.5	4.5
	Clay (%)	0 - 15 cm	3.75	4.5	4	4.25	3.5	4.75	3.75	3.5	3
		50 - 65 cm	8.5	9.25	7	9	5.75	17	6.75	13.25	12.75
Soil chemical properties	Organic carbon (%)	0 - 15 cm	0.305	0.413	0.353	0.388	0.318	0.378	0.378	0.34	0.41
		50 - 65 cm	0.263	0.418	0.283	0.28	0.178	0.25	0.273	0.39	0.33
	Ca^{2+} ($cmol_c\ kg^{-1}$)	0 - 15 cm	0.397	0.345	0.337	0.42	0.35	0.47	0.477	0.35	0.48
		50 - 65 cm	0.27	0.237	0.217	0.452	0.225	0.327	0.225	0.302	0.537
	Mg^{2+} ($cmol_c\ kg^{-1}$)	0 - 15 cm	0.258	0.228	0.23	0.285	0.25	0.278	0.26	0.258	0.313
		50 - 65 cm	0.21	0.13	0.138	0.2	0.145	0.2	0.143	0.173	0.338
	K^{1+} ($cmol_c\ kg^{-1}$)	0 - 15 cm	0.038	0.035	0.038	0.038	0.032	0.053	0.053	0.045	0.04
		50 - 65 cm	0.03	0.025	0.015	0.023	0.015	0.015	0.01	0.04	0.015
	Na^{1+} ($cmol_c\ kg^{-1}$)	0 - 15 cm	0.058	0.07	0.058	0.06	0.055	0.073	0.055	0.058	0.065
		50 - 65 cm	0.07	0.11	0.063	0.083	0.065	0.085	0.078	0.095	0.055
	pH (KCl)	0 - 15 cm	3.975	3.925	4.028	4.115	4.067	4.213	4.105	4.027	4.067
		50 - 65 cm	3.968	3.87	3.789	3.955	3.975	3.925	3.89	4.035	4.155

Appendix 2.2: Summary of analysis of variance for soil physical and chemical properties.

Summary of analysis of variance												
		Mean squares										
Source of variation	DF	Sand (%)	Silt (%)	Clay (%)	pH (KCl)	Organic carbon (%)	Ca^{2+} (cmol$_c$ kg^{-1})	Mg^{2+} (cmol$_c$ kg^{-1})	K^{1+} (cmol$_c$ kg^{-1})	Na^{1+} (cmol$_c$ kg^{-1})	S_value (cmol$_c$ kg^{-1})
Replications	3	149.87	8.162	88.2	0.071	0.126	0.048	0.025	0.001	0.0016	0.152
Treatment	8	40.31^{ns}	1.156^{ns}	29.46^{ns}	0.039^{ns}	0.019^{ns}	0.048*	0.016^{ns}	0.002^{ns}	0.0009^{ns}	0.113*
Level	1	512.00**	11.68**	654.01**	0.202*	0.085^{ns}	0.154**	0.106**	0.074***	0.0052**	0.531**
Treatment.Level	8	21.06^{ns}	0.274^{ns}	25.98^{ns}	0.032^{ns}	0.008^{ns}	0.018^{ns}	0.036^{ns}	0.003^{ns}	0.0005^{ns}	0.032^{ns}
Trees (residual)	51	55.91	0.966	55.41	0.036	0.038	0.021	0.01	0.003	0.0007	0.053
Total	71										
Summary of data											
Grand Mean		88.47	4.62	6.9	4.005	0.33	0.357	0.224	0.031	0.069	0.681
Mean (0 - 15 cm)		91.14	5.03	3.89	4.058	0.364	0.403	0.262	0.041	0.061	0.767
Mean (50 - 65 cm)		85.81	4.22	9.92	3.952	0.296	0.311	0.186	0.021	0.078	0.596
Standard error (treatment.level)		5.287	0.695	5.264	0.134	0.138	0.102	0.071	0.012	0.019	0.162

Appendix 2.3: Bartlett's test for homogeneity of variance for tree height, crown diameter and diameter at breast height.

Variate	Date measured	Calculated x^2 values (corrected)
Height (m)	19/12/90	17.52*
	20/01/91	17.33*
	20/02/91	16.22*
	22/03/91	7.74^{ns}
	25/04/91	8.72^{ns}
	22/05/91	10.25^{ns}
	19/06/91	7.49^{ns}
	25/07/91	8.41^{ns}
	05/09/91	8.24^{ns}
	04/12/91	16.51*
	17/03/92	19.16*
	16/06/92	21.74*
Crown diameter (cm)	19/12/90	14.92^{ns}
	20/01/91	7.77^{ns}
	20/02/91	7.77^{ns}
	22/03/91	12.29^{ns}
Dbh_{ob} (cm)	16/06/92	15.57*
	28/09/92	13.68^{ns}
	14/12/92	11.01^{ns}
	24/03/93	8.42^{ns}
	13/07/93	7.38^{ns}
	11/05/94	8.26^{ns}
	20/04/95	8.41^{ns}
	29/05/96	9.83^{ns}

Note : The presence of heterogenous variance was detected where the calculated x^2 values (corrected) were greater than $x^2_{(8df)} = 15.51$ ($p<0.05$).

Appendix 2.4: Bartlett's test for homogeneity of variance for the tree variates when felled at seven years of age.

Variate	Calculated x^2 values (corrected)
Height (m)	19.82*
Dbh_{ob} (cm)	11.96^{ns}
Stem area (m^2)	9.68^{ns}
Basal area (m^2 ha^{-1})	8.10^{ns}
Total volume (m^3)	7.23^{ns}
Merchantable volume per hectare (m^3 ha^{-1})	7.62^{ns}
Bark thickness at 1.3 m (cm)	8.21^{ns}
Underbark diameter at 7 cm overbark (cm)	5.29^{ns}
Taper (m m^{-1})	0.72^{ns}

Note : The presence of heterogenous variance was detected where the calculated x^2 values (corrected) were greater than $x^2_{(8df)} = 15.51$ ($p<0.05$).

Appendix 3

Appendix 3.1: Treatment means, standard errors and *F*. probabilities for height measurements (m).

Variate measured	Date measured	Days after planting	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F*. pr.	*lsd* ($p<0.05$)
ht 1	19/12/90	58	0.384	0.421	0.388	0.356	0.357	0.405	0.365	0.372	0.395	0.383	0.0188	0.004	0.0369
ht 2	20/01/91	90	0.501	0.605	0.562	0.443	0.449	0.579	0.515	0.436	0.539	0.514	0.0268	<0.001	0.0528
ht 3	20/02/91	121	0.639	0.885	0.845	0.556	0.552	0.797	0.703	0.56	0.697	0.693	0.0417	<0.001	0.082
ht 4	22/03/91	151	0.761	1.105	1.004	0.696	0.685	0.958	0.888	0.744	0.882	0.858	0.0538	<0.001	0.1057
ht 5	25/04/91	185	0.919	1.416	1.252	0.875	0.854	1.171	1.154	1.013	0.903	1.062	0.0655	<0.001	0.1288
ht 6	22/05/91	212	1.008	1.686	1.451	0.979	0.956	1.352	1.304	1.189	1.059	1.22	0.0812	<0.001	0.1597
ht 7	19/06/91	240	1.108	1.9	1.662	1.112	1.079	1.537	1.461	1.342	1.194	1.377	0.09	<0.001	0.1769
ht 8	25/07/91	276	1.301	2.237	1.965	1.323	1.302	1.831	1.761	1.587	1.398	1.634	0.1012	<0.001	0.1991
ht 9	05/09/91	318	1.587	2.708	2.341	1.617	1.619	2.256	2.215	1.91	1.642	1.988	0.1179	<0.001	0.2317
ht 10	04/12/91	408	2.818	4.416	4.011	2.879	3.029	3.904	3.836	3.488	3.169	3.505	0.1645	<0.001	0.3233
ht 11	17/03/92	512	4.45	6.77	6.555	4.613	4.952	6.2	6.26	5.528	5.34	5.63	0.2348	<0.001	0.4616
ht 12	16/06/92	603	5.457	8.052	7.78	5.926	6.479	7.492	7.671	6.856	6.715	6.936	0.2774	<0.001	0.5453
Height (H_{top})	18/10/97	2553	16.48	19.54	18.82	17.45	18.53	18.91	18.78	18.61	18.41	18.39	0.559	<0.001	1.009
Height to 7 cm overbark ($H_{0.07}$)	18/10/97	2553	11.89	15.32	14.6	12.61	14.17	14.45	14.61	14.2	13.96	13.98	0.793	<0.001	1.56

Appendix 3.2: Treatment means, standard errors and *F.* probabilities for height growth rate measurements (m day^{-1}).

