Improving and maintaining productivity of eucalypt plantations in India and Australia

Final report of research projects
Phase I (KFRI 281/97) and Phase II (422/2004)

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In collaboration with

CSIRO Forestry and Forest Products, Perth, Western Australia
Centre for International Forestry Research, Indonesia
Kerala Forest Department
Hindustan Newsprint Ltd and
Kerala Forest Development Corporation

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Peechi 680653, Kerala
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This report only deals with results of the work done in India. Those who are interested in the work carried out in Australia, please refer to:

O'Connell, A.M. and Sankaran, K.V. 2002. Improving and maintaining productivity of eucalypt plantations in India and Australia. Final report submitted to Australian Centre for International Agriculture Research, Australia, 60p.

The above report gives a concise account of the results of the work done in both the countries.

Contents

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Abstract

The impact of site management practices viz., harvest residue retention, weeding, fertilizer application, legume intercropping, thinning and trenching on tree growth was evaluated in *Eucalyptus tereticornis* and *E. grandis* plantations in Kerala for a full rotation during 1998-2005. Biomass and nutrient content of the tree crop, forest floor and understory of the previous stands were determined before establishing the experiments. Soils were classified and changes in soil nutrient stores and nutrient cycling consequent to the treatments evaluated. The decay rate of harvest residues and nutrient release during decay were quantified. Photosynthesis, leaf water potential and tree water status in the sites were also assessed.

The sites used in this study represent the range of eucalypt plantations in Kerala with contrasting fertility at both highland and lowland areas. Sites at Kayampoovam (*E.tereticornis)* and Vattavada *(E.grandis)* had relatively high fertility while Punnala *(E.tereticiornis)* and Surianelli (*E.grandis)* were poor in fertility. Eucalypt productivity was highest at Vattavada and lowest at the least fertile sites.

Quantities of carbon and nutrients in the soil were much higher than those found in the above ground biomass of plantations. The highland sites had higher organic C than the lowland sites. Total cumulative N at the two highland sites was approximately double that at the lowland sites. Soil cations were significantly lower at the least fertile sites compared to the fertile sites.

Removal of harvest residues (leaf, bark and branches) and understory from the sites was found to cause significant loss of N, P and cations from the site. Burning of residues, which is the normal practice in Kerala, will also result in volatilization and loss of major nutrients. These losses cannot be replenished through natural inputs. Ameliorating this situation will require return of nutrients to the site or retaining nutrient rich harvest residues at sites since nutrient availability is already a limiting factor to growth of eucalypts in Kerala.

Of the various treatments, retention of residues did not significantly improve eucalypt productivity at the sites probably due to the low amount of residues. However, it is recommended that harvest residues may be retained at the sites to improve site nutrient capitals in the long-term. Results indicate that the mean standing volume in harvest residue treatments was significantly higher than the previous rotation at all sites. The productivity increase at the end of the rotation was in the range 47-119% at *E.tereticornis* sites and 77-224% at the *E.grandis* sites which shows that use of good quality planting stock and periodic weeding alone can improve eucalypt productivity in Kerala.

Intercropping of legumes in eucalypt plantations may be advantageous since *Pueraria* and *Stylosanthes* improved productivity at one of the *E.tereticontis* sites. However, choice of climbers like *Mucuna* and *Pueraria* may be avoided since they can smother trees if not managed periodically.

The thinning experiments at the *E. grandis* sites showed that it would be ideal to keep 2300 stems ha^{-1} to get higher productivity in intensively managed eucalypt plantations.

Though not significant, a trend for consistent higher productivity in plots with either contour or staggered trenching was observed in one *E.tereticornis* and one *E.grandis* plantation. Trenching will have an impact in sites where water becomes a limiting factor for growth. Also, conservation of top soil by trenching may have an impact on productivity at steep sites which are prone to erosion.

