KFRI Research Report No. 453 ISSN No. 0970-8103

MANAGEMENT AND MONITORING OF GROWTH OF COPPICE CROP IN THE EXPERIMENTAL PLANTATIONS OF EUCALYPTUS TERETICORNIS (KAYAMPOOVAM & PUNNALA) AND E. GRANDIS (SURIANELLI & VATTAVADA)

PK Chandrasekhara Pillai
KV Sankaran
RC Pandalai

KFRI
Kerala Forest Research Institute
An Institution of Kerala State Council for Science, Technology and Environment (KSCSTE)
Peechi - 680 653, Kerala, India

October 2012

KFRI Research Report No. 453 **ISSN 0970-8103**

Management and monitoring of growth of coppice crop in the experimental plantations of *Eucalyptus tereticornis* (Kayampoovam & Punnala) and *E. grandis* (Surianelli & Vattavada)

(Final Report of project KFRI 514/2006)

PK Chandrasekhara Pillai (Silviculture Department)
KV Sankaran (Director)
RC Pandalai (Extension & Training Division)

KFRI

Kerala Forest Research Institute
(An Intitution of Kerala State Council for Science, Technology and Environment)
Peechi 680 653, Thrissur, Kerala, India

October 2012

Project Proposal

Project No.	:	KFRI 514/2006
Title	:	Management and monitoring of growth of coppice crop in the experimental plantations of *Eucalyptus tereticornis* (Kayampoovam & Punnala) and *E. grandis* (Surianelli & Vattavada).
Investigator	:	K.V. Sankaran R.C. Pandalai P. K. Chandrasekhara Pillai
Objectives	:	1. Maintenance of the experimental plots of *Eucalyptus tereticornis* and *E. grandis* at four sites viz. Kayampoovam, Punnala, Surianelli and Vattavada, to promote healthy growth of the second rotation (coppice) crop. 2. To evaluate response of coppice growth to the treatments applied in the first rotation.
Duration	:	April 2006 – March 2011
Funding Agency	:	Plan Grants

Contents

Acknowledgements

We express our sincere gratitude to Dr. J. K. Sharma and Dr. R. Gnanaharan, former Directors of KFRI. Acknowledgements are due to Dr. Jose Kallarackal, the former Programmme Coordinator, SFM Division for the support and help. Finally we thank Dr. M. Balaglalan, Dr. E.M. Muralidharan and Dr. S. Sandeep, the reviewers, for critically going through the manuscript and suggesting modifications.

Abstracts

Experimental plantations of eucalypts were established at four sites in Kerala during 1998 as part of an India-Australia collaborative project aimed at enhancing productivity through site management practices. These included a plantation of *Eucalyptus tereticornis* established at Punnala (9°06' N & 76°54' E) in Kollam District and *E. grandis* at Surianelli (10°02' N & 77°10' E) in Idukki District. The treatments applied included addition of N fertilizer and weed management which resulted in enhanced productivity of both the species. The plantations were harvested in 2005 at the age of 6.5 yrs. The second rotation coppice crop was managed in the above plantations to analyze whether any residual effect of the treatments that applied in the first rotation.

The seedling crop received five doses of nitrogen (as urea) viz., 0, 18, 60, 187and 375 kg per ha which were supplemented by an initial application of phosphorus (as super phosphate @ 63 kg per ha except in the control plot). There were two levels of weed management viz., no-weeding and periodic full weeding. The size of each experimental plot was 20 x 20 m which was planted with 100 seedlings (2 x 2 m spacing between plants). Each treatment was replicated four times.

During the first rotation, yield response to nitrogen input at the age of 48 months varied between 11.6 to 22.1 m^3 ha^{-1} yr^{-1} in *E. tereticornis* and 18.7 to 36.2 m^3 ha^{-1} yr^{-1} in *E. grandis* plantations respectively and the treatment effects were significant. However, in the second rotation, productivity of coppice crop at the age of 48 months ranged from 8.2 to 10.8 and 15.2 to 20.2 m^3 ha^{-1} yr^{-1} for *E. tereticornis* and *E. grandis*, respectively, indicating that residual effect of nitrogen application in the first rotation did not occur in the second rotation.

Weed management resulted in significant improvement of productivity in plantations during the first rotation, especially in *E. tereticornis* (6.0 to 14.1 m^3 ha^{-1} yr^{-1}). However, this treatment had no effect on *E. grandis* (21.1 to 24.5 m^3 ha^{-1} yr^{-1}). Suppression of weed growth in *E. grandis* can be ascribed to early canopy closure and the resultant shading effect. On the other hand, *E. tereticornis* has a very sparse crown cover which allows greater light penetration promoting weed growth. This affects tree growth throughout the rotation. Significant residual effect of weed management was observed till 18^{th} month in coppice crop of *E. tereticornis*. Productivity of 4-year-old coppice crop of *E. tereticornis* and *E. grandis* was 7 and 13 m^3 ha^{-1} yr^{-1}, respectively.

The study revealed that silvicultural interventions like fertilizer application and weed control had significant influence on enhancing productivity of first rotation eucalypt plantations; however, it has no residual effect on the second rotation crop. The results indicate the need for further silvicultural inputs for enhancing productivity of subsequent rotations.

1. Introduction

The suitability of *Eucalyptus* as an excellent pulpwood species prompted its wide introduction and cultivation in the tropics and sub-tropics. The species currently occupies an area of around 12 million ha in the tropics (FAO, 2011). Poor productivity, increasing demand for pulpwood, shortage of suitable land for cultivation and changing environmental policies necessitated maximising productivity from the already existing plantations. To achieve this, silvicultural interventions such as nutrient input, water conservation, weed management and use of genetically superior planting stock are attempted widely. These treatments help to accelerate early growth and to bring down the rotation period which ensures maximum returns from investment. It has been shown through long-term studies that management practices aimed at conservation of soil organic matter and enhanced soil nutrient status can contribute significantly to sustain productivity of forest plantations (Nambiar, 1996).

1.1. *Eucalyptus* plantations in India

Eucalyptus is cultivated in around 5 million ha of land across India as they contribute to the supply of pulp and fuel wood in a major way. In Kerala, the major species planted are *Eucalyptus tereticornis* (<500 m asl) and *E. grandis* (500-2000 m asl). The area under eucalypts in the state was over 40,000 ha in the 1990's. Currently, eucalypts occupies only an area of 6,500 ha in the state while the area is on the increase in other states like Tamil Nadu, Karnartka, Punjab etc. (Sivaram *et al.*, 2012). The main reason for such shrinkage in area is poor productivity of the plantations (<10 m^3 ha^{-1} $yr^{-1)}$ and the lack of interest by stakeholders in growing eucalypts. The low productivity is ascribed to repeated planting at the same site with out any nutrient input, poor quality of the planting material and lack of proper maintenance of the plantations (Sharma *et al.*, 1985; Nair *et al.*, 1997). In contrast, average productivity of eucalypt plantations in Brazil is 20-60 m^3 ha^{-1} yr^{-1} (Gonçalves *et al.*, 2004; Rockwood *et al.*, 2008). Kerala State has only limited land available for increasing area under plantations, and the demand for eucalypt pulpwood is very high (3,50,000 t yr^{-1}). Thus, it is imperative that productivity of the existing plantations be improved considerably to meet at least part of the demand. In this context, field trials were carried out in Kerala during 1998–2005 to evaluate the effect of intensive site management practices in improving productivity of eucalypt plantations (Sankaran *et al.*, 2008).

1.2. Coppice management

Managing coppice growth of *Eucalyptus* is a common practice, especially in countries like India, Australia, South Africa and Brazil. It allows growers to have a 2nd and sometimes even 3rd rotation crop without replanting and thereby saving on re-establishment costs. The advantages of coppicing are: (i) regeneration is more reliable and cheaper (ii) yields higher than the original seedling crop, and (iii) less capital investment (Colac, 2000). It may also be noted that coppice crop rotations are usually shorter than seedling crop. However, harvesting will have to be done carefully so as to ensure maximum survival of stumps. Studies have shown that the time of harvesting is crucial since it affects stump survival (Archibald, 2002). In India, March is the most preferred month for stump harvest. This timing can vary for other countries. Coppice management involves removal of logging debris from the stump surface and thinning of the coppice shoots. Though numerous studies have been carried out to evaluate the effect of silvicultural inputs on productivity of eucalypts, residul effect of these inputs on the coppice crop has not been analyzed in any detail. This study was planned to evaluate this residual effect on experimental plantations of *E. tereticornis* and *E. grandis* which were intensively managed during the first rotation seedling crop. The study was also aimed at developing suitable management practices for coppice crops in eucalypt plantations.