Variate measured	Date measured	Days between measurements	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F.* pr.	*lsd* (p<0.05)
GR_{ht} 1	20/01/91	32	0.0035	0.0057	0.0053	0.0029	0.0029	0.0054	0.0047	0.0019	0.0045	0.0041	0.0004	<0.001	0.0008
GR_{ht} 2	20/02/91	31	0.0045	0.0091	0.0091	0.0037	0.0033	0.0071	0.0060	0.0039	0.0051	0.0057	0.0007	<0.001	0.0014
GR_{ht} 3	22/03/91	30	0.0040	0.0072	0.0053	0.0047	0.0044	0.0054	0.0062	0.0061	0.0062	0.0055	0.0007	<0.001	0.0014
GR_{ht} 4	25/04/91	34	0.0047	0.0092	0.0073	0.0052	0.0050	0.0063	0.0078	0.0079	0.0006	0.0060	0.0009	<0.001	0.0018
GR_{ht} 5	22/05/91	27	0.0033	0.0100	0.0073	0.0039	0.0038	0.0067	0.0056	0.0065	0.0058	0.0059	0.0014	<0.001	0.0028
GR_{ht} 6	19/06/91	28	0.0036	0.0076	0.0075	0.0048	0.0044	0.0066	0.0056	0.0055	0.0048	0.0056	0.0013	<0.031	0.0027
GR_{ht} 7	25/07/91	36	0.0054	0.0094	0.0084	0.0059	0.0062	0.0082	0.0083	0.0068	0.0057	0.0071	0.0069	<0.001	0.0014
GR_{ht} 8	05/09/91	78	0.0037	0.0060	0.0048	0.0038	0.0041	0.0055	0.0058	0.0042	0.0031	0.0046	0.0004	<0.001	0.0008
GR_{ht} 9	04/12/91	90	0.0137	0.0190	0.0186	0.0140	0.0157	0.0183	0.0180	0.0175	0.0170	0.0169	0.0010	<0.001	0.0020
GR_{ht} 10	17/03/92	104	0.0157	0.0223	0.0245	0.0167	0.0185	0.0221	0.0233	0.0196	0.0209	0.0204	0.0011	<0.001	0.0022
GR_{ht} 11	16/06/92	91	0.0111	0.0141	0.0135	0.0144	0.0168	0.0142	0.0155	0.0146	0.0151	0.0144	0.0010	<0.001	0.0020

Appendix 3.3: Treatment means, standard errors and *F.* probabilities for crown diameter measurements (cm).

Variate measured	Date measured	Days after planting	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F.* pr.	*lsd* (p<0.05)
cr 1	19/12/90	58	26.56	38.68	32.74	23.94	30.88	30.39	36.42	31.46	35.64	31.86	2.304	<0.001	4.53
cr 2	20/01/91	90	23.4	57.42	50.33	22.74	36.36	36.4	48.89	33.76	45.9	39.47	3.071	<0.001	6.038
cr 3	20/02/91	121	41.6	94.6	83.1	36	60.6	64.8	81.1	45.1	70.8	64.2	4.33	<0.001	8.52
cr 4	22/03/91	151	60.3	120.8	107.6	56.5	76	88.2	102.7	63.3	73.2	83.2	5.29	<0.001	10.39

Appendix 3.4: Treatment means, standard errors and *F.* probabilities for crown diameter growth rate measurements (cm day^{-1}).

Variate measured	Date measured	Days between measurements	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F.* pr.	*lsd* (p<0.05)
GR_{cr} 1	20/01/91	32	-0.109	0.586	0.536	-0.026	0.172	0.188	0.389	0.056	0.321	0.2350	0.0591	<0.001	0.1162
GR_{cr} 2	20/02/91	31	0.588	1.198	1.056	0.427	0.783	0.916	1.038	0.349	0.803	0.7950	0.0793	<0.001	0.1559
GR_{cr} 3	22/03/91	30	0.622	0.875	0.818	0.684	0.514	0.781	0.721	0.606	0.080	0.6340	0.0901	<0.001	0.1772

Appendix 4

Appendix 4.1: Treatment means, standard errors and *F*. probabilities for diameter at breast height measurements (cm).

Variate measured	Date measured	Days after planting	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F*. pr.	*lsd* ($p<0.05$)
Dbh_{ob} 1	16/06/92	603	4.557	7.836	7.169	4.876	5.392	6.923	7.005	6.09	5.606	6.162	0.385	<.001	0.7576
Dbh_{ob} 2	28/09/92	707	5.24	8.95	7.99	5.71	6.46	7.73	7.87	6.8	6.52	7.03	0.424	<0.001	0.834
Dbh_{ob} 3	14/12/92	784	5.97	9.85	8.8	6.59	7.41	8.48	8.67	7.68	7.34	7.86	0.441	<0.001	0.868
Dbh_{ob} 4	24/03/93	884	6.86	10.82	9.57	7.58	8.48	9.31	9.49	8.61	8.19	8.77	0.475	<0.001	0.934
Dbh_{ob} 5	13/07/93	995	7.5	11.67	10.14	8.37	9.24	9.98	10.14	9.3	8.94	9.47	0.516	<0.001	1.015
Dbh_{ob} 6	11/05/94	1297	9.44	13.69	11.84	10.33	11.21	12	11.99	11.3	10.93	11.42	0.602	<0.001	1.184
Dbh_{ob} 7	20/04/95	1641	10.95	15.17	13.25	11.8	12.59	13.51	13.41	12.68	12.36	12.86	0.672	<0.001	1.322
Dbh_{ob} 8	29/05/96	2046	12.1	16.28	14.42	12.94	13.78	14.68	14.48	13.86	13.71	14.03	0.778	<0.001	1.529
Dbh_{ob} 9	18/10/97	2553	12.99	17.27	15.37	13.83	14.86	15.41	15.3	14.78	14.5	14.92	0.848	<0.001	1.667
Dbh_{ub}	18/10/97	2553	11.7	15.61	13.89	12.46	13.42	13.9	13.81	13.35	13.11	13.47	0.757	<0.001	1.488
$d_{0.07}$	18/10/97	2553	5.63	6.05	5.81	5.75	5.79	5.9	5.87	6.02	5.83	5.85	0.247	0.819	n.s.
Bark thickness	18/10/97	2553	1.28	1.65	1.47	1.36	1.44	1.51	1.49	1.43	1.39	1.45	0.095	0.016	0.187

Appendix 4.2: Treatment means, standard errors and *F*. probabilities for growth rate measurements (cm day $^{-1}$)(diameter at breast height).

