INFLUENCE OF HARVEST RESIDUE MANAGEMENT, WEED CONTROL, LEGUME COVER CROPPING AND SOIL TRENCHING ON *EUCALYPTUS* PRODUCTIVITY IN KERALA, INDIA

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SANKARAN, K. V., CHACKO, K. C., PANDALAI, R. C., BALASUNDARAN, M., GROVE, T. S., MENDHAM, D. S. & O'CONNELL, A. M. 2004. **Influence of harvest residue management, weed control, legume cover cropping and soil trenching on *Eucalyptus* productivity in Kerala, India.** The impact of harvest residue management, weed control, cover cropping with legumes and soil trenching on productivity of *Eucalyptus tereticornis* and *E. grandis* was examined for three years after establishment of four plantations in Kerala, India. Four sites were examined in this study, two each with *E. tereticornis* and *E. grandis*, representing a wide range in climate and fertility. Harvest residue management had no effect on plantation productivity in the short term of this study. Complete weeding enhanced plantation productivity of *E. tereticornis* at three years, with volume increases of up to 141% compared with spot-weeded treatments. Strip weeding (1 m strips along the tree rows) did not improve productivity compared with spot-weeded treatments. Effects of legume intercropping on the growth of *E. tereticornis* was tested using three legume species, namely, *Pueraria phaseoloides*, *Stylosanthes hamata* and *Mucuna bracteata*. Legume cover-cropping had no effect on tree growth, suggesting that the legume cover crops had a lower competitive effect compared with weeds. Soil trenching also had no short-term effect on plantation productivity of *E. grandis* and *E. tereticornis*.

Key words: *Eucalyptus* plantation management

SANKARAN, K. V., CHACKO, K. C., PANDALAI, R. C., BALASUNDARAN, M., GROVE, T. S., MENDHAM, D. S. & O'CONNELL, A. M. 2004. **Pengaruh pengurusan sisa tuai, kawalan rumpai, penanaman legum penutup dan peparitan tanih terhadap produktiviti *Eucalyptus* di Kerala, India.** Pengaruh pengurusan sisa tuai, kawalan rumpai, penanaman legum penutup dan peparitan tanih terhadap produktiviti *Eucalyptus tereticornis* dan *E. grandis* dikaji selama tiga tahun selepas ditanam di empat ladang di Kerala, India. Empat tapak dikaji, iaitu dua tapak *E. tereticornis* dan dua tapak *E. grandis*. Kesemuanya mewakili julat iklim dan kesuburan yang luas. Pengurusan sisa tuai tidak mempunyai kesan pada produktiviti ladang sepanjang tempoh kajian yang singkat ini. Setelah tiga tahun, perumpaian lengkap meningkatkan produktiviti ladang *E. tereticornis*, dengan peningkatan isi padu sebanyak 141% berbanding rawatan perumpaian setempat. Perumpaian jalur (jalur

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1 m sepanjang barisan pokok) tidak meningkatkan produktiviti pokok berbanding rawatan perumpaian setempat. Kesan penanaman selingan pokok legum terhadap pertumbuhan *E. tereticornis* diuji menggunakan tiga spesies legum iaitu *Pueraria phaseoloides*, *Stylosanthes hamata* dan *Mucuna bracteata*. Penanaman legum penutup tidak memberi kesan terhadap pertumbuhan pokok. Ini menunjukkan tanaman legum penutup mempunyai kesan saingan yang lebih rendah berbanding rumpai. Peparitan tanih juga tidak mempunyai kesan jangka pendek terhadap produktiviti ladang *E. tereticornis* dan *E. grandis*.

Introduction

India has an extensive eucalypt plantation resource (> 8×10^6 ha, FAO 2001) but much of this area has relatively low productivity compared with growth rates obtained in other countries (Jayaraman & Krishnankutty 1990, Sankaran *et al.* 2000). In Kerala state, south-west India, the majority of the eucalypt plantation area was established in the 1960's. Since then, most sites have been through several harvest cycles (rotation length 7–10 years), generally with a marked decline in productivity in more recent rotations (Nair *et al.* 1997). Reasons for low productivity in these plantations include limitations due to nutrition, disease and soil moisture availability and the use of poor quality genetic material in the planting stock (Sharma *et al.* 1985, Kallarackal & Somen 1997, Sankaran 1999). Potential exists for improving productivity through more intensive management of plantations during inter-rotation, such as harvest residue management, trenching, weed control, and planting of legume cover crop.