2. Materials and methods

2.1. Study area

Four eucalypt plantations, two each with *E. tereticornis* and *E.grandis*, were established at different sites in Kerala during 1998 to study the effect of silvicultural treatments such as harvest residue retention, nutrient addition, weeding, legume intercropping and soil trenching to evaluate their efficacy in improving productivity of the plantations. Two of them were used in the current study to assess residual effects of the above treatments on the coppice crop. The experimental sites are spread over two distinct geographic zones in Kerala (Fig. 1). One of the sites was at Punnala in Kollam District which is a lowland region along the foothills of Western Ghats. The area was 4.48 ha in extent and was planted with *E. tereticornis*. The second site was at Surianelli in Idukki District, a highland region in the Western Ghats. The total area of the plantation was again 4.48 ha and the site was planted with *E. grandis*. Geographical position, elevation, mean annual rainfall and soil characteristics of both the sites are provided in Table 1. Climate in Kerala is tropical warm humid with South-West and North-East monsoons. The South-West monsoon starts from early June to September and the North-East monsoon, from October till February with occasional rains and the summer months extend from March to May. Mean annual atmospheric temperature is 27°C (20-42°C) and relative humidity ranged between 64 (February – March) and 93% (June – July).

Table 1. Characteristics of the study sites

Site features	**Punnala** (*E. tereticornis*)	**Surianelli** (*E. grandis*)
Latitude	9°06' N	10°02' N
Longitude	76°54' E	77°10' E
Elevation (m asl)	150	1280
Rainfall (mm $year^{-1}$)	2000	3000
Soil texture	Sandy loam-clay loam	Medium clay-sandy loam
pH	5.1	4.8
Total C (mg g^{-1})	43.6	40.9
Total N (mg g^{-1})	2.89	2.49
Total P (mg g^{-1})	0.40	0.55
Previous vegetation	Moist deciduous forest	Grassland

Source: Sankaran *et al.* (2000)

2.2. History and description of plantations

The site at Punnala, a degraded moist deciduous forest prior to planting with eucalypt, previously supported two rotations (the first, a seedling crop and the second a coppice crop of *E. tereticornis*). Surianelli, a high altitude grassland previously, had supported four previous rotations (initial seedling crop followed by two coppice rotations and the fourth seedling crop of *E. grandis*). Seedlings for planting were raised from selected provenances of eucalypts (screened for disease resistane and high productivity) obtained from CSIRO, Australia.

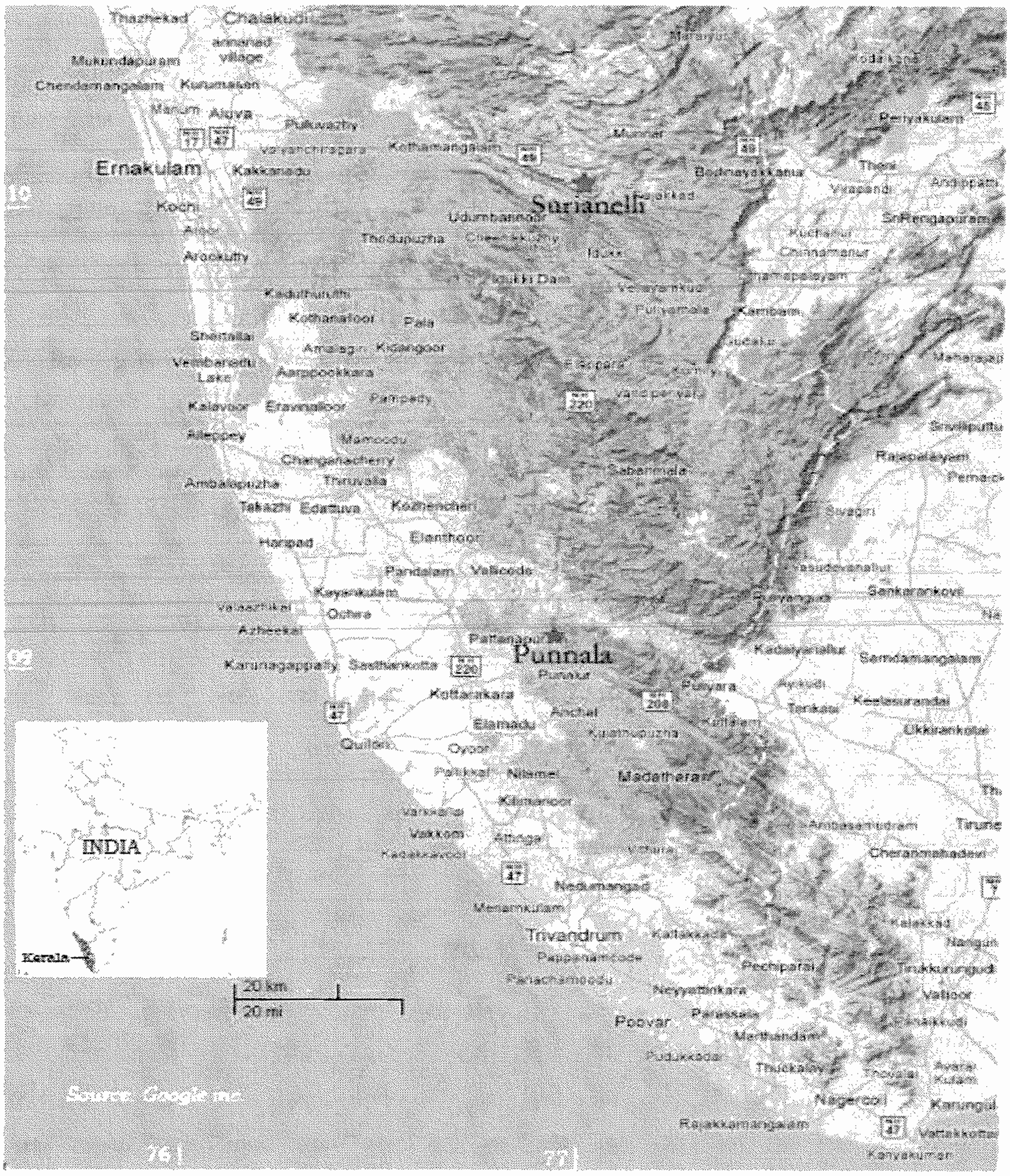


Fig. 1. Study sites

All the experiments including nitrogen (N) and phosphorus (P) input and weeding were conducted on a single factor basis at each of the sites. Dosage of N and P were determined based on a previous study conducted by the Kerala Forest Research Institute (Balagopalan *et al.*, 1998). The experiments were laid out in a randomized block design with four replications. Plot size was 20 x 20 m with trees in 2 x 2 m spacing (2500 stems ha^{-1}). Details of the experiments and treatments applied in the 1st rotation plantations are provided in Table 2. Among the experiments, N input and weed management gave significant improvement in productivity of both the species. Hence, the residual effect on productivity of coppice crop was evaluted from these experimental plots at the two sites.

Table 2. Experiments and treatments in the 1st rotation plantations

Experiment	Treatment	Description
Nitrogen fertilizer input	N_0P_0	Control (neither N nor P fertilizer added)[1]
	N_0 (N_1)	0 nitrogen input (supplemented with P_4)
	N_{18} (N_2)	18 kg N ha^{-1}
	N_{60} (N_3)	60 kg N ha^{-1}
	N_{187} (N_4)	187 kg N ha^{-1}
	N_{375} (N_5)	375 kg N ha^{-1}
Phosphorus fertilizer input	St	Control (initial dose of fertilizer only)[1]
	P_0 (P_1)	0 phosphorus input (supplemented with N_4)
	P_6 (P_2)	6.3 kg P ha^{-1}
	P_{21} (P_3)	21 kg P ha^{-1}
	P_{63} (P_4)	63 kg P ha^{-1}
	P_{131} (P_5)	131 kg P ha^{-1}
Weed management[1]	NW	Control (no weeding)
	CW	Complete weeding
Harvest residue management (organic matter manipulation - (OM)	NoS	Control (all harvest residues removed)[1]
	SS	Single slash (normal residue load)[1]
	DS	Double slash[1]
	L	Leaf slash[1]
	BS	Burn with initial dose of fertilizer[1]
	B	Burn (all residues burnt)

[1]Treatments received an initial dose of fertilizer at the establishment stage (42.4 kg N ha^{-1}, 18.5 kg P ha^{-1} and 23 kg K ha^{-1} plus trace elements). Initial application of P @ 63 kg ha^{-1} (P_4) in the N experiment except N_0P_0. Initial application of N @ 187 kg ha^{-1} (N_4) in the P experiment except St.

Source: Sankaran *et al.* (2000)

2.3. Plantation management

The first rotation crop was harvested during 2005 at the age of 6.5 years. The plantations were then weeded and stumps of both *E. tereticornis* and *E. grandis* were cleaned in order to encourage coppicing. New sprouts emerged from the stumps within one week after harvest. Excess coppice shoots were physically removed to retain three shoots in the first year and then to a single stem in the second year. Coppice shoots were retained at windward side of the stumps in order to prevent wind throw. The shoots arising from the top cut portion of the stump were retained wherever possible. The retained healthy leading shoots were marked for monitoring growth. The experimental sites were maintained by weeding and removal of excess coppice sprouts. Weeding was carried out twice a year during July-August and November-December. No additional cultural operations were carried out in the coppice growth. Data on growth were recorded form these experimental plots at periodic intervals.