Variate measured	Date measured	Days between measurements	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F*. pr.	*lsd* ($p<0.05$)
GR_{dbh} 1	28/09/92	104	0.0066	0.0107	0.0079	0.0080	0.0102	0.0078	0.0083	0.0068	0.0088	0.0083	0.0007	<0.001	0.0014
GR_{dbh} 2	14/12/92	77	0.0095	0.0116	0.0105	0.0115	0.0124	0.0097	0.0103	0.0114	0.0104	0.0108	0.0006	<0.001	0.0012
GR_{dbh} 3	24/03/93	100	0.0088	0.0098	0.0077	0.0099	0.0107	0.0084	0.0082	0.0093	0.0085	0.0090	0.0007	<0.001	0.0014
GR_{dbh} 4	13/07/93	111	0.0058	0.0077	0.0051	0.0071	0.0069	0.0060	0.0059	0.0062	0.0067	0.0064	0.0006	0.0020	0.0012
GR_{dbh} 5	11/05/94	302	0.0064	0.0067	0.0056	0.0065	0.0065	0.0067	0.0061	0.0067	0.0066	0.0064	0.0004	0.1050	n.s.
GR_{dbh} 6	20/04/95	344	0.0044	0.0043	0.0041	0.0043	0.0040	0.0044	0.0041	0.0040	0.0041	0.0042	0.0003	0.9150	n.s.
GR_{dbh} 7	29/05/96	405	0.0028	0.0027	0.0029	0.0028	0.0029	0.0029	0.0026	0.0029	0.0033	0.0030	0.0033	0.7080	n.s.
GR_{dbh} 8	18/10/97	507	0.0017	0.0019	0.0019	0.0017	0.0016	0.0014	0.0016	0.0018	0.0019	0.0017	0.0002	0.4930	n.s.

Appendix 4.3: Treatment means, standard errors and *F*. probabilities for stem area measurements (cm^2).

Variate measured	Date measured	Days after planting	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F*. pr.	*lsd* (p<0.05)
Stem area 1	16/06/92	603	21.6	50.2	42.1	24.1	26.6	40.5	41.2	33	26.5	33.9	3.5	<0.001	6.887
Stem area 2	28/09/92	707	27.6	65.2	52.2	31.9	36.7	50.1	51.7	40.6	35.7	43.5	4.34	<0.001	8.53
Stem area 3	14/12/92	784	34.3	78.7	63	40.8	47.4	59.8	62.4	50.6	45	53.5	5.1	<0.001	10.02
Stem area 4	24/03/93	884	43.9	95.2	74.5	52.7	61.5	72	74.6	62.6	55.8	65.9	6.16	<0.001	12.11
Stem area 5	13/07/93	995	52	110.6	83.9	63.8	73.1	82.8	85.1	72.6	66.7	76.7	7.25	<0.001	14.26
Stem area 6	11/05/94	1297	79.9	152.3	114.6	95.1	107.2	119.8	118.9	106.2	99.1	110.3	10.17	<0.001	20
Stem area 7	20/04/95	1641	106	187.5	143.5	123.2	134.8	152.3	148.9	133	125.9	139.4	12.67	<0.001	24.91
Stem area 8	29/05/96	2046	130	217.1	170.9	149.7	162.5	181.6	174.5	160.5	155.6	166.9	16.01	<0.001	31.47
Stem area 9	18/10/97	2553	150.3	245.2	194.7	172.6	186	201.1	196.1	183.7	174.6	189.4	18.67	<0.001	36.7

Appendix 4.4: Treatment means, standard errors and *F*. probabilities for stem area growth rate measurements (cm^2 day^{-1}).

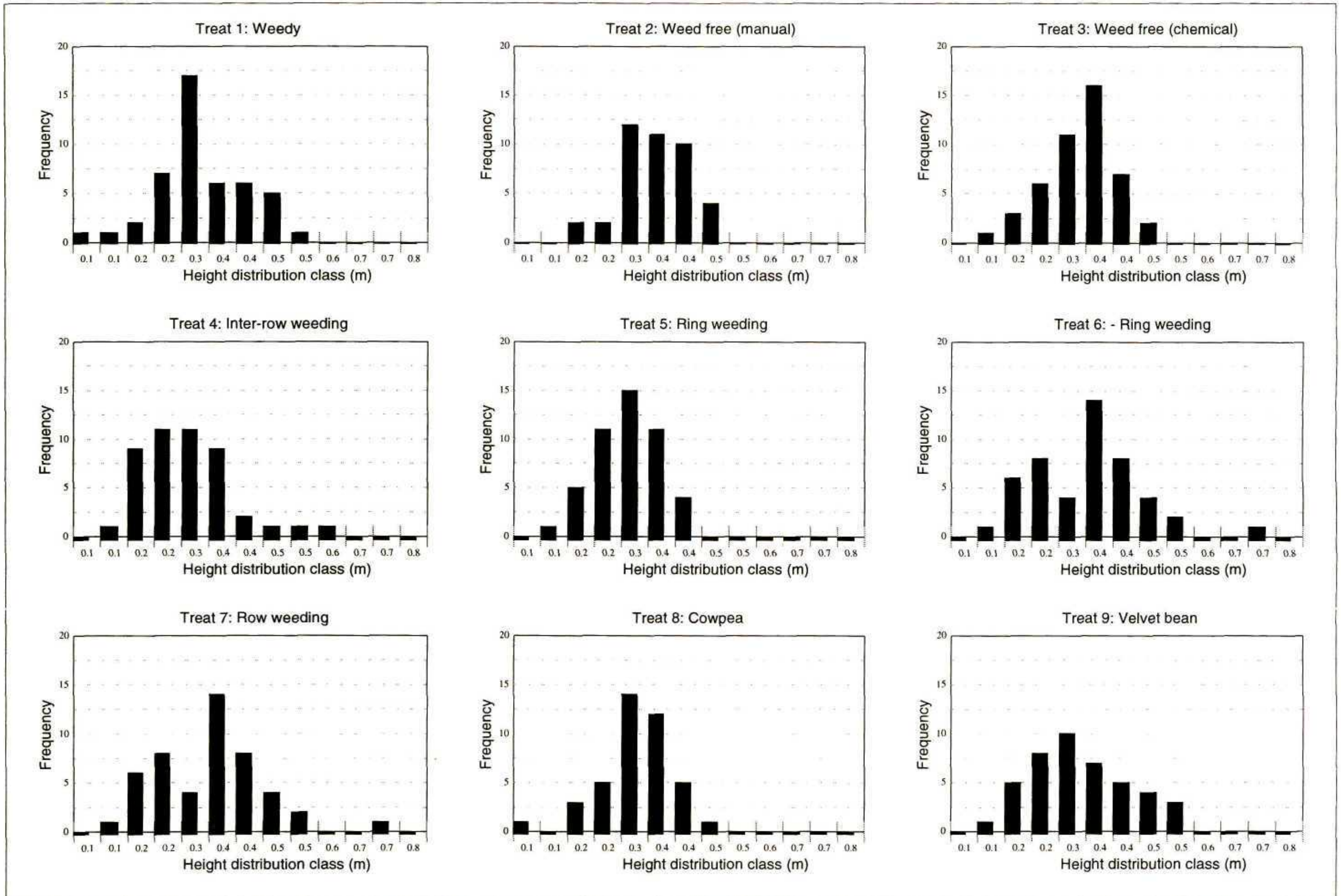
Variate measured	Date measured	Days between measurements	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F*. pr.	*lsd* (p<0.05)
$GR_{stem}1$	28/09/92	104	0.0586	0.1449	0.0971	0.0746	0.0979	0.0926	0.1011	0.0734	0.0889	0.0921	0.0104	<0.001	0.0205
$GR_{stem}2$	14/12/92	77	0.0863	0.1747	0.1402	0.1157	0.1380	0.1262	0.1387	0.1294	0.1200	0.1299	0.0122	<0.001	0.0239
$GR_{stem}3$	24/03/93	100	0.0959	0.1647	0.1151	0.1191	0.1413	0.1218	0.1220	0.1195	0.1085	0.1231	0.0139	<0.001	0.0274
$GR_{stem}4$	13/07/93	111	0.0733	0.1387	0.0843	0.1002	0.1048	0.0975	0.0954	0.0902	0.0982	0.0981	0.0126	<0.001	0.0249
$GR_{stem}5$	11/05/94	302	0.0923	0.1382	0.1018	0.1036	0.1127	0.1223	0.1117	0.1113	0.1071	0.1112	0.0105	0.0020	0.0207
$GR_{stem}6$	20/04/95	344	0.0758	0.1022	0.0841	0.0815	0.0802	0.0946	0.0873	0.0780	0.0779	0.0846	0.0092	0.0720	n.s.
$GR_{stem}7$	29/05/96	405	0.0593	0.0733	0.0675	0.0655	0.0684	0.0723	0.0633	0.0678	0.0734	0.0679	0.0095	0.8540	n.s.
$GR_{stem}8$	18/10/97	507	0.0388	0.0555	0.0470	0.0452	0.0398	0.0384	0.0424	0.0455	0.0447	0.0442	0.0073	0.4040	n.s.