Of particular importance is the way harvest residues are managed since they represent a significant proportion of the organic matter and plant available pool of nutrients at each site. The common practice of burning or removal of harvest residues results in losses of large quantities of site nutrients, especially nitrogen, which is lost in volatile forms during fire (Sankaran *et al.* 2000). Such practices may potentially be detrimental to site fertility if practised over multiple rotations (Jones *et al.* 1999). Research on effects of residue retention on plantation growth in other countries has produced a range of results, with variable responses in *Pinus radiata* (Smith *et al.* 2000), *Eucalyptus globulus* (Jones *et al.* 1999, O'Connell *et al.* 2000) and several other plantation species (Tiarks & Nambiar 2000). Retention of residues in eucalypt plantations in India may be important for conserving nutrients on site, but the immediate or potential long-term effects on growth have not previously been evaluated.

Cover cropping with legume species is another practice with potential to maintain or improve site fertility and long-term plantation productivity. Benefits of legume cover cropping include N input through fixation of atmospheric N, woody weed suppression, improvement in quality of organic matter and potential for multiple uses of the land base (Ofori & Stern 1987, Alley *et al.* 1999). Depending on species planted, legumes may also compete directly for site resources, sometimes at the expense of tree growth (Cogliastro *et al.* 1990, Alley *et al.* 1999, Malik *et al.* 2001). Similarly, weedy vegetation competes for site resources, and its control can, in some circumstances, markedly improve plantation productivity (Smethurst & Nambiar 1989, Cogliastro *et al.* 1990, Wilkins 1990).

Excavation of trenches in the soil (approximately 1 m long, 0.3 m wide and 0.3 m deep) is another practice that is often used in India for plantation species other than eucalypts (e.g. rubber) to conserve water and minimise soil erosion (Singh *et al.* 1993). However, the impacts of this and other site management options on productivity of eucalypt plantations have not been evaluated, despite the need to increase productivity from Kerala's plantation resource to meet domestic demand (Sankaran *et al.* 2000). Thus the effects of harvest residue manipulation, legume cover cropping, weed management and soil trenching on early *E. grandis* and *E. tereticornis* performance were evaluated at four sites in Kerala, India.

Materials and methods

Study sites

Experiments were established at four sites in Kerala, two with *E. tereticornis* and two with *E. grandis* (Table 1). Total soil C (0–10 cm) across the sites range from 22 mg g^{-1} (Kayampoovam) to 52 mg g^{-1} (Vattavada), and soil pH's are all mildly acidic (4.8–5.3). The *E. tereticornis* sites (Kayampoovam and Punnala) are located on the coastal plains (120 and 150 m asl respectively), while the *E. grandis* sites (Surianelli and Vattavada) are located in the highland regions (1300 and 1800 m asl respectively) of the Western Ghats. Soils at all these sites were derived from saprolite, or saprolitic colluvium originating from Precambrian granites and gneiss. The rainfall pattern is monsoonal, with most rainfall occurring from June to September (the south-west monsoon). The north-east monsoon (October to February) also brings occasional rain to the sites, with Vattavada more strongly influenced by this monsoon than the other sites. The average annual rainfall for the state of Kerala is 3000 mm (range 2200–3600 mm) spread over 120 rainy days. Mean annual atmospheric temperature is 27 °C. Relative humidity ranges between 64% (February to March) and 93% (June to July). There were four previous rotations of eucalypts at Vattavada and Surianelli, an initial seedling and two coppice rotations, followed by another seedling rotation. At the other two sites there were two previous rotations (one seedling and one coppice rotation). Trees were felled in mid 1998 in preparation for establishment of the current experiments in June till August 1998.

Seeds of *E. tereticornis* and *E. grandis* were obtained from the Australian Tree Seed Centre, Canberra, ACT. The seed lots were selected after screening a number of provenances for disease resistance and higher productivity (Balasundaran *et al.* 2000). Seedlings were raised in 10 × 20 cm polyethylene bags filled with forest soil-sand mix (2:1 by volume). Six-month-old seedlings were planted in the field in June till August 1998.

Experimental design

Effects of harvest residue manipulation, legume cover cropping, weed management, and soil trenching were evaluated in separate randomised block experiments, each with four replicate blocks. Details of treatments in each experiment are listed in Table 2. Legume experiments were conducted at both of the *E. tereticornis* sites, and the soil trenching experiment at three of the four sites (Punnala, Surianelli and Vattavada). All sites were established at 2500 stems ha^{-1}. The *E. grandis* sites were subsequently thinned non-selectively to 1667 stems ha^{-1} at 24 months.