2.4. Measurement of growth

Each replicate plot (20 x 20 m) contained 100 trees at 2 x 2 m spacing in ten rows. The outer two rows were regarded as buffer zone trees and the six inner rows as measurement trees (Fig. 2). Buffer zone trees were excluded from measurements in order to rule out any possible border effect from the adjoining treatment plots. Height and GBH of coppice shoots were recorded from the measurement shoots at six-monthly interval from 12, 18, 24, 30, 36, 42 and 48 months after the harvest.

Fig. 2. Plot pattern and position of measurement trees

2.5. Estimation of conical volume and stand volume

The tree volume was determined using data on girth at breast height (GBH) and tree height. The stand volume was estimated as sum of the tree volumes, expressed per ha. The volume of each stem (over bark) was calculated as volume of a cone treating the tree as a cone. Conical volume (CV) of each tree was derived from the formula

$$\tfrac{1}{3}\pi r^2 h$$

where, h = height of the tree in cm measured by hypsometer

r = radius of the tree at the base derived from girth measured at breast height (GBH)

A correction factor was applied to the GBH value in order to get the radius at the base point. This was calculated by the following equation

$$\frac{\text{height}}{\text{height} - 137}$$

The formula, $\tfrac{1}{3}\pi r^2 h$ was modified by incorporating the above correction factor.

$$\frac{(\pi\, h\, ((GBH/\pi)\, (h/\, (h-137)))^2)}{12}$$

Since the spacing provided in the plantation is 2 x 2 m, area of the plot with 6 rows of measurement trees will be 144 m^2. Tree volume per ha (m^3 ha^{-1}) was calculated as follows.

(Sum of Conical Volume of trees in cm^3 ÷ 1000000) ÷ 144) x 10000

i.e., $$\frac{\text{Sum of CV of trees in } cm^3}{14400}$$

2.6. Statistical analysis

Statistical analysis (ANOVA) of treatment effects was carried out on mean values of the stand volume using the software SPSS. Stand volume of 1st and 2nd rotation crops were compared and statistically analysed to test significant difference between them by MANOVA procedure in SPSS through the following model.

$$y_{ijk} = \mu + \alpha_i + e_{ij} + \beta_j + \gamma_{ij} + e_{ijk}$$

where y_{ijk} is the observation on *k*th replication in the *i*th treatment at *j*th rotation.

(i=1,2….6; in the case of weed management i=1,2)

j=1, 2; k=1,2,3,4

μ is the general mean,

α_i is the effect of *i*th level of treatment,

β_j is the effect of *j*th level rotation,

γ_{ij} is the interaction effect of the *i*th level of the treatment and *j*th level of rotation.

In the model, the random component e_{ij} are assumed to be independently and normally distributed with mean zero and variance σ_{ε}^2. The above model was implemented after taking log transformation.

3. Results and discussion

3.1. Residual effect of nitrogen input on second rotation coppice crop

Mean stand volume of the coppice crop of *E. tereticornis* and *E. grandis* is given in Tables 3 & 4. Statistical analysis of the growth data revealed that nitrogen fertilizer added in the first rotation had no significant residual effect on coppice growth in plantations of both the species (Tables 5 & 6). Stand volume of coppice crop between treatments was also found to be insignificant.

The highest growth in coppice crop was recorded from plots which received N_{18} treatment in *E. tereticornis* plantation up to 48 months (till the growth was measured). This was followed by N_{187}, N_0, N_{375} and N_{60} in the decreasing order up to 24th months of growth of the coppice crop. The trend in growth response during the 30th month was in the order of N_{18}, N_0, N_{187} and N_{375} respectively. The treatment N_{60} showed poor growth during 30, 36 and 42 months of growth. During 36th and 42nd months, the growth response was in the order N_{18}, N_{187}, N_0 and N_{375}. At the end of 48th month, growth response was in the order N_{18}, N_0 and N_{187}; the stand volume in N_{60} and N_{375} was lower than control. In *E. grandis*, maximum growth of coppice crop was found in N_{375} treatment plots followed by N_{187}, N_{18}, N_{60} and N_0 in the decreasing order. Generally, the response to N addition was more in the plots of *E. tereticornis* which received a dosage of 18 kg N ha^{-1} and in *E. grandis* plots with 375 kg N ha^{-1} compared to other dosages.

Table 3. Mean stand volume (m^3 ha^{-1}) of second rotation *E. tereticornis* plantation in the plots of different dosages of nitrogen fertilizer input

Age	**Treatment**					
(months)	**N_0P_0**	**N_0**	**N_{18}**	**N_{60}**	**N_{187}**	**N_{375}**
12	5.47	6.22	6.88	5.73	6.60	5.83
18	7.89	8.51	9.76	7.91	8.77	8.14
24	10.24	11.30	12.77	10.62	11.59	10.95
30	16.16	17.60	19.72	15.94	17.52	17.03
36	20.72	22.44	25.38	20.19	23.01	22.27
42	25.31	26.93	31.60	24.21	27.12	26.81
48	36.26	36.84	43.02	32.75	36.45	36.20

Note: *N_0P_0 - control (no N or P added); N_0 - zero nitrogen input; N_{18} - 18 kg N ha^{-1}; N_{60} - 60 kg N ha^{-1}; N_{187} - 187 kg N ha^{-1}; N_{375} - 375 kg N ha^{-1} (treatments applied during the 1st rotation)*

Table 4. Mean stand volume (m^3 ha^{-1}) of second rotation *E. grandis* plantation in the plots of different dosages of nitrogen fertilizer input

Age (months)	Treatment					
	N_0P_0	N_0	N_{18}	N_{60}	N_{187}	N_{375}
12	3.77	4.10	4.37	4.34	4.82	5.46
18	6.53	6.96	7.50	7.37	8.41	9.55
24	12.47	13.46	14.22	13.61	15.93	18.37
30	29.54	29.68	31.47	30.02	31.76	37.20
36	40.41	41.33	42.99	40.61	43.33	49.83
42	55.30	58.19	60.13	57.37	64.35	71.93
48	58.10	65.42	72.12	60.63	76.49	80.66

Note: as above.

Table 5. F- values and significance levels corresponding to treatment source of variation in stand volume of second rotation *E. tereticornis* plantation

Age (months)	Experiment			
	N	Weeding	P	OM
12	0.770^{ns}	7.288^{*}	-	-
18	0.659^{ns}	6.680^{*}	-	-
24	0.610^{ns}	4.087^{ns}	-	-
30	0.586^{ns}	2.398^{ns}	-	-
36	0.755^{ns}	2.446^{ns}	-	-
42	0.946^{ns}	2.279^{ns}	-	-
48	0.674^{ns}	2.314^{ns}	1.205^{ns}	1.404^{ns}

*Note: ns – non-significant; * - significant at $P \leq 0.05$. N – nitrogen input; Weeding – weed management;, P – phosphorus input; OM – harvest residue management*

Table 6. F- values and significance levels corresponding to treatment source of variation in stand volume of second rotation *E. grandis* plantation

Age (months)	Experiment			
	N	Weeding	P	OM
12	0.970^{ns}	5.478^{ns}	-	-
18	0.675^{ns}	5.397^{ns}	-	-
24	0.579^{ns}	5.361^{ns}	-	-
30	0.351^{ns}	4.182^{ns}	-	-
36	0.327^{ns}	3.228^{ns}	-	-
42	0.432^{ns}	0.308^{ns}	-	-
48	0.213^{ns}	1.082^{ns}	1.107^{ns}	0.143^{ns}

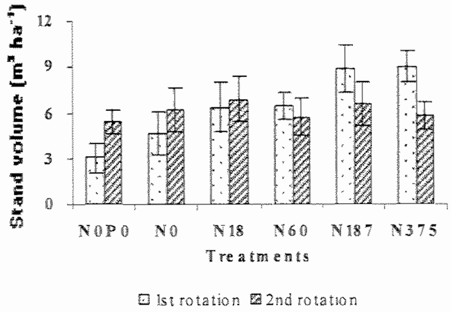
Note: ns – non-significant; N – nitrogen fertilizer input; Weeding – weed management;, P – phosphorus fertilizer input; OM – harvest residue (organic matter) management

3.2. Comparison of 1st and 2nd rotation productivity in N input plots

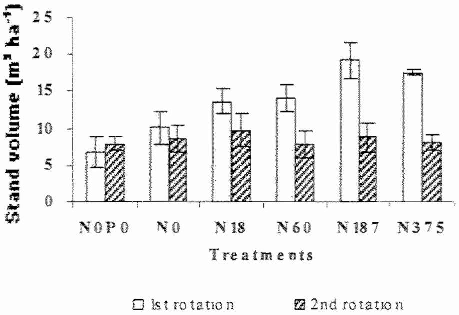
Stand volume of the coppice crop of second rotation *E. tereticornis* (Table 3) when compared with that of first rotation showed variation in residual effect of nitrogen treatment between rotations. Figure 3a-e shows that the stand volume of first and second rotation *E. tereticornis* plantation had comparable growth upto 12 months. This suggests a residual effect of N in these sites for 12 months of coppice crop and additions of nitrogenous fertilizers before the lapse of this period may boost the rate of tree growth. There was a general increase in yield with levels of N upto $N_{187} + P_4$ in the first rotation and the trend got reversed in $N_{375} + P_4$. The yield reduction in $N_{375} + P_4$ may be due to a disproportion between N and P at higher doses of N (as P was applied at a constant rate of 63 kg ha^{-1} for all N levels).