Appendix 4.5: Treatment means, standard errors and *F.* probabilities for basal area ($m^2 ha^{-1}$) and stocking measurements (stems ha^{-1}).

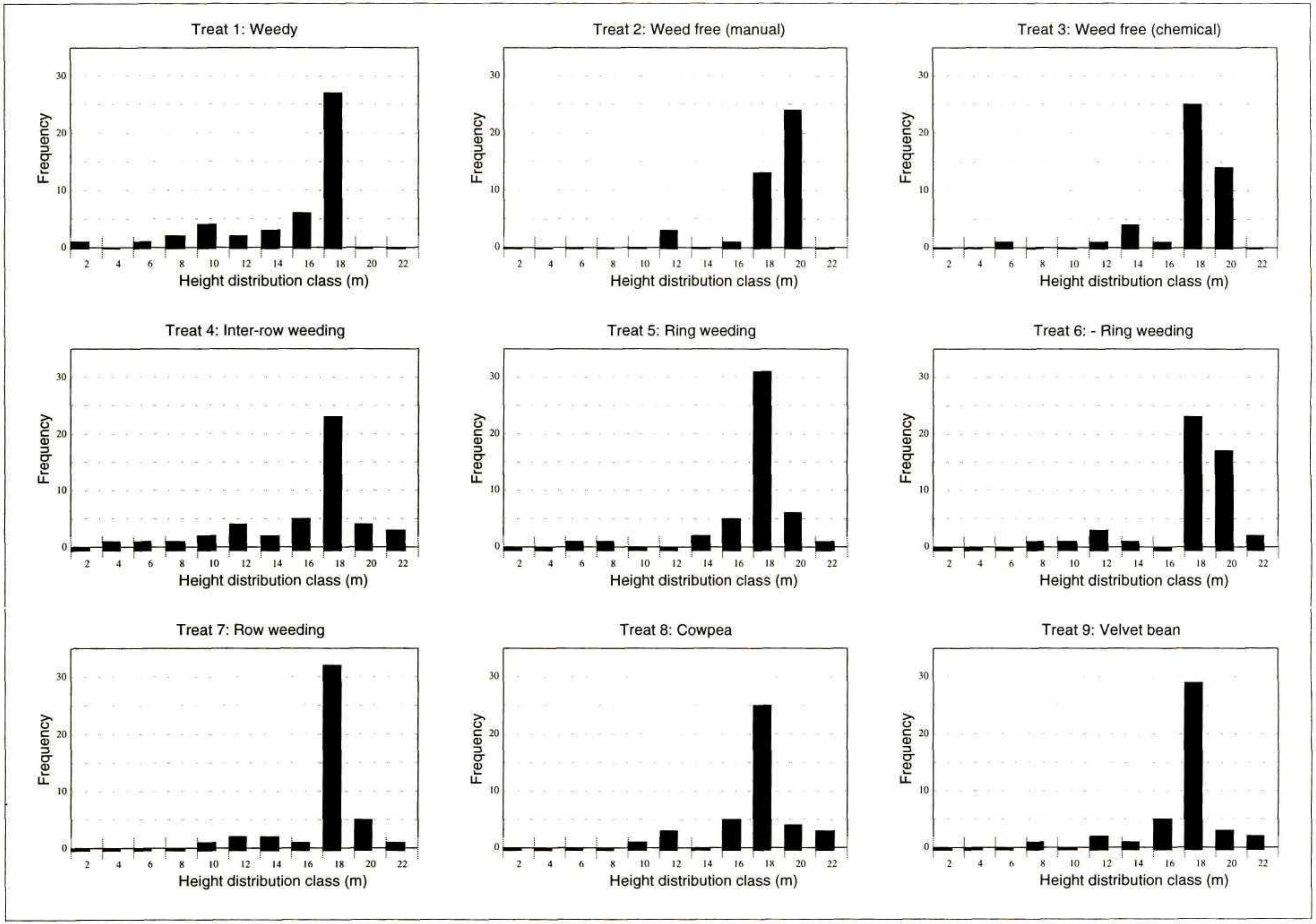
Variate measured	Date measured	Days after planting	1	2	3	4	5	6	7	8	9	grand mean	s.e.d.	*F.* pr.	*lsd* (p<0.05)
Basal area 1	16/06/92	603	2.76	5.72	5.37	3.05	3.54	5.4	5.05	3.77	3.22	4.21	0.798	0	1.647
Basal area 2	28/09/92	707	3.54	7.43	6.66	4.04	4.9	6.68	6.33	4.63	4.35	5.4	0.992	0	2.048
Basal area 3	14/12/92	784	4.39	8.96	8.05	5.18	6.32	7.98	7.63	5.76	5.48	6.64	1.174	0.01	2.423
Basal area 4	24/03/93	884	5.61	10.83	9.52	6.69	8.2	9.6	9.12	7.1	6.82	8.16	1.308	0.01	2.699
Basal area 5	13/07/93	995	6.64	12.58	10.72	8.1	9.75	11.04	10.41	8.22	8.16	9.51	1.443	0.01	2.979
Basal area 6	11/05/94	1297	10.2	17.33	14.66	12.09	14.29	15.97	14.52	12.03	12.12	13.69	1.826	0.017	3.768
Basal area 7	20/04/95	1641	13.53	21.34	18.36	15.67	17.97	20.31	18.19	15.06	15.39	17.31	2.152	0.021	4.442
Basal area 8	29/05/96	2046	16.58	24.73	21.86	19.05	21.66	24.21	21.31	18.16	19.04	20.73	2.412	0.035	4.979
Basal area 9ob	18/10/97	2553	18.71	27.93	24.91	21.98	24.3	26.81	23.94	20.79	20.87	23.36	2.581	0.027	5.326
Basal area 9ub	18/10/97	2553	15.17	22.8	20.33	17.82	19.8	21.78	19.49	16.94	17.03	19.02	2.095	0.024	4.323
Basal area (trees over 7 cm diam.)	18/10/97	2553	18.24	27.84	24.91	21.77	24.23	26.71	23.75	20.61	20.73	23.2	2.706	0.031	5.585
Stocking (all trees)	18/10/97	2553	1250	1139	1278	1278	1305	1333	1222	1139	1194	1238	79.8	0.202	n.s.
Stocking (trees over 7 cm diam.)	18/10/97	2553	1028	1111	1278	1139	1250	1278	1167	1083	1139	1163	113.9	0.339	n.s.

Appendix 4.6: Normal order scores used in the normal order plots of Figures 4.2 and 4.3.