Periodic weeding significantly improved eucalypt productivity especially at the *E. t* sites (by 77 and 150% at Kayampoovam and Punnala, respectively). The study has demonstrated that weeding alone can improve eucalypt productivity in *E. tereticronis* plantations.

Responses to fertilizers were quite variable across sites with one each of the *E. tereticornis* (Punnala) and *E.grandis* (Surianelli) sites showing good responses to N and P fertilizer which reflect the inherent difference in the nutrient supply characteristics of soils. It is thus clear that nutrient application will have to be targeted to sites that respond to treatments.

The current (CAI) and mean annual increment (MAI) values of the standing crop show that 5-6 yrs may be an appropriate time to harvest intensively managed *E tereticornis* and *E.grandis* plantations in Kerala.

The influence of harvest residue retention on soil N, P and C was relatively minor in the short term period of this study with only a few detectable changes to the soil characteristics explored. Retention of harvest residues at the sites did increase the N mineralization and microbial biomass and it is evident that the residues contain large quantities of these critical nutrients.

The incubation experiment with legume and eucalypt residues proved that the degree of N mineralization and immobilization was directly related to the N concentration of the residues. Net N release from plant residues decreased in the order *Mucuna*>*Pueraria*> *Eucalyptus*> *Stylosanthes*.

N mineralization rates quantified from plots applied with N fertilizer have shown that the best indicator of response to fertilizer across sites was the net N released during aerobic incubation.

Studies on slash decay have shown that the residues decayed rapidly especially at the *E.tereticornis* site. Almost all of the leaf and bark residues decayed by the end of the first year and over 50% of the twigs also had disappeared. The decay rate was significantly slower at the *E. g* sites.

Release of K during decomposition of residues was rapid with most of K lost in the first month of decay. Release of other nutrients was slower with P followed by Mg most rapid at most sites. Eucalypt bark is a rich source of nutrients (especially Ca) compared to leaves and twigs. But, the decay rate of bark is lower than that of leaves after an initial rapid phase.

Comparison of estimated volume of standing trees and measured volume of harvested logs showed that conical approximation is a robust measure of the volume of standing trees in tropical eucalypt plantations. Moisture loss measured from stacked logs indicates that judicious stacking and choice of stacking season will optimize moisture loss from logs of different sizes.

Studies on plant physiological aspects showed that applied treatments influenced plantation growth through increase in leaf area rather than increases in photosynthesis per unit leaf area. Severe water stress is probably unlikely in Kerala where soil depth is over 5-6 m and the water table is shallow. And, increased productivity through intensive management only marginally increases water use but improves water use efficiency of wood production.

It is concluded that large increase in eucalypt productivity in Kerala could be achieved by use of good quality planting stock, timely and efficient weeding and judicious application of fertilizers wherever necessary. Intercropping of legumes will help to enhance productivity at nitrogen deficient sites. Retention of harvest residues (slash) at sites will be useful to enrich soil nutrient stores in the longer term.

1. Introduction

Eucalypts are amongst the most widely utilized tree species for plantations throughout the world. In countries like Brazil and South Africa, high rates of wood production are achieved from short rotation eucalypt plantations (growth cycles 5-10 years). In India, eucalypts are grown for production of pulpwood and fuel wood. The country has over 8 million ha of land under eucalypts (FAO, 2001). However, the productivity of these plantations has been relatively low (averaging less than 10 m^3 $ha^{-1}yr^{-1}$). In Kerala, the main eucalypt species used for planting are *Eucalyptus tereticornis* Sm. (grown at lower elevations) and *E. grandis* Hill ex Maiden (grown at 500 to 2000 m asl).These plantations are generally grown on a 6-7 year rotation. Poor productivity has resulted in abandoning of eucalypt plantations in Kerala state, decreasing the total area of the state-owned plantations from 40, 000 ha (in the 1990's) to less than 25,000 ha (early 2000). However, though eucalypt is a low priority species in Kerala now, there are extensive areas under eucalypts in the neighboring states in Southern India and elsewhere in northern India.