Stand volume of the second rotation coppice crop showed an increase in control (N_0P_0), N_0 and N_{18} treatment plots at the age of 12 months over the first rotation. However, stand volume was lower in treatments $N_{60,}$ N_{187} and N_{375} of the coppice crop compared to the first rotation. At the age of 18th month, stand volume in control plots of second rotation slightly increased whereas, the other treatments were lower than the first rotation. During the other measurement periods, the second rotation coppice crop of *E. tereticornis* in all the nitrogen treatments showed a lower stand volume than the first rotation. Stand volume of the second rotation *E. grandis* when compared with the first rotation (Table 5, Figs. 4a-e) showed an increased growth over the first rotation in control treatment, $N_{0,}$ N_{18} and N_{60} treatments during 12th month. However, treatments with N_{187} and N_{375} showed a lower growth when compared to the first rotation. At the 18th month, stand volume increased only in control and N_0 treatments in the second rotation crop. In all other cases, the second rotation crop had lower stand volume compared to the first rotation.

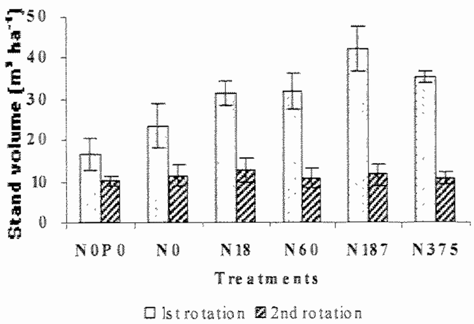
The overall productivity of the *E. tereticornis* coppice plantation during 4th year was 9-11 m^3 ha^{-1} yr^{-1}, whereas in *E. grandis* plantation it was 15-20 m^3 ha^{-1} yr^{-1}. Productivity in the second rotation *E. tereticornis* plantation with respect to different nitrogen treatments was inconsistent as in the case of the first rotation. However, in the second rotation *E. grandis*, the productivity generally increased with respect to treatment levels. The mean annual increment (MAI) of second rotation in *E. tereticornis* (19-59%) and *E. grandis* (18-48%) was lower than that of the first rotation. It is thus clear that nitrogen applied in the first rotation was not available to the seond rotation coppice crop. The overall stand productivity in N plots in the first rotation was significantly higher than that in the coppice crop (Table 10).



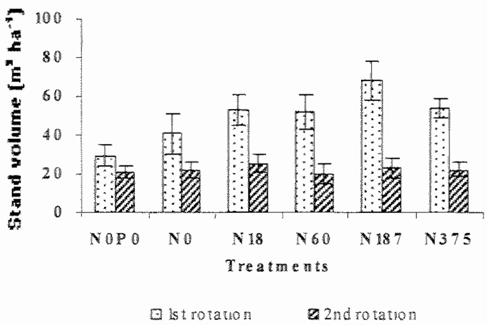
a. 12th month



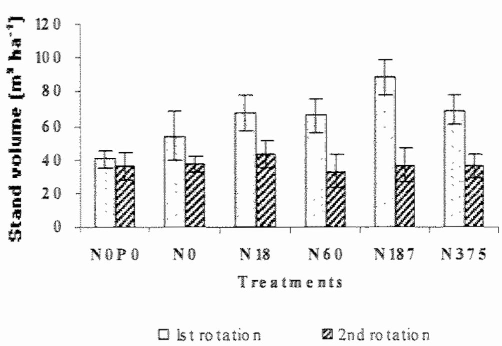
b. 18th month



c. 24th month

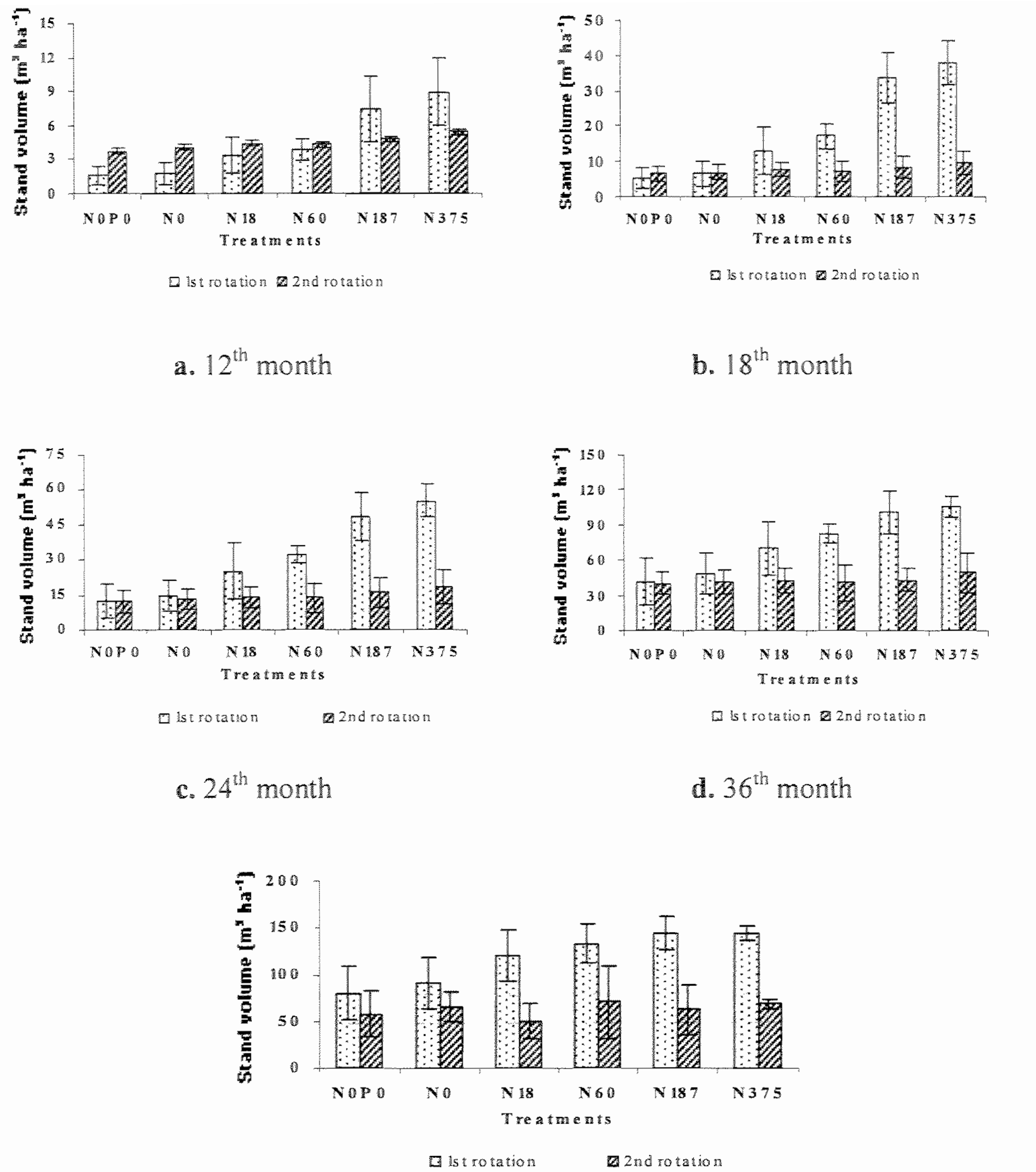


d. 36th month



e. 48th month

Fig. 3. Comparison of stand volume of first and second rotation *E. tereticornis* plantations in nitrogen experiment



a. 12th month

b. 18th month

c. 24th month

d. 36th month

e. 48th month

Fig. 4. Comparison of stand volume of first and second rotation *E. grandis* plantations in nitrogen experiment

Productivity of *E. tereticornis* across India is ranged from 4 to 18 m^3 ha^{-1} yr^{-1} (Ajith Kumar, 2001). In *E. grandis*, on an average, it is to the tune of 20-27 m^3 ha^{-1} yr^{-1}. However, studies done elsewhere have shown that through proper site management practices, including nutrient input, the productivity of *E. grandis* plantations could be improved from 10 to 70 m^3 ha^{-1} yr^{-1} (FAO, 2006; Gonçalves *et al.*, 2008). According to

Gonçalves *et al.* (2004), nitrogen and phosphorus are the two major nutrients which influence the productivity of eucalypt plantations. Responses to fertilizer inputs will vary between and among the sites, suggesting the inherent differences in the nutrient availability and characteristics of soils. In our previous study on the first rotation, nutrient input significantly improved productivity of both *E. tereticornis* and *E. grandis*. Nitrogen fertilization in *E. tereticornis* and *E. grandis* plantations in the first rotation enhanced productivity by about 23 to 60 and 51 to 81%, respectively compared to controls (Sankaran *et al.*, 2008). Sharma *et al.* (1986) reported that when a combination of urea and super phosphate (75 g each per plant) was applied to one-year-old *E. grandis* growing in a severely degraded soil, there was a 16-fold increase in the above-ground biomass. Similarly, Balagopalan and Rugmini (2003) also noticed a significant increase in tree volume in a 3-year-old *E. tereticornis* plantation when NPK was added in the ratio 30:30:15 g per tree.