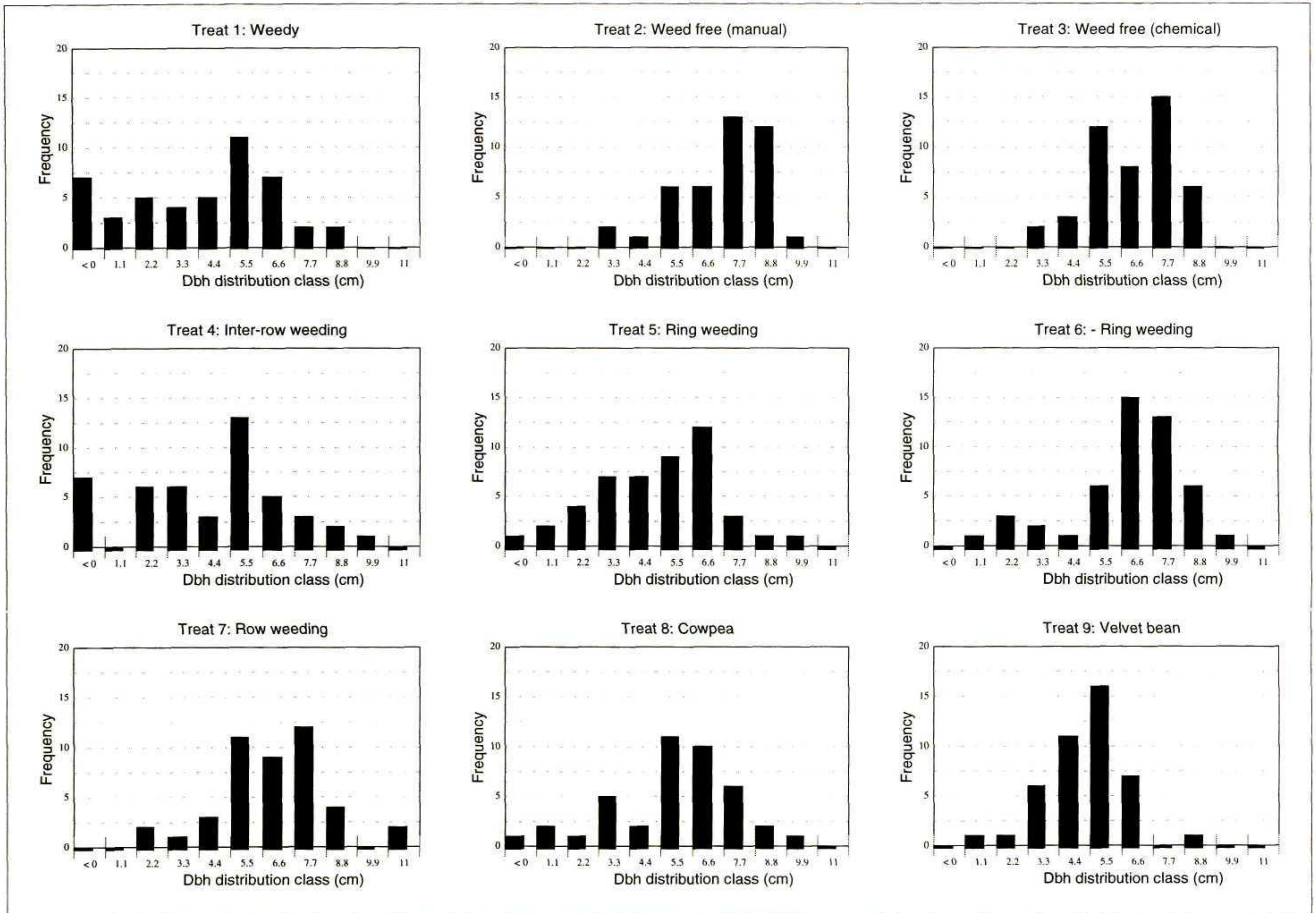
	Stem area		Basal area	
Normal order scores	Treatment means (cm^2)	Treatment labels	Treatment means (m^2 ha^{-1})	Treatment labels
1.49	245.2	2	27.93	2
0.93	201.1	6	26.81	6
0.57	196.1	7	24.91	3
0.27	194.7	3	24.3	5
0	186	5	23.94	7
-0.27	183.7	8	21.98	4
-0.57	174.6	9	20.87	9
-0.93	172.6	4	20.79	8
-1.49	150.3	1	18.71	1
Standard error of the grand mean	13.2		1.825	



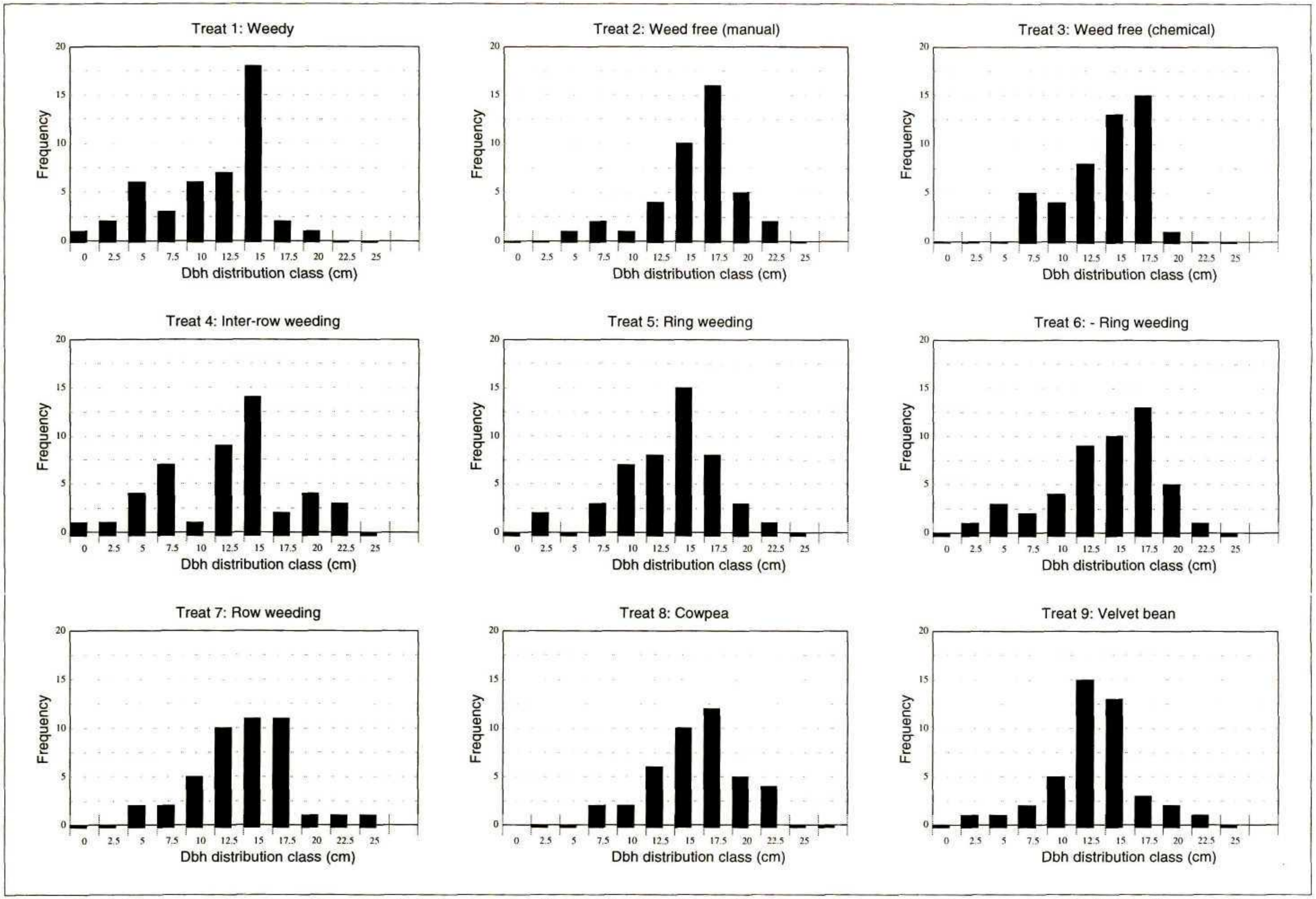
Appendix 4.7: Height frequency distribution for the different treatments when the trees were 2 months of age.



Appendix 4.8: Height frequency distribution for the different treatments when the trees were felled at 7 years of age.



Appendix 4.9: Diameter at breast height frequency distribution for the different treatments when the trees were 20 months of age.



Appendix 4.10: Diameter at breast height frequency distribution for the different treatments when the trees were felled at 7 years of age.

Appendix 4.11: Summary of simple linear regression for competition indices and diameter at breast height when felled.