The low productivity of eucalypt plantations in Kerala has resulted in a big mismatch between demand and supply of eucalypt wood for the paper industries in the State. Part of this demand is met from plantations (which are limited in area) grown by the industries especially the Hindustan Newsprint Ltd. or by using wood of other species such as *Acacia auriculiformis.* Low productivity of eucalypt plantations in Kerala results from several causes – poor planting stock derived from seed lots with poor genetic base, disease outbreak, limited management of the plantations after establishment (especially weed control), declining soil fertility over successive rotations due to poor site/stand management, water stress and inadequate attention to stand nutrient requirement (Sharma et al., 1985; Ghosh et al., 1989; Kallarackal and Somen, 1997a).

Long-term studies elsewhere have shown that improvement in plantation productivity can be achieved through use of genetically superior planting stock and adoption of site management practices such as harvest residue retention, nutrient addition and weed control (Nambiar, 1996; Tiarks et al., 2000). In this context, the present study was aimed to evaluate management of site resources (soil organic matter, nutrients and available water) to improve and maximize productivity of eucalypt plantations in Kerala. The overall objective of the project was to identify and develop practices for manipulating soil organic matter, and soil and tree nutrient and water status as a basis for implementing silvicultural regimes which optimize conservation and use of site resources. These are expected to improve and ensure sustainable wood production from eucalypt plantations. The focus of the work was the inter-rotation period, which

is a period of high risk for potential loss of site resources but also a period when there is significant opportunity for judicious management intervention to enhance productivity of the next crop.

The research structure was as follows:

Sub Project 1: Nutrient cycling

Includes inventory of site nutrient pools in soils, trees, shrubs and litter; decomposition of harvest residues; and impact of harvest residue treatments on soil carbon, Nitrogen pools and phosphorous.

Sub Project 2: Plant physiology and water relations

Quantify degree of tree water stress and impact of silvicultural treatments on water stress, photosynthesis, leaf area index, transpiration and stand water use

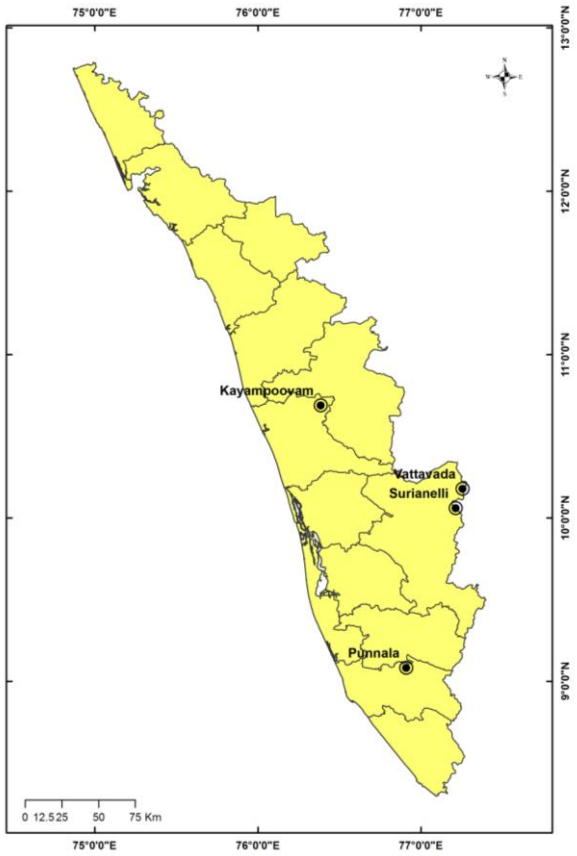
Sub Project 3: Tree growth and nutrient uptake

Measurement of tree growth at regular intervals in all experiments at all sites and evaluation of nutrient uptake.