3.3. Residual effect of weed management in the 2nd rotation crop

Stand volume of coppice crop of *E. tereticornis* and *E. grandis* in the weed management plots is given in Table 7. A significant ($P \leq 0.05$) residual effect of weed management was evident till the age of 18 months in the coppice crop of *E. tereticornis*. This effect was found to be non-significant therefter (Table 5).

Stand volume of second rotation coppice crop was higher in the fully weeded plots of *E. tereticornis* compared to unweeded plots throughout the 4 yrs. However, the effect was not significant after 18 months clearly, due to the fact that the weeds were not retained in the unweeded plots in the coppice crop since our aim was to understand the residual effect of weed management in the first rotation. Eitherway, the study indicated that weed management has profound effect on the growth of the second rotation crop as well. In *E. grandis*, the effect of weeding was significant only during the intial stages of growth in the first rotation. The result was similar in the coppice crop also. Stand productivity at 48 months in the fully weeded treatment plots of second rotation *E. tereticornis* plantation was 7 m^3 ha^{-1} yr^{-1} which is around 46% more than that in the un-weeded plots. However, the productivity of first rotation seedling crop was 14 m^3 ha^{-1} yr^{-1} (139% more in fully weeded plots over un-weeded polots). The productivity in weeded treatments of *E. grandis* coppice crop was 13 m^3 ha^{-1} yr^{-1} whereas of first rotation seedling crop was 24 m^3 ha^{-1} yr^{-1}.

3.4. Comparison of 1st and 2nd rotation productivity in weed management plots

Figures 5 and 6 depict stand volume of first rotation seedling crop and second rotation coppice crop grown in the weed management plots. Stand volume in the un-weeded plots of 12-month-old *E. tereticornis* coppice crop was around 26% more than that in the first rotation. The increase was 25% in 12-month-old *E. grandis* plots in the similar situation. Later, with the increase in age, the stand volume in un-weeded plots of coppice crop was lower compared to the first rotation crop of both the species. Stand volume of coppice crop in the fully weeded plots of both the species was lower than the first rotation at all stages of growth. The increase in stand volume in un-weeded plots of coppice crop in the first year is evidently due to weed removal before commencing the experiment. Weeding effect was highly significant throughout the growth period in the first rotation seedling crop of *E. tereticornis* (Sankaran *et al.*, 2004, 2008, 2012). However, the effect of weeding was not significant in the first as well as second rotation *E. grandis* plantation. The stand volume of the first rotation crop in the weed management plot was significantly higher than that in the coppice crop (Table 10).

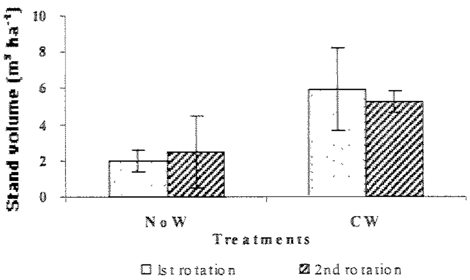
Table 7. Mean stand volume (m^3 ha^{-1}) of coppice crop of eucalypt plantations in the weed management plots

Age	*E. tereticornis*		*E. grandis*	
(months)	NoW	CW	NoW	CW
12	2.47	5.22	5.30	3.46
18	3.41	6.90	8.90	5.75
24	5.17	9.30	17.55	10.83
30	9.08	13.48	34.73	22.90
36	11.87	17.53	46.81	32.21
42	14.22	20.85	60.82	46.78
48	19.34	28.00	69.26	51.47

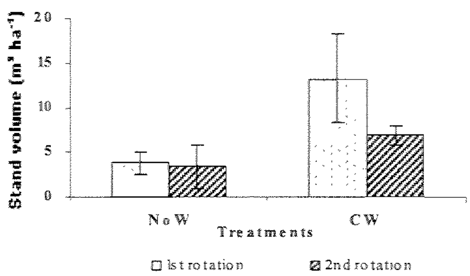
Note: NoW – control treatment for weed management (no weeding); CW – complete weeding (treatments applied during the 1st rotation)

Weeds usually compete with trees for site resources and water, and adversely affect tree growth. An investigation in *Pinus radiata* plantations of South Australia revealed that weeds directly compete with trees for nitrogen, and thereby aggravate nitrogen deficiency (Smethurst & Nambiar, 1989). Increase in diameter of trees in *E. grandis* plantations of New South Wales in response to weeding was reported by Wilkins (1990).

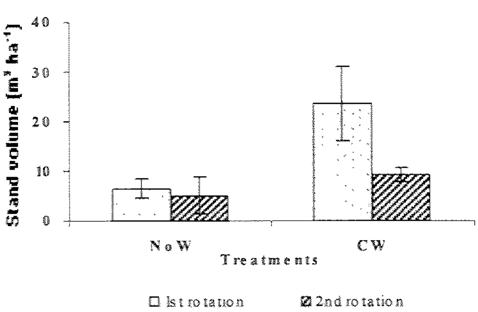
According to Glover and Zutter, (1993), weed control helps substantial gains in survival, individual tree growth and stand yield in forest plantations. Results of the studies conducted by Little *et al.* (2003) in plantations of *Eucalyptus* hybrid clone (*E. grandis* x *E. camaldulensis*) in South Africa also agree with the above observation. Data



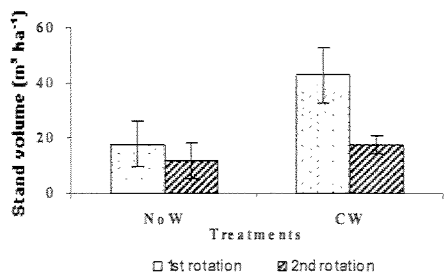
a. 12th month



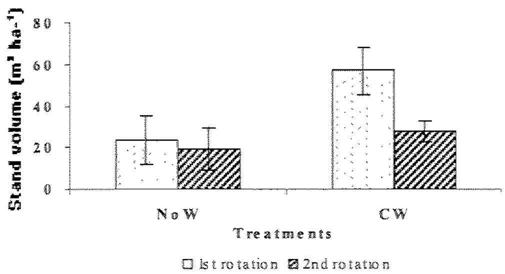
b. 18th month



c. 24th month

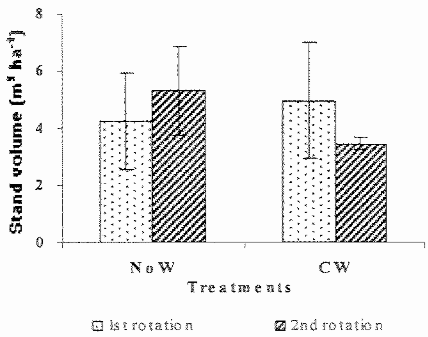


d. 36th month

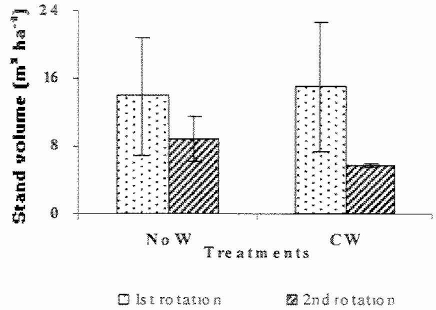


e. 48th month

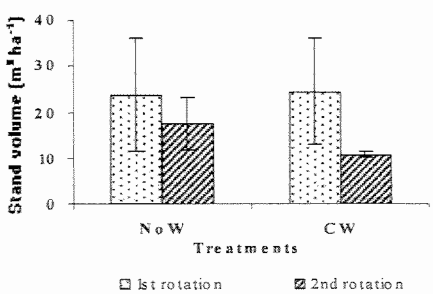
Fig. 5. Comparison of stand volume of first and second rotation *E. tereticornis* plantations in weeding experiment



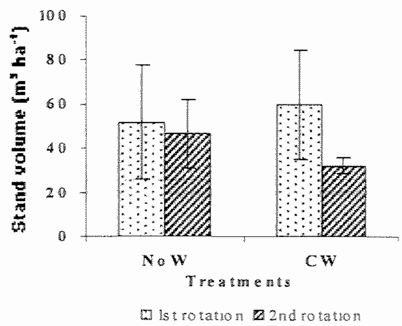
a. 12th month



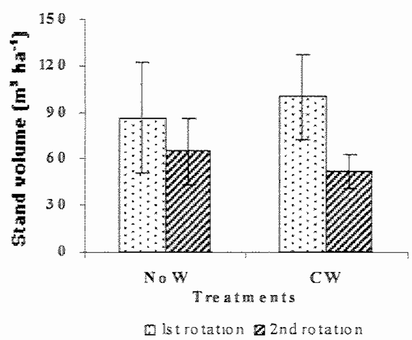
b. 18th month



c. 24th month



d. 36th month



e. 48th month

Fig. 6. Comparison of stand volume of first and second rotation *E. grandis* plantations in weeding experiment

on stand volume of the first rotation crop in the present study revealed that weed control alone can double the productivity of *E. tereticornis* plantations in Kerala (Sankaran *et al.* 2008 & 2012). Comparable results were obtained for *Pinus taeda* in Georgia, USA where a combination of weeding and fertilizer inputs in plantations resulted in the production of 180 t ha^{-1} of stem biomass in 15 years, which is about twice the productivity than that of control stands (Borders *et al.*, 2004). All these studies point to the fact that weed control significantly improves productivity of forest plantations.