Summary of simple linear regression analysis with treatments as groups

		Mean squares								
Source of variation	DF	CI_1 2.5 m	CI_1 3 m	CI_1 4 m	CI_2 2.5 m	CI_2 3 m	CI_2 4 m	CI_3 2.5 m	CI_3 3 m	CI_3 4 m
Regression	1	3629.7***	3954.1***	4511.2***	241.1***	3917.6***	4543.2***	7.32^{ns}	18.78^{ns}	2.20^{ns}
Residual	399	9.33	8.52	7.12	17.82	8.61	7.04	18.41	18.38	18.42
Total	400	18.38	18.38	18.38	18.38	18.38	18.38	18.38	18.38	18.38
r^2		49.2	53.7	61.3	3	53.2	61.7	0	0	0
Estimate of parameters										
Constant		19.52***	19.78***	20.87***	15.49***	19.61***	20.99***	15.33***	15.81***	14.47***
CI		-5.52***	-3.11***	-2.25***	-0.19***	-1.09***	-0.72***	-0.04^{ns}	-0.05^{ns}	0.01^{ns}

Appendix 4.12: Students *t*-test between slopes for different stem area classes of unequal sizes: Weedy control.

Stem area class (expressed as dbh class)	0 - 5 cm vs. 5 - 10 cm		5 - 10 cm vs. 10 - 15 cm		10 - 15 cm vs. 15 - 20 cm	
	0 - 5 cm	5 - 10 cm	5 - 10 cm	10 - 15 cm	10 - 15 cm	15 - 20 cm
Mean	0.0056	0.0215	0.0215	0.0645	0.0645	0.0977
Variance	0.0002	0.0009	0.0009	0.0003	0.0003	0.0008
n	3	9	9	12	12	20
df	10		19		30	
$t_{(calc)}$	-2.74*		-6.86*		-7.32*	
$t_{(0.05)}$	2.23		2.09		2.04	

Appendix 4.13: Students *t*-test between slopes for different stem area classes of unequal sizes: Weedfree (manual).

Stem area class (expressed as dbh class)	5 - 10 cm vs. 10 - 15 cm		10 - 15 cm vs. 15 - 20 cm		15 - 20 cm vs. 20 - 25 cm	
	5 - 10 cm	10 - 15 cm	10 - 15 cm	15 - 20 cm	15 - 20 cm	20 - 25 cm
Mean	0.0185	0.0545	0.0545	0.1055	0.1055	0.1624
Variance	0.0005	0.0002	0.0002	0.0003	0.0003	0.0004
n	3	5	5	26	26	7
df	6		29		31	
$t_{(calc)}$	-4.22*		-6.54*		-7.82*	
$t_{(0.05)}$	2.44		2.04		2.04	

Appendix 4.14: Students *t*-test between slopes for different stem area classes of unequal sizes: Weedy control vs. Weedfree (manual).

Stem area class (expressed as dbh class)	5 - 10 cm		10 - 15 cm		15 - 20 cm	
	Weedy	Weed-free	Weedy	Weed-free	Weedy	Weed-free
Mean	0.0215	0.0185	0.0645	0.0545	0.0977	0.1055
Variance	0.0009	0.0005	0.0003	0.0002	0.0008	0.0003
n	9	3	12	5	20	26
df	10		15		44	
$t_{(calc)}$	0.49^{ns}		1.17^{ns}		-1.93^{ns}	
$t_{(0.05)}$	2.23		2.13		2.02	

Appendix 5

Appendix 5.1: Summary of simple linear regression of bark thickness (cm) and diameter at breast height (cm).

Source of variation	d.f.	s.s.	m.s.	v.r.	*F*. prob
Regression	1	83.823	83.823	5622.22	<0.001
Residual	399	5.949	0.0149		
Total	400	89.772	0.2244		
r^2		93.4			
Std. Error		0.122			

Estimate of parameters

	Estimate	s.e.	*t*(399)	*t* pr.
constant	-0.1455	0.0221	-6.59	<0.001
diameter at breast height	0.10677	0.0014	74.98	<0.001

Appendix 6

Appendix 6.1: Individual tree and pulping data for the Weedy Control (Treatment 1).

Treat. no.	Rep. no.	Plot no.	Tree no.	Top height (m)	Dbh overbark (cm)	Daim. last disc (mm)	Merch. tree vol. (m^3)	Merch. vol. hectare (m^3 ha^{-1})	Density Dbh (kg m^{-3})	Weighted density (kg m^{-3})	Timber yield (tons ha^{-1})	Fibre length (wtd. mean) (mm)	Fibre coarseness (mg m^{-1})	Alcohol extractives (%)	Hot water extractives (%)	Total extractives (%)	Active alkali (%)	Screened pulp (%)	Pulp yield per hectare (tons ha^{-1})
1	1	15	4	19.4	15.9	0.053	0.161	166	505.39	524.38	87.05	0.72	0.065	1.33	2.77	4.10	83.4	51.1	44.48
1	1	15	5	19.5	15.3	0.052	0.147	151.04	508.67	517.62	78.18	0.73	0.06	1.24	2.53	3.77	91.3	51	39.87
1	1	15	6	19.5	16.9	0.05	0.168	172.41	547.99	525.09	90.53	0.72	0.061	1.39	2.79	4.18	91.3	51	46.17
1	1	15	7	19.2	17.5	0.064	0.165	169.64	515.55	522.52	88.64	0.72	0.059	1.44	3.14	4.58	86.9	50.9	45.12
1	1	15	12	19.4	17.0	0.050	0.171	175.70	509.46	507.93	89.24	0.72	0.065	1.37	3.10	4.47	93	51.2	45.69
1	2	18	2	17.8	11.4	0.056	0.069	70.92	517.54	500.33	35.48	0.74	0.06	1.04	2.26	3.30	96.5	51.4	18.24
1	2	18	5	19.1	16.3	0.059	0.159	163.01	509.25	527.85	86.04	0.78	0.062	1.38	2.28	3.66	90.4	51.7	44.48
1	2	18	8	19.0	16.2	0.061	0.151	154.74	507.09	536.86	83.07	0.74	0.065	1.40	2.56	3.96	93	50.6	42.04
1	2	18	10	18.8	16.5	0.058	0.169	174.10	506.92	529.86	92.25	0.74	0.066	1.30	2.71	4.01	93	50.4	46.49
1	2	18	11	19.5	17.4	0.059	0.184	189.58	569.08	533.13	101.07	0.76	0.071	1.78	2.35	4.13	93	50.3	50.84
1	3	7	2	14.7	9.1	0.055	0.031	31.71	443.17	464.55	14.73	0.73	0.063	1.04	2.24	3.28	86.9	52.5	7.73
1	3	7	5	18.1	14.1	0.068	0.117	120.28	382.32	427.84	51.46	0.77	0.062	1.35	1.17	2.52	88.7	52.5	27.02
1	3	7	6	18.2	14.2	0.055	0.122	125.67	488.41	493.64	62.04	0.77	0.06	1.26	1.89	3.15	93.9	52.4	32.51
1	3	7	7	18.6	16.6	0.059	0.168	173.22	486.83	530.25	91.85	0.76	0.068	1.41	2.53	3.94	92.2	51.6	47.39
1	3	7	12	17.3	14.0	0.054	0.124	127.31	534.87	539.69	68.71	0.77	0.065	1.42	2.12	3.54	92.2	52.3	35.94
1	4	36	3	16.9	11.2	0.051	0.065	66.91	480.44	493.92	33.05	0.76	0.072	1.07	1.93	3.00	92.2	52.1	17.22
1	4	36	4	18.0	11.3	0.058	0.069	71.36	483.56	508.16	36.26	0.73	0.069	1.25	2.27	3.52	92.7	52.2	18.93
1	4	36	5	18.6	22.0	0.058	0.296	303.81	543.04	549.49	166.94	0.78	0.074	1.77	3.36	5.13	92.2	51	85.14
1	4	36	7	17.7	14.8	0.056	0.128	131.68	500.10	452.22	59.55	0.75	0.062	1.17	2.49	3.66	91.3	51.2	30.49
1	4	36	8	10.9	6.9	0.049	0.011	11.07	440.35	506.07	5.60	0.72	0.078	1.37	2.40	3.77	93.7	51	2.86
Mean				18.0	14.7	0.056	0.134	137.51	499.00	509.57	71.09	0.75	0.07	1.34	2.44	3.78	91.39	51.42	36.43
Standard error				0.5	0.8	0.001	0.014	14.53	9.27	6.93	8.05	0.00	0.001	0.04	0.11	0.13	0.659	0.157	4.08
CV %				11.3	23.1	8.630	47.243	47.24	8.31	6.08	50.67	2.9	7.98	14.51	19.96	15.65	3.22	1.37	50.09

Appendix 6.2: Individual tree and pulping data for the Manually weeded treatment (Treatment 2).