All treatments received fertiliser at establishment (equivalent to 18.5 kg P ha^{-1}, 42.4 kg N ha^{-1} and 23 kg K ha^{-1} plus trace elements), applied in a circle at 20–30 cm from the base of the tree, and buried approximately 5 cm below the soil surface. An additional 42 kg ha^{-1} of P was broadcast applied to all plots in the legume experiment. Harvest residues remaining on the sites were uniformly distributed over all plots. Within each block of the residue manipulation experiments, one plot was allocated to the single residue treatment, and a double residue treatment was established by addition of the residues from a zero residue plot. On a further treatment, all woody material was removed, leaving just the leaf residue (simulating fuel removal), and on another treatment, all residues were burnt (the standard practice in eucalypt plantations in Kerala). Harvest residue (branches, bark and leaves) quantities in the 1R treatment (single residue) at the *E. tereticornis* sites were 19.4 Mg ha^{-1} (27% of total aboveground tree biomass) and 6.4 Mg ha^{-1} (28%) at Kayampoovam and Punnala respectively, and for *E. grandis*, 11.8 Mg ha^{-1} (29%) and 18.9 Mg ha^{-1} (18%) at Surianelli and Vattavada respectively (Sankaran *et al.* 2000). Harvest residues in all plots of the other experiments were evenly redistributed and burnt.

Weed competition in the weeding experiments was minimised by cutting off the weeds close to the soil surface. Weeding was performed when necessary to ensure minimal weed competition effects, thus both of the *E. tereticornis* experiments were weeded three times each year (March–April, July–August and November–December) while the *E. grandis* sites were weeded in the first and second years only. Weed growth was reduced by the third year under *E. grandis*, and so weeding was only required twice during that year, in July–August and November–December. Details of weed treatments are given in Table 2. All plots in the other experiments (except legume intercropping) were maintained free of weeds (FW). Weed biomass in the spot-weeded treatments was approximately 6.7, 4.6, 3.3 and 2.3 Mg ha^{-1} at Kayampoovam, Punnala, Surianelli and Vattavada respectively at one year after establishment at each of the sites (Sankaran *et al.* 2000).

The perennial legume species (*Mucuna bracteata* and *Pueraria phaseoloides*) were grown in a nursery for two months prior to transplanting in the field at a 2 × 2 m spacing in the legume intercropping experiments. The annual legume species *Stylosanthes hamata* was established by sowing seed at a rate equivalent to 9 kg ha^{-1} in shallow linear furrows across the plot area. An area around the tree stem (0.5 × 0.5 m) was cleared of weeds and legumes in all treatments. The control plots were kept free from competing vegetation through regular manual weeding. Legume biomass varied seasonally, with maxima of 6.1, 4.6 and 1.8 Mg ha^{-1} respectively for *Stylosanthes*, *Mucuna* and *Pueraria* at Kayampoovam at 15 months after establishment. At Punnala, the corresponding figures were 6.3, 2.8 and 2.1 Mg ha^{-1} respectively for *Stylosanthes*, *Mucuna* and *Pueraria*. Values for maximum biomass of *Stylosanthes* and *Mucuna* were recorded at 15 months, but *Pueraria*

Statistical analysis

Treatment effects on stand volume at each measure time and for each experiment was assessed using single-factor analysis of variance (Genstat 5, 1987). Absolute growth data from each treatment were used in the analysis of variance, but relative growth data were mostly presented to illustrate treatment effects over time. ANOVA error degrees of freedom were as follows: 12 for the harvest residue management experiment, 6 for the weeding and trenching experiments, and 9 for the legume intercropping experiment. Where the ANOVA test indicated a significant difference between treatments in the weeding experiment, the Duncan's multiple range test was applied to determine which means were different amongst the treatments.