However, in *E. grandis* plantation, weed control did not significantly affect stand volume except for early in the rotation. This can be ascribed to the fact in *E. grandis* plantation, the canopy closes within 2 yrs of growth and shading effectively suppresses weed growth and as such weed growth was insignificant. Conversely, *E. tereticornis* develops a sparse crown cover which allows greater light penetration to the soil surface and promotes weed growth (Pillai *et al.*, 2012, in press).

3.5. Residual effect of P input on coppice crop

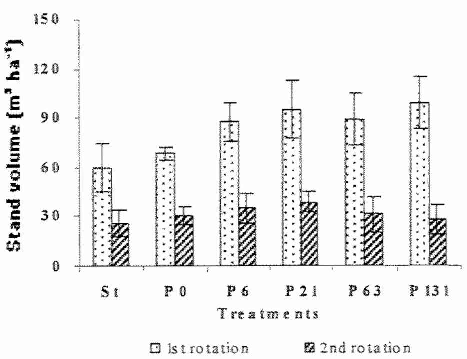
Stand volume of 48-month-old coppice crop of *Eucalyptus* maintained in the P input plots is shown in Table 8. Stand volume of the coppice crop varied between P treatments and the MAI ranged between 7-10 and 12-21 m^3 ha^{-1} yr^{-1} respectively, for *E. tereticornis* and *E. grandis* plantations. The higher stand volume of coppice crop of *E. grandis* at P_{131} + N_{187} (Table 8; Fig. 7b) than all other treatments (both N and P) also indicates a positive influence of N/P balance in improving stand yield. However, growth differnces in coppice crops were not signficant between treatments indicating that there was no residual effect of P applied in the first rotation (Tables 5 & 6). It may be noted that P fertilizer input significantly improved productivity of both *E. tereticornis* and *E. grandis* plantations in the first roation (Sankaran *et al.*, 2008). Productivity of the P plots differed significantly between rotations with the first rotation having significantly higher productivity than the coppice crop (Table 10) (Figs. 7a & b). Enahnced productivity of forest plantations in response to P application has been reported by several workers (Balagopalan & Rugmini, 2003; Du Toit *et al.*, 2008; Vu Dinh Huong *et al.*, 2008).

Depletion of site nutrients is likely to affect growth in future rotations of the site unless nutrients are replenished (Sankaran *et al.*, 2004). Xu *et al.*, (2008) reported a similar experience in China where the coppice crop of *E. urophylla* showed lower productivity compared to the first rotation seedling crop. But, coppice trees grew better than re-planted trees when NPK fertilizer was applied. It was shown that well-developed root system helps the coppice to utilize soil nutrients effectively and thus better growth. These studies indicate that nutrient input in coppice crop will give higher productivity than the first rotation seedling crop.

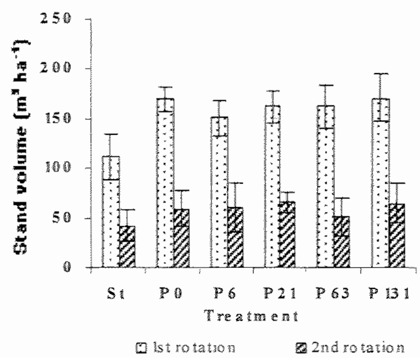
Table 8. Mean stand volume and MAI of 48-month-old coppice crop of eucalypts applies with different dosages of P in the 1st rotation.

Treatment	*E. tereticornis*		*E. grandis*	
	Stand volume ($m^3 ha^{-1}$)	MAI ($m^3 ha^{-1} yr^{-1}$)	Stand volume ($m^3 ha^{-1}$)	MAI ($m^3 ha^{-1} yr^{-1}$)
St	26.09	6.52	42.04	10.51
P_0	29.95	7.49	53.95	13.49
P_6	34.57	8.64	49.63	12.41
P_{21}	38.74	9.69	56.14	14.03
P_{63}	31.49	7.87	47.39	11.85
P_{131}	28.04	7.01	82.68	20.67

Note: St - control for P experiment (Initial dose of fertilizer only); P_0 - zero phosphorus input; P_6 - 6.3 kg P ha^{-1}; P_{21} - 21 kg P ha^{-1}; P_{63} - 63 kg P ha^{-1}; P_{131} - 131 kg P ha^{-1}



a. *E. tereticornis*



b. *E. grandis*

Fig. 7. Comparison of stand volume of 48-month-old 1st rotation and coppice crop in P experiment

Absence of treatment effect across plots treated with different levels of P (in the first rotation) in the coppice crop indicates lack of residual effect. However, further studies involving different combinations of N and P is required to establish conclusive results in this direction.

3.5. Residual effect of harvest residue management (OM) on coppice crop

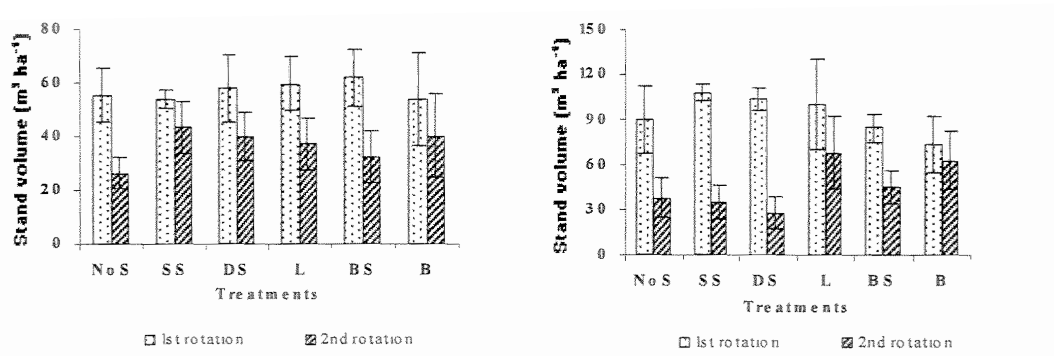
Stand volume of 48-month-old coppice crop of *Eucalyptus* grown in the plots of harvest residue management (OM) is given in Table 9. The results showed that residual effect of slash management in the coppice crop of *E. tereticornis* and *E. grandis* crop was not significant (Tables 5 & 6). The first rotation crop at these sites also had a minimal effect on productivity due to harvest residue retention (Sankaran *et al.*, 2008). However, productivity of the first rotation crop in these plots had significantly higher productivity compared to the coppice crop under both the species (Table 10, Figs. 8a & b).

Jones *et al.* (1999) reported that retention of harvest residues at the site after harvest is important for ensuring soil fertility and improved productivity of later rotations. It helps nutrient retention in the soil and protection of soil structure. O'Conell *et al.* (2004) reported that retention of harvest residues will favour the conservation of N following logging for a short period. Increase in nitrogen and organic carbon in the surface soil and improved plantation productivity due to slash retention has been reported by others (Tiarks & Ranger, 2008; Vu Dinh Huong *et al.*, 2008; Xu *et al.*, 2008). However, some other studies have shown that slash management has no significant impact on plantation productivity (Du Toit *et al.*, 2008; Mendham *et al.*, 2008). Decrease in growth response of trees to residue management is a general pattern when the soil fertility is very high, and the main processes that influence growth response to harvest residue management is related to soil microclimate and soil nutrient availability (Deleporte *et al.*, 2008). It also depends on the volume of slash available and retained in the plantation. Accumulation of soil mineral N following harvesting due to reduced plant uptake will result in leaching of N early in rotation and thereby fail to sustain the effect during later phases (Van Drecht et al., 2009). These results need not preclude slash retention in eucalypt plantations since enhancement of site nutrients is a long term process expected to be achieved through this silvicultural intervention and it depends on several factors as discussed above.