Treat. no.	Rep. no.	Plot no.	Tree no.	Top height (m)	Dbh overbark (cm)	Daim. last disc (mm)	Merch. tree vol. (m^3)	Merch. vol. hectare (m^3 ha^{-1})	Density Dbh (kg m^{-3})	Weighted density (kg m^{-3})	Timber yield (tons ha^{-1})	Fibre length (wtd. mean) (mm)	Fibre coarseness (mg m^{-1})	Alcohol extractives (%)	Hot water extractives (%)	Total extractives (%)	Active alkali (%)	Screened pulp (%)	Pulp yield per hectare (tons ha^{-1})
2	1	3	3	20.1	17.8	0.056	0.184	204.35	493.88	522.01	106.67	0.77	0.065	1.58	3.04	4.62	92.2	51.2	54.62
2	1	3	4	19.9	15.2	0.050	0.151	167.76	489.49	533.04	89.42	0.78	0.065	1.28	2.78	4.06	93	52.2	46.68
2	1	3	7	19.6	17.1	0.062	0.170	188.46	547.86	529.30	99.75	0.76	0.067	1.85	3.48	5.33	93	51.5	51.37
2	1	3	8	20.1	16.8	0.058	0.177	196.39	509.57	515.90	101.32	0.78	0.069	1.4	2.60	4.00	93.9	51.9	52.58
2	1	3	11	20.1	18.6	0.065	0.221	245.48	544.85	520.66	127.81	0.77	0.065	2.20	3.34	5.54	92.2	51.2	65.44
2	2	6	2	20.1	17.4	0.059	0.195	216.65	516.17	533.72	115.63	0.77	0.066	1.73	2.86	4.59	92.6	51.7	59.78
2	2	6	4	20.1	19.0	0.068	0.226	250.54	531.47	520.99	130.53	0.8	0.068	1.76	2.96	4.72	91.6	50.9	66.44
2	2	6	5	19.7	19.3	0.055	0.214	237.96	493.08	503.80	119.88	0.76	0.067	1.62	2.71	4.33	91.6	51.1	61.26
2	2	6	7	20.3	19.7	0.054	0.226	251.59	558.63	529.63	133.25	0.78	0.065	2.42	3.44	5.86	92.3	51.4	68.49
2	2	6	11	20.4	18.9	0.055	0.218	242.07	494.70	524.78	127.04	0.76	0.066	1.95	2.86	4.81	92.4	51.2	65.04
2	3	33	6	19.9	19.3	0.052	0.222	246.11	564.34	535.99	131.91	0.78	0.064	1.62	2.94	4.56	93	51.9	68.46
2	3	33	8	20.1	16.4	0.050	0.169	187.46	497.83	497.93	93.34	0.77	0.063	1.59	2.93	4.52	92	51.4	47.98
2	3	33	10	17.6	11.1	0.048	0.066	73.07	485.41	511.25	37.36	0.72	0.061	1.25	1.94	3.19	91	51.6	19.28
2	3	33	11	19.4	14.3	0.056	0.124	137.37	530.04	520.17	71.46	0.75	0.06	1.60	2.57	4.17	92.3	52.3	37.37
2	3	33	12	20.0	16.9	0.055	0.168	186.66	533.33	494.55	92.31	0.79	0.068	1.89	2.36	4.25	92.1	51.8	47.82
2	4	11	1	19.9	17.5	0.048	0.219	243.27	513.02	508.53	123.71	0.79	0.061	1.91	2.52	4.43	92.8	51.4	63.59
2	4	11	2	20.0	23.2	0.057	0.344	381.92	549.08	535.62	204.56	0.78	0.061	1.99	3.21	5.20	91.9	51.2	104.74
2	4	11	4	21.2	22.1	0.061	0.310	344.30	511.71	517.29	178.10	0.78	0.064	1.56	2.20	3.76	91.9	52.1	92.79
2	4	11	5	21.6	20.0	0.066	0.268	297.94	540.32	516.87	154.00	0.77	0.065	2.03	3.01	5.04	92.3	51.3	79.00
2	4	11	9	21.3	20.4	0.074	0.265	294.04	528.67	520.43	153.03	0.78	0.069	2.09	3.20	5.29	92.2	51.1	78.20
Mean				20.1	18.1	0.057	0.207	229.67	521.67	519.62	119.55	0.77	0.06	1.77	2.85	4.61	92.32	51.52	61.55
Standard error				0.2	0.6	0.002	0.014	15.48	5.49	2.67	8.25	0	0.001	0.07	0.09	0.14	0.141	0.090	4.22
CV %				4.0	14.9	12.013	30.148	30.15	4.70	2.30	30.87	2.21	4.16	17.11	14.16	13.93	0.68	0.78	30.68

Appendix 6.3: Individual tree and pulping data for the 1.2 m Row weeding treatment (Treatment 4).

Treat. no.	Rep. no.	Plot no.	Tree no.	Top height (m)	Dbh overbark (cm)	Daim. last disc (mm)	Merch. tree vol. (m^3)	Merch. vol. hectare (m^3 ha^{-1})	Density Dbh (kg m^{-3})	Weighted density (kg m^{-3})	Timber yield (tons ha^{-1})	Fibre length (wtd. mean) (mm)	Fibre coarseness (mg m^{-1})	Alcohol extractives (%)	Hot water extractives (%)	Total extractives (%)	Active alkali (%)	Screened pulp (%)	Pulp yield per hectare (tons ha^{-1})
7	1	1	1	13.8	7.5	0.055	0.021	24.65	482.13	504.83	12.44	0.69	0.061	1.42	1.61	3.03	91	51.8	6.45
7	1	1	6	20.1	18.6	0.076	0.204	237.58	515.00	536.57	127.48	0.77	0.062	1.78	2.37	4.15	90.1	51.4	65.52
7	1	1	8	19.7	12.9	0.053	0.104	121.12	503.70	522.00	63.23	0.76	0.063	1.83	2.88	4.71	89.2	52.2	33.00
7	1	1	10	19.8	17.6	0.065	0.172	200.74	536.90	531.66	106.73	0.75	0.064	1.73	3.16	4.89	90	51.5	54.96
7	1	1	12	19.5	15.5	0.060	0.155	180.33	528.46	530.73	95.71	0.75	0.067	2.08	3.40	5.48	89.2	51	48.81
7	2	16	1	19.8	17.5	0.065	0.190	221.27	529.74	551.12	121.95	0.77	0.064	2.21	2.77	4.98	87.9	51.2	62.44
7	2	16	4	14.7	11.1	0.065	0.062	72.62	495.57	504.61	36.65	0.71	0.064	1.30	2.51	3.81	91.3	51.9	19.02
7	2	16	8	19.9	17.7	0.050	0.182	212.43	535.64	528.85	112.34	0.76	0.064	1.78	3.90	5.68	90.8	50.8	57.07
7	2	16	9	19.6	16.6	0.049	0.156	182.13	572.18	551.98	100.53	0.76	0.062	1.21	3.49	4.70	92.2	51	51.27
7	2	16	12	19.5	16.5	0.058	0.176	205.95	547.40	554.83	114.27	0.75	0.063	1.09	3.66	4.75	90.5	50.9	58.16
7	3	20	2	19.8	18.4	0.052	0.207	241.70	517.58	500.59	120.99	0.80	0.062	1.59	2.95	4.54	90.4	51.1	61.83
7	3	20	3	17.0	12.4	0.052	0.095	111.41	489.72	510.41	56.87	0.76	0.06	1.46	2.29	3.75	89.9	52.3	29.74
7	3	20	8	19.5	17.2	0.057	0.187	218.13	479.70	516.56	112.68	0.74	0.065	1.21	3.06	4.27	90.7	52.2	58.82
7	3	20	9	18.9	13.8	0.057	0.109	127.03	552.56	509.12	64.67	0.76	0.06	1.45	2.67	4.12	89.8	51.2	33.11
7	3	20	12	19.2	14.1	0.056	0.119	138.97	499.38	505.62	70.26	0.75	0.065	1.31	2.71	4.02	89.5	52.4	36.82
7	4	34	1	18.6	15.0	0.054	0.127	148.05	537.59	525.20	77.76	0.77	0.066	1.36	3.34	4.70	89.6	52	40.43
7	4	34	4	19.5	15.8	0.050	0.149	174.30	507.72	526.70	91.80	0.76	0.058	1.75	2.85	4.60	88.3	51.8	47.55
7	4	34	8	23.2	25.5	0.052	0.414	483.58	593.69	611.70	295.81	0.82	0.066	1.68	3.01	4.69	92.8	51.6	152.64
7	4	34	9	18.6	12.3	0.061	0.078	91.37	552.63	511.90	46.77	0.75	0.063	1.25	2.22	3.47	93.8	52.4	24.51
7	4	34	10	14.9	8.6	0.053	0.031	35.78	479.77	485.59	17.37	0.71	0.068	0.96	1.96	2.92	90.4	52.5	9.12
Mean				18.8	15.2	0.057	0.147	171.46	522.85	526.03	92.32	0.75	0.06	1.52	2.84	4.36	90.37	51.66	47.56
Standard error				0.5	0.9	0.002	0.019	21.84	7.06	6.09	13.25	0.01	0.001	0.07	0.13	0.16	0.315	0.126	6.81
CV %				11.5	26.0	11.817	56.953	56.95	6.04	5.18	64.16	3.81	3.94	21.57	20.32	16.55	1.56	1.09	64.00