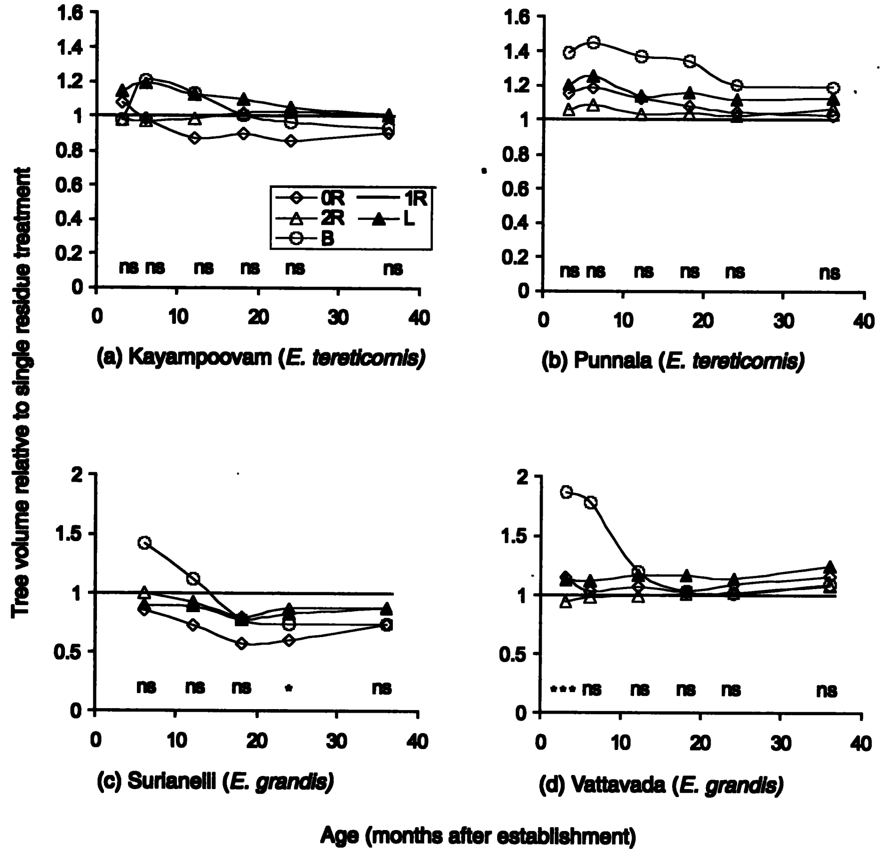
Results

Growth responses to silvicultural treatments

Relative volume response was plotted instead of absolute stand volume at each measure time to better illustrate the response pattern. Harvest residue manipulation had no apparent effect on tree growth up to age three years (Figure 1). Mean stand volumes in the harvest residue management experiment at three years for *E. tereticornis* were 40.5 and 35.5 m^3 ha^{-1} at Kayampoovam and Punnala respectively, and 47.4 and 116.2 m^3 ha^{-1} for *E. grandis* at Surianelli and Vattavada respectively (Table 3). Burning improved tree productivity at three months at Vattavada ($p < 0.001$). At Surianelli the 0R treatment at 24 months performed poorer than the 1R treatment ($p = 0.028$) (Figure 1).

The treatment free of weeds had significantly increased the growth of *E. tereticornis* at all measures (Figure 2). A weeding response was only apparent for *E. grandis* at the Vattavada site from 6–18 months; no response was observed at Surianelli. Volume production of *E. tereticornis* at three years in the treatment free of weeds was significantly greater than in the spot-weeded (NW) and strip-weeded (SW) treatments (Table 4). However there were no differences in standing volume at three years between free of weed treatments and spot-weeded treatments for *E. grandis* at Surianelli and Vattavada (Table 4). Strip weeding did not significantly improve stand volume compared with spot-weeded treatment at any of the sites. Weeding effects on volume increments were significant at most of the measure times at Kayampoovam, Punnala and Vattavada (Figures 3(a), (b) and (d)), but not significant at any of the measure times at Surianelli (Figure 3(c)). At the *E. tereticornis* sites, the free of weed treatment had consistently higher growth increment at each measure compared with the treatments with lower weeding intensity. At Vattavada, i.e. the *E. grandis* site, the free of weed treatment had higher growth increments up to 18 months, but between 18 and 24 months the growth increment in the treatment decreased to be significantly lower than that in the spot-weeded treatment. At 36 months, growth increments in Vattavada showed no significant difference in all weeding treatments.