Table 9. Mean stand volume and MAI of second rotation eucalypt plantations in the plots of harvest residue management (OM) during 48th month

Treatment	*E. tereticornis*		*E. grandis*	
	Stand volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Stand volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})
NoS	26.52	6.63	61.33	15.33
SS	43.73	10.93	75.19	18.80
DS	47.55	11.89	66.31	16.58
L	37.25	9.31	72.31	18.08
BS	32.38	8.09	70.27	17.57
B	40.23	10.06	75.95	18.99

N_0S - control (no slash); SS - single slash; DS - double slash; L - leaf slash only; BS - Burn with initial dose of fertilizer; B - Burn (all residues burnt); (treatments applied during 1st rotation)



a. *E. tereticornis* b. *E. grandis*

Fig. 8. Comparison of stand volume of 48-month-old 1st and 2nd rotation eucalypt plantations in OM experiment

In general, comparison between the first and second rotation crops showed that the stand volume of second rotation coppice crop was significantly lower than that of first rotation seedling crop (Table 10). Our observations reveal that this low productivity was due to a significant reduction in the number of trees in the coppice crop of both the species due to mortality of parental stumps.

Table 10. F value and levels of significance with respect to stand volume between 1st rotation and coppice crop in *E. tereticornis* and *E. grandis* plantations

Species	Source of variation	N input	Weed manageme nt	P input	Harvest residue management (OM)
E. tereticornis	Rotation	167.69***	47.60***	503.75***	51.41***
E. grandis	Rotation	27.89***	25.82**	75.72***	60.52***

***p<0.001, **p<0.01, *<0.05, ns=non-significant

3.6. Coppice management

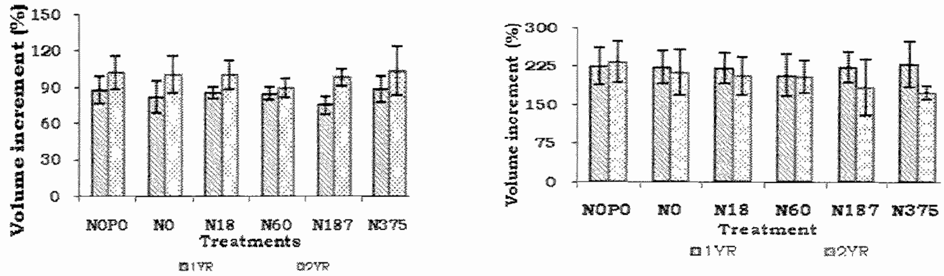
A number of coppice shoots sprouted one week after harvest. Retention of more shoots usually leads to poor growth, so it was reduced to original stocking in two operations (Plate 1). Increment of stand volume of the coppice crop after shoot reduction each time is depicted in Figures 9 and 10. Table 11 represents significance levels of volume increment between first and second coppice reduction in eucalypt plantations. Significant increase in stand volume was found in N_{187} treatment plots of *E. tereticornis* plantation and N_{375} and NoW treatment plots of *E. grandis* plantation.

PLATE 1. Coppice shoots and its different stages of growth after each coppice reduction; **a.** 2-month-old coppice; **b.** Shoot reduced to 3 at 1 year after harvest on stump side; **c.** Shoot reduced to 3 at 1 year after harvest on stump top; **d.** Shoot reduced to 1 at 2 year after on stump side; **e.** Shoot reduced to 1 at 2 year after harvest on stump top; **f.** 3-year-old coppice shoot on stump side; **g.** 3-year-old coppice shoot on stump top growing as true stem; **h.** Wind fallen coppice shoot from stump side

Reduction of multiple coppice shoots to a single stem helped to avoid butt sweep formation. The singling out of the coppice stems also enables all the site resources to be utilized by the single shoot. According to Archibald (2002), coppice should be reduced to 1-3 shoots per stump when they are about 2 m height. Little and Gardner (2003) noted that it would be advantageous if the number of coppice shoots is reduced to equal mother stumps. Coppice shoots that were retained on the windward side were less liable to wind throw. Shoot retained on top of the stump got wrapped up by callus over a period of time. The shoot, thus formed continued to grow as a true stem with firm attachment to the stump and this could withstand wind shear (Plate 1g). Shoot retained on one side of the stump which grows as a separate stem from the stump will usually be with weak attachment, and susceptible to wind damage (Plate 1f & h)

Table 11. F value and levels of significance with respect to % volume increment between 1st and 2nd coppice reduction in euclaypt plantations

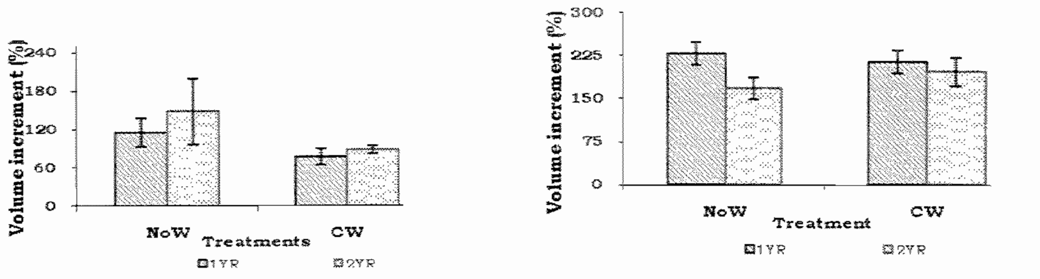
Treatments	*E. tereticornis*	*E. grandis*
N_0P_0	2.617^{ns}	0.093^{ns}
N_0	3.315^{ns}	0.130^{ns}
N_{18}	5.281^{ns}	0.386^{ns}
N_{60}	0.920^{ns}	0.012^{ns}
N_{187}	19.676^{**}	1.565^{ns}
N_{375}	1.754^{ns}	5.903^{*}
NoW	1.407^{ns}	18.243^{**}
CW	2.420^{ns}	1.209^{ns}



a. *E. tereticornis* **b.** *E. grandis*

Note: 1YR = one year after shoot reduction (multiple shoots reduced to 3); 2YR = 1 year after reducing the shoots from 3 to 1.

Fig. 9. Volume increment (%) after each shoot reduction in the nitrogen experimental plots of eucalypt plantation



a. *E. tereticornis* b. *E. grandis*

Note: 1YR = one year after shoot reduction (multiple shoots reduced to 3); 2YR = 1 year after reducing the shoots from 3 to 1.

Fig. 10. Volume increment (%) after each shoot reduction in the weeding experimental plots of eucalypt plantations

According to Luna (2005), during the first three to four years, coppice shoots grow fast at the rate of 2 to 3 m per year and thereafter growth is at par with the seedling crop. The height and the diameter of coppice shoots were significantly higher in the stumps of larger diameter. By reducing the multiple coppice shoots to a single stem, though the number of stems and possibly the stand volume got reduced, there was no formation of butt sweep that affects the pulpwood quality. When two or more shoots are retained, the shoots will usually bend at the bottom and this result in the formation of reaction wood. When reaction wood is formed it affects the wood density and influenced characteristics of fibres associated with them which are undesirable qualities for paper pulp (Kaeiser & Boyce, 1964).

The decision to reduce the coppice into a single stem (second coppice reduction) during the present study was to avoid the formation of reaction (tension) wood when more than one stem is retained. The study indicated that coppice reduction indirectly affects stand volume. Here, the option is left to the plantation manager whether to choose a higher stand volume by retaining more stems or to ensure pulp quality by retaining a single stem. If the former is important, the coppice shoots should not be reduced from three per stump. The stump diameter is a useful indicator to schedule the felling of any coppicing species and the stem diameter is positively correlated with growth of coppice shoot (Boivin-Chabot *et al.*, 2004). This study has also shown that coppice removal has a positive effect on volume increment and it need be practiced as a routine silvicultural practice in 2nd rotation eucalypt plantations.

4. Conclusions

The study indicates that, in general, the treatment effects due to nitrogen and phosphorus fertilizer and slash and weed management (applied in the first rotation) were not significant as a residual effect in the second rotation (coppice) plantations of *E. tereticornis* and *E. grandis* in Kerala. It implies that silvicultural inputs will have to be repeated and continued for improving productivity of the subsequent rotation of eucalypt plantations. It is also evident from this study that though retention of three stems in a stump in a coppice growth enhances stand productivity, it affects pulping quality of wood by formation of reaction (tension) wood. So, if the pulping quality is the concern, it is advisable to retain only one stem per stump. The option is left to the plantation manager. In any case, reduction of stems in a stump (up to 3) in a coppice crop is a silvicultural practice which must be practiced regularly to ensure maximum yield.

5. References

Ajith Kumar, K.G. 2001. *Clonal variability in Eucalyptus tereticornis* Sm. Ph.D. thesis, FRI Deemed University, Dehra Dun: 164 pp.

Archibald, R. 2002. Managing blue gum (*Eucalyptus globulus*) coppice. *Tree Note No. 35*, May 2002. Department of Agriculture and Food, Government of Western Australia. 7 pp.

Balagopalan, M., Rugmini, P. & Basha, S.C. 1998. Enhancement of productivity in *Eucalyptus* through fertilizer inputs and other cost effective treatments. *KFRI Research Report No. 153*. Kerala Forest Research Institute, Peechi, Kerala.