Appendix 6.4: Bartlett's test for homogeneity of variance

Variate	Calculated x^2 values (corrected)
Height (m)	8.0774*
Dbh_{ob} (cm)	3.407^{ns}
Diam. of last disc (cm)	0.462^{ns}
Merchantable volume per tree (m^3)	5.255^{ns}
Merchantable volume per hectare (m^3 ha^{-1})	5.253^{ns}
Weighted mean density (kg m^3)	2.582^{ns}
Density at breast height (kg m^3)	5.285^{ns}
Timber yield (tons ha^{-1})	3.453^{ns}
Fibre length (weighted mean) (mm)	1.865^{ns}
Fibre coarseness (mg m^{-1})	6.289*
Hot water extractives (%)	0.616^{ns}
Ethanol Benzene extractives (%)	5.050^{ns}
Total Extractives (%)	0.099^{ns}
Screened pulp yield (%)	0.766^{ns}
Active alkali (%)	7.251*
Pulp yield per hectare (tons ha^{-1})	3.510^{ns}

Note : The presence of heterogenous variance was detected where the calculated x^2 values (corrected) were greater than $x^2_{(2df)} = 5.991$ ($p<0.05$).

Appendix 6.5: Fisher-Behrens test for samples with unequal variances: Height (m).

	Weedy vs. Weed free		Weedy vs. Row weeding		Weed free vs. Row weeding	
	Weedy	Weed free	Weedy	Row weed	Weed free	Row weed
Mean	18.01	20.07	18.01	18.78	20.07	18.78
Variance	4.15	0.65	4.15	4.69	0.65	4.69
n	20	20	20	20	20	20
df	25		38		24	
$t_{(calc)}$	4.21*		-1.158^{ns}		2.496*	
$t_{(0.05)}$	2.06		2.024		2.064	

Appendix 6.6: Fisher-Behrens test for samples with unequal variances: Fibre coarseness (mg m^{-1}).

	Weedy vs. Weed free		Weedy vs. Row weeding		Weed free vs. Row weeding	
	Weedy	Weed free	Weedy	Row weed	Weed free	Row weed
Mean	0.0654	0.0649	0.0654	0.0633	0.0649	0.0633
Variance	2.719^{-05}	7.313^{-06}	2.719^{-05}	6.239^{-06}	7.313^{-06}	6.239^{-06}
n	20	20	20	20	20	20
df	29		27		38	
$t_{(calc)}$	0.305^{ns}		1.547^{ns}		1.944^{ns}	
$t_{(0.05)}$	2.045		2.052		2.024	

Appendix 6.7: Fisher-Behrens test for samples with unequal variances: Active alkali (%).

	Weedy vs. Weed free		Weedy vs. Row weeding		Weed free vs. Row weeding	
	Weedy	Weed free	Weedy	Row weed	Weed free	Row weed
Mean	91.39	92.31	91.39	90.37	92.31	90.37
Variance	8.677	0.396	8.677	1.991	0.396	1.991
n	20	20	20	20	20	20
df	21		27		26	
$t_{(calc)}$	1.37^{ns}		1.39^{ns}		5.63*	
$t_{(0.05)}$	2.08		2.05		2.05	

Appendix 6.8: 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

Appendix 6.9: Latent vectors (loadings) for the x and y axis.

density	0.1571	-0.2209
ex-OH	0.5693	0.0249
ex-water	0.3486	-0.1818
fibre-l	0.4859	0.075
fibre-c	-0.0082	0.2449
AA	0.2152	0.3365
spulp	0.0599	-0.1645
	TREAT AX1	TREAT AX2

Appendix 6.10: Correlation coefficients of the wood and pulping properties used in the Canonical Variate Analysis.

density	1						
ex-OH	0.3464	1					
ex-water	0.5661	0.4474	1				
fibre-l	0.3012	0.4941	0.2274	1			
fibre-c	0.1077	0.091	0.0664	0.068	1		
AA	0.117	0.018	-0.048	0.2236	0.2679	1	
spulp	-0.356	-0.323	-0.508	0	-0.149	-0.06	1
	density	ex-OH	ex-water	fibre-l	fibre-c	AA	spulp

Appendix 6.11: Summary of Monte Carlo test performed to test for significance in the Canonical Variate Analysis performed.

99 permutations under full test

Test of significance of first canonical axis :	eigen values	=	0.55
	F-ratio	=	19.28
	P-value	=	0.01
Overall test :	Trace	=	0.85
	F-ratio	=	5.43
	P-value	=	0.01

Appendix 6.12: 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	DF	Sum of squares	Mean squares	*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}	00545^{-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: Within each column, values followed by the same letter are not significantly different; $p<0.05$ according to Students *t*-test.

Appendix 6.13: Summary of simple linear regression of weighted mean density (kg m^{-3}) (excluding hot water and ethanol benzene extractives) and slope of growth rate for stem area.

Source of variation	d.f.	s.s.	m.s.	v.r.	*F*. prob
Regression	1	31024	31023	31.7	<0.001
Residual	58	56768	978		
Total	59	87792	1488		
r^2		34.2			
Std. Error		31.3			

Estimate of parameters

	Estimate	s.e.	*t*(58)	*t* pr.
Constant	498.6	8.01	62.22	<0.001
Slope	-779593	138472	-5.63	<0.001

Appendix 6.14: Summary of simple linear regression of extractable content (%) (hot water and ethanol benzene combined) and slope of growth rate for stem area.

Source of variation	d.f.	s.s.	m.s.	v.r.	*F*. prob
Regression	3	12.97	4.3247	12.96	<0.001
Residual	56	18.69	0.3338		
Total	59	31.66	0.5367		
r^2		37.8			
Std. Error		0.578			

Estimate of parameters

	Estimate	s.e.	*t*(56)	*t* pr.
Constant	3.361	0.165	20.41	<0.001
Slope	-11736	2834	-4.14	<0.001
Treat. 2	0.472	0.202	2.34	0.023
Treat. 7	0.446	0.186	2.4	0.02