2. Location, Climate and Site Description

The research plots were located at four sites that represented two geographic regions where eucalypts are planted in the state, the undulating coastal plains (< 1000 m asl) and high ranges (1000-2000 m asl). At the low elevation sites, *Eucalyptus tereticornis* was typically established on ex-degraded moist deciduous forests while in the high ranges, *E. grandis* was planted either on ex-grasslands or after clearing of natural semi-evergreen/shola forests. Kerala state is located between latitudes 8.2^{o} – 12.8^{o} N and between the Arabian Sea and the Western Ghats ranges in South India.

The geographical position of the sites, rainfall, soil characteristics and information on stocking density (stems ha^{-1}) and basal area and productivity of the original plantations are given in Table 1 (see also Map 1). The climate is tropical warm humid with two monsoonal periods, the southwest (the main monsoon) which starts in early June and extends until October and the northeast monsoon which brings occasional rains from December to February. The dry season begins in March and continues through May. Average rainfall is 3000 mm (range 2200-3600 mm) spread over 120 rainy days. Mean atmospheric temperature is 27^{0}C (range 20-40^{0}C) and relative humidity ranges between 64% (February-March) and 93% (June-July) (Menon and Rajan, 1989).



Location map of the experimental sites

Experiments were established at four sites, two each planted with *E. tereticornis* and *E. grandis*. At all sites, the parent material of soils was saprolite or saprolitic colluvium derived from Precambrian granites and gneiss. These igneous and metamorphic rocks contain abundant ferro-magnesium minerals that contribute to the chemical fertility of sites where rocks are present at shallow depth or in outcrops. At all sites the local relief and depths to bedrock or saprolite is highly variable and may be reflected in the heterogeneity of stand performance. Most soil profiles contained a ferralic B horizon (FAO, 1988) although the persistence of rock structure as remnant geneissic saprolite fragments sometimes exceeded 5 volume percent which is the upper limit for the horizon and may require assignment to an argic B horizon. The soils have been broadly classified as ferralsols. The very low content of exchangeable cations present in the B horizon of some profiles may lead to their assignment as geric ferralsols.

Because of the complex interactions of erosions of saprolite and deposition of colluvium, there is a considerable variation in profile depth and morphology at each site. This variation is reflected in the very variable extent of root proliferation in subsoil horizons. It is possible that the capacity of the soil column to retain water is strongly dependent on the depth of soil over bedrock or saprolite.

The two *E. tereticornis* sites (Kayampoovam and Punnala) were located in the foothills adjacent to the coastal plain. These sites were originally under degraded moist deciduous forest with the first crop panted in 1977. Trees were first harvested in 1991 and the first coppice crop (second rotation) was harvested in early 1998 for the purpose of this study. The two *E. grandis* sites (Surianelli and Vattavada) were located in the high ranges of the Western Ghats. Surianelli was a grassland (composed mainly of *Chrysopogon* sp.) before planting with eucalypt in 1968. After three rotations of the first crop, the site was replanted in 1991. The site at Vattavada was planted with eucalypt in 1958 after clear-felling a natural semi-evergreen forest. The trees were clear-felled after three rotations of the crop and replanted in 1991. Stands at the both the sites were harvested in May-July 1998 as part of this study.

3. Experimental design

Following harvesting of the existing stands, 5 or six experiments were established at each of the sites during June - September 1998. This was essentially the inter-rotation period when plantations were harvested and re-established. Each experiment was in a randomized block design with 3-6 treatments and four replicates. The plot size was 20 x 20m, tree spacing 2 x 2 m (2500 stems ha^{-1}) with 100 trees per plot (36 measurement trees after allocating two buffer rows). At Kayampoovam, 18 x1 8 m plots were used due to restriction in area available.