Legume cover cropping caused a significant depression in the *E. tereticornis* stand growth compared with the control treatment at Punnala at 18 months



(a) Kayampoovam (*E. tereticornis*)

(b) Punnala (*E. tereticornis*)

(c) Surianelli (*E. grandis*)

(d) Vattavada (*E. grandis*)

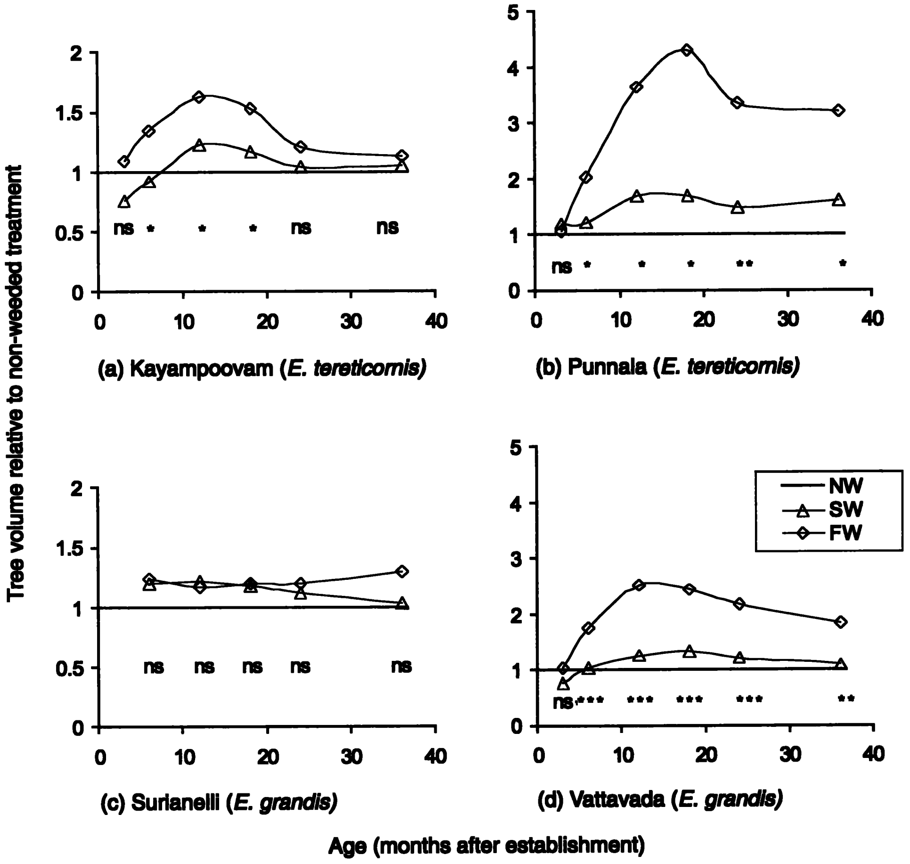
ns = not significant; * = $p < 0.05$; *** = $p < 0.001$

0R = no residue; IR = single residue; 2R = double residue; L = leaf residue; B = burn

Figure 1 Relative volume responses in the harvest residue manipulation experiment at the *Eucalyptus tereticornis* sites, Kayampoovam (a) and Punnala (b) and the *E. grandis* sites, Surianelli (c) and Vattavada (d). Results are shown relative to the single residues treatment.

Table 3 Mean stand characteristics in the harvest residue management experiment at each site at 36 months

Site	Height (m)	DBH (cm)	Basal area (m^{-2} ha^{-1})	Stand volume (m^3 ha^{-1})
Eucalyptus tereticornis				
Kayampoovam	9.17	6.98	3.06	40.5
Punnala	9.30	6.44	2.75	35.5
Eucalyptus grandis				
Surianelli	11.58	8.65	3.75	47.4
Vattavada	15.87	13.66	7.32	116.2