Balagopalan, M. and Rugmini, P. 2003. Improvement in productivity of *Eucalyptus tereticornis* through nutrient inputs and silvicultural treatments. *KFRI Research Report No. 250*. Kerala Forest Research Institute, Kerala, India. 30 pp.

Boivin-Chabot, S., Margolis, H.A. and Weber, J.C. 2004. Variation in coppice-shoot growth among provenances of *Calycophyllum spruceanum* Benth. in the Peruvian Amazon Basin. *Forest Ecology and Management* 198(1-3): 249-260.

Borders, B.E., Will, R.E., Markewitz, D., Clark, A., Hendrick, R., Teskey, R.O. and Zhang, Y. 2004. Effect of complete competition control and annual fertilization on stem growth and canopy relations for a chronosequence of loblolly pine plantations in the lower coastal plain of Georgia. *Forest Ecology and Management* 192: 21-37.

Colac, L.H. 2000. Managing coppice in eucalypt plantations. *Agriculture Notes*, Department of Primary Industries, State of Victoria, June 2000. 1-4.

Deleporte, P., Laclau, J.P., Nzila, J.D., Kazotti, J.G., Marien, J.N., Bouillet, J.P., Szwarc, M., D'Annunzio, R. and Ranger, J. 2008. Effects of slash and litter management practices on soil chemical properties and growth of second rotation eucalypts in the Congo. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004, Brazil and 6-9 November 2006, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 5-22.

Du Toit, B., Dovey, S.B. and Smith, C.W. 2008. Effects of slash and site management treatments on soil properties, nutrition and growth of a *Eucalyptus grandis* plantation in South Africa. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004, Brazil and 6-9 November 2006, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 63-77.

FAO. 2006. *Global planted forest thematic study: results and analysis. Planted Forest and Trees.* FAO Working Papers, FP38E. Rome, Italy. 168 pp.

FAO. 2011. *Planted Forests and Trees Working Papers: Eucalypts in East Africa, Socio-economic and Environmental Issues.* Working Paper FP 46/E, Forestry Department, FAO, Rome, Italy. 30 pp.

Glover, G.R. and Zutter, B.R. 1993. Loblolly pine and mixed hardwood stand dynamics for 27 years following chemical, mechanical, and manual site preparation. *Canadian Journal of Forest Research* 23: 2126-2132.

Gonçalves, J.L.M, Stape, J.L., Laclau, J.P., Smethurst, P. and Gava, J.L. 2004. Silvicultural effects on the productivity and wood quality of eucalypt plantations. *Forest Ecology and Management* 193: 45-61.

Gonçalves, J.L.M., Stape, J.L., Laclau, J.P., Bouillet, J.P., Ranger, J. 2008. Assessing the effects of early silvicultural management on long-term site productivity of fast-growing eucalypt plantations: the Brazilian experience. *Southern Forests* 70 (2): 105-118.

Jones, H.E., Maderia, M., Harraez, L., Dighton, J., Fabiao, A., Gonzalez-Rio, F., Marcos, M.F., Gomez, C., Tome, M., Feith, H., Magalhaes, M.C. and Howson, H. 1999. The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. *Forest Ecology and Management* 122: 73-86.

Kaeiser, M. and Boyce, J.G. 1964. Averages and correlation coefficients between specific gravity and a number of wood properties on Eastern cotton wood, including gelatinous fibers. *American Journal of Botany* 51: 673.

Little, K.M. and Gardner, R.A.W. 2003. Coppicing ability of 20 *Eucalyptus* species grown at two high-altitude sites in South Africa. *Canadian Journal of Forest Research* 33: 181-189.

Little, K.M., van Staden, J., Clarke, G.P.Y. 2003. The relationship between vegetation management and the wood and pulping properties of a *Eucalyptus* hybrid clone. *Annals of Forest Science* 60: 673-680.

Luna, R.K. 2005. *Plantation Trees*. International Book Distributors, Dehra Dun. 975 pp.

Mendham, D.S., Grove, T.S. and O'Connell, A.M. 2008. Impact of inter-rotation site management practices on soil nutrients and plantation productivity in *Eucalyptus* in South-Western Australia. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004, Brazil and 6-9 November 2006, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 23-37.

Nair, K.S.S., Jayaraman, K. and Chacko, K.C. 1997. Productivity of teak and eucalypt plantations in Kerala. *Final Report of Research project 250/1996*. Kerala Forest Research Institute, Peechi, Kerala, India.

Nambiar, E.K.S. 1996. Sustained productivity of forest is a continuing challenge to soil science. *Soil Science Society of America Journal* 60: 1629-1642.

O'Conell, A.M., Grove, T.S., Mendham, D.S. and Rance, S.J. 2004. Impact of harvest residue management on soil nitrogen dynamics in *Eucalyptus globulus* plantations in south western Australia. *Soil Biology and Biochemistry* 36: 39-48.

Pillai, P.K.C., Sankaran, K.V. and Pandalai, R.C. 2012. Regeneration of understory vegetation in eucalypt plantations in South India. *Forest Ecology and Management* (in press).

Rockwood, D.L., Rudie, A.W., Ralph, S.A., Zhu, J.Y. and Winandy, J.E. 2008. Energy product options for *Eucalyptus* species grown as short rotation woody crops. *International Journal of Molecular Sciences* 9: 1361-1378.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Kallarackal, J., Somen, C.K., Sharma, J.K., Balagopalan, M., Balasundaran, M., Kumaraswamy, S., Sankar, S., Gilkes, R. J., Grove, T.S., Mendham, D.S. and O'Connell, A.M. 2000. Effect of site management on *Eucalyptus* plantations in the monsoonal tropics: Kerala, India. *In*: Nambiar, E.K.S., Tiarks, A., Cossalter, C. and Ranger, J. (eds.) *Site Management and Productivity in Tropical Plantation Forests: A Progress Report*: Workshop Proceedings Kerala, India. 7-11 December 1999. Center for International Forestry Research, Bogor, Indonesia: 51-60.

Sankaran, K.V., Chacko, K.C., Pandalai, R.C., Balasundaran, M., Grove, T.S., Mendham, D.S. and O'Connell, A.M. 2004. Influence of harvest residue management, weed control, legume cover cropping and soil trenching on *Eucalyptus* productivity in Kerala, India. *Journal of Tropical Forest Science* 24(2): 232-247.

Sankaran, K.V., Mendham, D.S., Chacko, K.C., Pandalai, R.C., Pillai, P.K.C., Grove, T.S. and O'Connell, A.M. 2008. Impact of site management practices on growth of eucalypt plantations in the monsoonal tropics in Kerala, India. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004 Piracicaba, Brazil and 6-9 November 2006, Bogor, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 23-38.

Sankaran, K.V., Chandrasekhara Pillai, P.K. and Pandalai, R.C. 2012. Impact of weeds on productivity of *Eucalyptus tereticornis* plantations in Kerala. National Seminar on 'Forest Health Management (FHM-2012)' held at IFGTB, Coimbatore, during 21-22 March, 2012.

Sharma, J.K, Mohan, C., Florence, E.J.M. 1985. Disease survey in nurseries and plantations of forest tree species grown in Kerala. *KFRI Research Report No. 36*. Kerala Forest Research Institute, Peechi, Kerala. 275 pp.

Sivaram, M, Sujith, K. S., Nayana K.G and Rini G. 2012. *KFSTAT 2.0* (Kerala Forestry Statistical Database). Kerala Forest Research Institute, Peechi (unpublished).

Smethurst, P.J. and Nambiar, E.K.S. 1989. Role of weeds in the management of nitrogen in a young *Pinus radiata* plantation. *New Forests* 3: 203-224.

Tiarks, A. and Ranger, J. 2008. Soil properties in tropical plantation forests: Evaluation and effect of site management. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26

November 2004 Piracicaba, Brazil and 6-9 November 2006, Bogor, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 191-204.

Van Drecht, G., Bouwman, A.F., Harrision, J. and Knoop, J.M. 2009. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. *Global Biogeochem. Cycles* 13: 647-662, dio: 10.1029/2009GB003458.

Vu Dinh Huong, Le Thanh Quang, Nguyen Thanh Binh and Pham The Dung. 2008. Site management and productivity of *Acacia auriculiformis* plantations in South Vietnam. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004 Piracicaba, Brazil and 6-9 November 2006, Bogor, Indonesia, Center for International Forestry Research, Bogor, Indonesia: 123-138.

Wilkins, A.P. 1990. Influence of silvicultural treatment on growth and wood density of *Eucalyptus grandis* grown on a previous pasture site. *Australian Forestry* 53(3): 168-172.

Xu, D.P., Yang, Z.J. and Zhang, N.N. 2008. Effects of site management on tree growth, aboveground biomass production and nutrient accumulation of a second-rotation plantation of *Eucalyptus urophylla* in Guangdong province, China. *In*: Nambiar, E.K.S. (ed.) *Site Management and Productivity in Tropical Plantation Forests*: Workshop Proceedings, 22-26 November 2004 Piracicaba, Brazil and 6-9 November 2006, Bogor, Indonesia, Center for International Forestry Research, Bogor, Indonesia. 39-49.