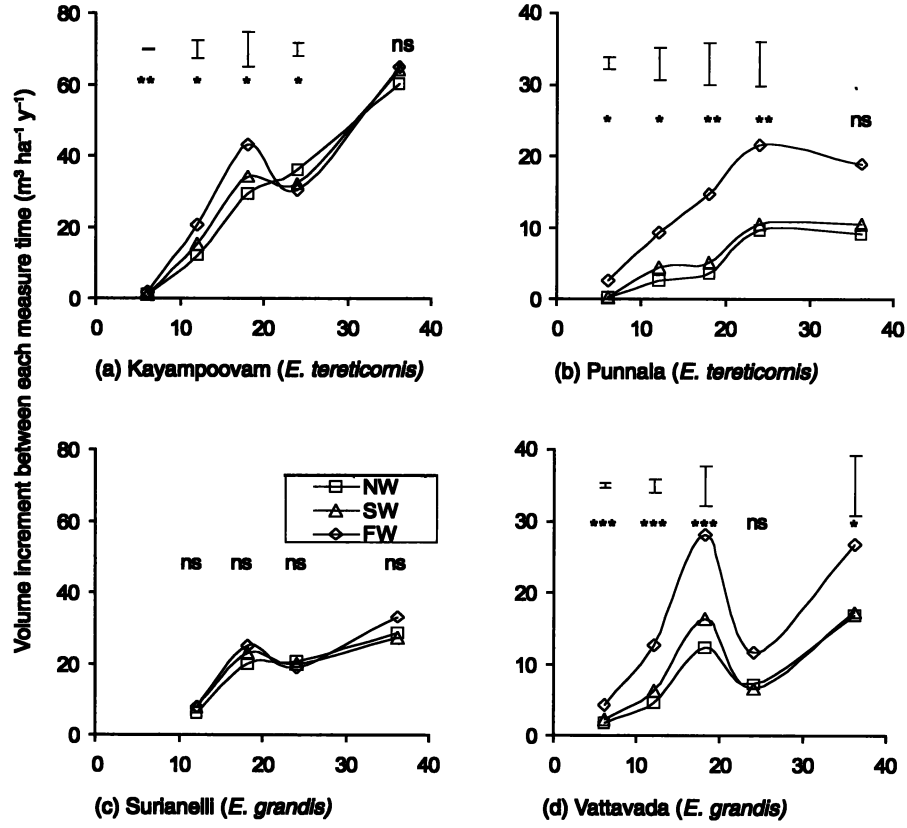
ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$
NW = spot-weeded; SW = strip-weeded; FW = free of weeds

Figure 2 Relative volume responses in the weed management experiment at the *Eucalyptus tereticornis* sites, Kayampoovam (a) and Punnala (b) and the *E. grandis* sites, Surianelli (c) and Vattavada (d). Results are shown relative to the spot-weeded treatment.

Table 4 Weed management effects on tree volume (m^3 ha^{-1}) at three years

Treatment	*Eucalyptus tereticornis*		*Eucalyptus grandis*	
	Kayampoovam	Punnala	Surianelli	Vattavada
NW	29.8a[*]	17.9a	53.1a	99.9a
SW	32.9a	21.5a	54.0a	106.3a
FW	54.5b	43.1b	60.4a	113.0a
Mean	39.1	27.5	55.8	106.4
LSD	11.28	16.61	16.75	14.28

[*] Means with the same letter in each column are not significantly different, tested using Duncan's multiple range test ($p < 0.05$).
NW = spot-weeded; SW = strip-weeded; FW = free of weeds



(a) Kayampoovam (*E. tereticornis*)

(b) Punnala (*E. tereticornis*)

(c) Surianelli (*E. grandis*)

(d) Vattavada (*E. grandis*)

Measure time (months after establishment)

ns = not significant; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$
NW = spot-weeded; SW = strip-weeded; FW = free of weeds

Figure 3 Volume increment in weed experiment between each measure time at the *Eucalyptus tereticornis* sites, Kayampoovam (a) and Punnala (b), and the *E. grandis* sites, Surianelli (c) and Vattavada (d). Bars represent LSD ($\alpha = 0.05$) at each measure time where differences were significant.

(results not shown). Mean stand volumes across all treatments were 41.4 m^3 ha^{-1} at Kayampoovam and 42.8 m^3 ha^{-1} at Punnala.

Responses to trenching were not significant at all the three sites tested at any of the measure times up to three years. The values for mean stand volume in the trenching experiments were 57.1 m^3 ha^{-1} at Punnala, 34.5 m^3 ha^{-1} at Surianelli and 117.4 m^3 ha^{-1} at Vattavada.

Discussion

Harvest residue manipulation

Minimal responses to harvest residue manipulation have also been found on higher fertility sites for *E. globulus* plantations in south-western Australia (Mendham *et al.* 2003), in Spain and in Portugal (Jones *et al.* 1999), and for *Pinus* *radiata* plantations in New Zealand (Smith *et al.* 2000). Sites where nutrients are more limiting to growth generally show greater response to residue retention, including *E. globulus* sites in south-western Australia (Mendham *et al.* 2003), *P. elliottii* sites in north-eastern Australia (Simpson *et al.* 2000) and *P. radiata* sites in New Zealand (Smith *et al.* 2000). Responses to residue retention can occur early in the rotation (Simpson *et al.* 2000), but on some sites do not become apparent for several years (Smith *et al.* 2000). Tiarks *et al.* (2000) also noted an interaction with herbicide treatment in a *P. taeda* plantation, with significant responses to harvest residue treatments only being observed when weeds were controlled.

Responses to N and P fertilisers application at Kayampoovam and Vattavada were small (Sankaran *et al.* 2000), so the impact of residue retention on site productivity may not be apparent in the current rotation. However, significant responses to nutrient application have been reported at the other two sites, i.e. to N at Punnala and Surianelli, and to P at Punnala (Sankaran *et al.* 2000). Retention of residues at these sites has the potential to benefit plantation productivity through increased nutrient availability. Although growth at these sites was nutrient limited, the impact of residue retention on growth was minimal, probably due to (1) the relatively low quantities of harvest residues and, therefore, low nutrient stores in residues at these sites (Sankaran *et al.* 2000), and (2) the limited availability of nutrients from harvest residues to the developing root systems. Fertilisers were applied in a circle of about 30 cm radius from the base of each tree, and were, therefore, effective in supplying nutrients to the trees when root systems were small and nutrient demand was high. Where harvest residues were retained, the nutrients were spatially dispersed relative to developing root systems and most of the nutrients would not be readily accessible to young seedlings until their roots had occupied the surface area of the site. Immobilisation of N and P in harvest residues can also occur during decomposition and is another factor that may influence tree growth in treatments with residues retained. For example, eucalypt residues have been shown to immobilise N during initial stages of decomposition (Aggangan *et al.* 1999), although the N is released again as the decomposition process proceeds. This N immobilisation may help minimise N leaching before the plant roots fully explore the site.

Although there was only a minimal effect of residue retention on stand productivity across the sites, budgets based on nutrient contents of residues indicate that conservation of organic matter and nutrients will be important for sustainability of plantations in the longer term. It is estimated that if all the aboveground biomass was removed from the four experimental sites, export of nutrients would be 247–358 kg N ha^{-1} and 20–56 kg P ha^{-1}. These are equivalent to 2.6% of N and 0.6% of P of total site pools to 1 m depth (Sankaran *et al.* 2000). Nutrients lost through logging and removal of harvest residues are unlikely to be replaced through natural soil rejuvenation processes (weathering, atmospheric deposition) during the course of subsequent rotations (Sankaran *et al.* 2000). Thus depletion of site nutrient capital is likely to affect growth in future rotations of eucalypts unless the nutrients are replaced. Furthermore, the rate of nutrient depletion at each harvest will be greater if productivity is increased (everything else being equal) or the intensity of harvest is increased.

Weed control

Growth increments at each of the sites were influenced by seasonal effects and thinning of the *E. grandis* sites. However, weed removal had a significant effect on tree growth at Kayampoovam, Punnala and Vattavada. The significant benefit of full weed control to growth of *E. tereticornis* supported results found for other tree species. For example, weed control alone had a larger influence on *E. grandis* growth in Australia than either insecticide or fertiliser application (Wilkins 1990), but a combination of all treatments gave the highest yield. Weeds generally affect productivity of the tree crop where soil resources are limiting. For example, Smethurst and Nambiar (1989) found a reduction in stem biomass of up to 46% at 20 months after planting in unweeded *P. radiata* plots compared with weeded plots. Furthermore, the reduced productivity was attributed predominantly to competition for N. However, competition by weeds for water can also significantly reduce tree growth, as was shown by Virtue *et al.* (2000) for *Melaleuca alternifolia*. At the *E. tereticornis* sites in this study, the mechanism behind the response to weeding may have been different at the two sites. Trees at Punnala responded markedly to applications of both N and P fertilisers (Sankaran *et al.* 2000), so competition with weeds for nutrients was likely to cause the response to weeding at this site. Conversely, trees at Kayampoovam showed only minor response to N, and no response to P fertilisers (Sankaran *et al.* 2000), but at this site, the soil was shallower (rock outcrops common across the site), and there were symptoms of water stress in the trees during the dry inter-monsoonal period.

Whilst weeds can have a significant influence on early stand growth, it is possible that in some circumstances early volume gains due to weed control may not be significant by the end of the rotation. Weed control generally increases growth initially, and establishes a differential in standing volume compared with spot-weeded (Snowdon 2002), thus the significance of the treatment effect may decline as the stand volume increases but the volume difference between weeded and spot-weeded treatments remains the same. The growth differential between treatments may be smaller where the trees develop a closed canopy early in the rotation, such as at the *E. grandis* sites in this study, and shading effectively suppresses development of the weed stratum. The *E. tereticornis* plantations at Kayampoovam and Punnala have a sparser crown cover, and greater light penetration to the soil surface, so weeds persist and are more likely to affect tree growth throughout the rotation.

In this experiment, weeds were controlled by slashing with a knife due to social sensitivity regarding use of herbicides. The effects of both of these vegetation control methods would probably be similar as they remove the source of competition for the site resources. However, slashing was more labour intensive and needed to be done more frequently to prevent weed regrowth from getting to the competitive stage.

Legume cover cropping

The effect of the legumes on stand productivity was minimal at both sites after three years of planting compared with the treatment free of weeds (FW). This result contrasts with other reported legume cover cropping experiments. For example, Malik *et al.* (2001) found growth depression (27–41%) in sweetgum (*Liquidambar stryaciflua*) caused by two legume species, and Alley *et al.* (1999) reported suppression in height and diameter in walnut (*Juglans nigra*), honeylocust (*Gleditsia triacanthos*) and a hybrid pine species (*P. rigida* × *P. taeda*) resulting from growth of eight legume species up to two years after planting. Similarly, Cogliastro *et al.* (1990) found that growth of seven deciduous tree species was significantly suppressed by both weeds and legume cover crops compared with herbicide-treated plots. In contrast to their experiments where treatment differences occurred in the third year after planting the effects of legume cover cropping in the current study were apparent soon after planting but disappeared by the third year. This was despite vigorous growth of legumes during the post-monsoon period (*Stylosanthes* aboveground biomass of 6 Mg ha^{-1}, Mendham *et al.* 2003). The limited effect of legumes on tree growth may be due to a combination of factors, including (1) the more competitive growth habit of the evergreen eucalypt species compared with the deciduous species reported above, and (2) the different rooting patterns between the eucalypts and legume cover crops causing less competition for limited resources, i.e. water and nutrients. A significant response to N fertiliser was found at Punnala (Sankaran *et al.* 2000), thus the legume cover crop had potential to improve stand growth through enhanced N supply. Although this effect was not realised up to 36 months, the stand may benefit at a later stage of the rotation, and/or in future rotations.

Whilst legume cover cropping had little effect on tree growth up to three years, it had several potential indirect or longer-term benefits, including suppression of weeds, lowered erosion risk (Malik *et al.* 2001), potential for multiple landuse through livestock grazing, input of biologically fixed atmospheric N, input of organic residues to soil, and minimisation of leaching losses during the initial stand establishment phase before the site is fully occupied by the tree crop. The impact of these effects may be difficult to detect in the shorter term, but are consistent with conservative management practices which aim to sustain production in the longer term.

Soil trenching

There was no effect of soil trenching on tree growth at any of the sites. As with some of the other silvicultural treatments, trenching may only have an impact at a later stage in the rotation when water becomes limiting to growth. Also the conservation of topsoil may have a beneficial effect on productivity over several rotations especially at steep sites, which are susceptible to erosion. However, trenching is a relatively expensive practice requiring a significant amount of manual labour, so the economics and effectiveness of trenching need to be evaluated thoroughly.

Conclusions

A number of management practices can be implemented to improve eucalypt plantation productivity in India. The practices that were examined can be separated into those with impacts during the current rotation, and those with potential longer-term impacts on plantation productivity. Of the short-term impacts, full weeding had a significant positive effect on stand productivity of *E. tereticornis* at the two lowland sites, but early responses to weeding the Vattavada *E. grandis* site was not maintained. In contrast to the competitive effects of weeds, legume cover crops did not result in reduced productivity of *E. tereticornis* at three years. The competitive difference between the legume cover crop and the weedy vegetation was probably a combination of lower competition for N by the legumes, compared with the weeds (due to legume N fixation), and potentially lower competition for water by the legumes, due to a shallower root system, compared with the broad range of woody and herbaceous weedy species that colonise eucalypt plantations.

Potential long-term benefits may be derived by adopting management practices which conserve and/or enhance site resources. Legume cover cropping and harvest residue retention did not have a direct benefit to stand productivity up to three years, but conservation of soil organic matter and nutrients will be critical for long-term sustainability. Trenching is also a useful mechanism of retaining water and soil on the steeper sites, and may be important in the long term for conservation of site resources, but it had no effect on stand productivity at three years.

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