However, the same spacing was retained (25 measurement trees after allocating two buffer rows). The size of the experimental area was 4. 48 ha at Punnala, Surianelli and Vattavada and 3.24 ha at Kayampoovam. The seed lots for raising nurseries were obtained from Australian Tree Seed Centre, Canberra, Australia. The provenances used were seed lot Nos. 13446 (Nth of Cardwell Qld), 13487 (Palmer River Qld), 19010 Morehead R Cape York Qld), 10837 (16 km N Woolgoolga NSW), 13418 (Sirinumu Sogeri Plat Png), 13541 (9 K SW of Imbil Qld) and 15198 (80 km MNW Cooktown Qld) (*E. tereticornis*) and 17563 (45 K SSW Cairns Qld), 18569 Wongabel SF Qld), 13289 (Mount Lewis, T.Res.66 Qld) and 17562 (30 K SW Cairns Qld) (*E. grandis*).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 x 20 cm polyethylene bags filled with forest soil- sand mix (2:1 by volume) during February – March 1998. Seedlings were transplanted in the field during June till August 1998.

Harvest residues were burnt in all treatments prior to planting except in the residue retained and zero residue plots of the organic matter experiments. All treatments except burn only (B) and N and P trials received a starter fertilizer (100g per tree- NPK 17: 17:17 placed at 10 cm depth) applied in two doses at the time of planting and 3 months later to assist seedling establishment.

Table 1. Selected properties of the study sites and soils prior to the experiment

Properties/Site	Kayampoovam (*E.tereticornis*)	Punnala (*E.tereticornis*)	Surianelli (*E. grandis*)	Vattavada (*E. grandis*)
Latitude & longitude	10° 41′N. 76° 23′E	9° 06′N. 76° 54′E	10° 02′N. 77° 10′E	10° 08′N. 77° 15′E
Altitude (m)	120	150	1280	1800
Slope (°)	10	5	4	15
Rainfall (mm yr^{-1})	2700	2000	3000	1800
Soil texture	Coarse sandy, light clay to medium day	Sandy loam to clay loam	Medium clay to sandy loam	Silt clay loam to medium clay
Previous land use	Moist deciduous forest	Moist deciduous forest	Grassland	Semi-deciduous forest
Plantation density (stems ha^{-1})	1356	965	1056	3898
Plantation basal area ($m^2 ha^{-1}$)	12.9	7.3	10.3	33.7
Age of previous rotation (years)	7	7	7	7
Plantation productivity ($m^3 ha^{-1}yr^{-1}$)	11.6	6.1	9.0	31.3
pH (1:5 H_2O)	5.3	5.1	4.8	5.3
Total C (0-10 cm) mg g^{-1}	16.0	43.0	37.2	50.4
Total N mg g^{-1}	1.23	2.43	2.15	3.61
C:N ratio	11.8	15.1	16.4	11.6
Total P (mg g^{-1})	0.61	0.40	0.55	0.75

E. grandis grew rapidly and canopies closed early at both sites. So, stands were thinned to 1667 stems ha^{-1} in May –June 2000 at Surianelli and Vattavada. The *E. tereticornis* sites remained un-thinned. Additional basal N and P fertilizer was applied to the trenching and thinning experiments in mid- 2000 and 2001. Plots with legume inter-cropping received P at the rate of 42 kg^{-1} (in split doses) during July-Nov. 1998. Atmospheric temperature, humidity, soil temperature and soil moisture content were measured regularly at all sites.

4. Treatments applied

1. *Organic matter manipulation (all sites)*

- No slash (0S) - all harvest residues (branches, bark and leaves) removed
- Single slash (SS) - harvest material retained and spread evenly on each plot. It amounted to 19.4 t ha^{-1} (27% of total above ground tree biomass) at K'poovam, 6.4 t (28%) at Punnala, 11.8 t (29%) at Suianelli and 18.9 t (18%) at Vattavada.
- Double slash (DS) – normal residue plus residues added from zero slash and spread evenly
- Leaf slash only (L) – all wood residues removed (simulates fire wood removal)
- Burn (BS) – all residues burnt and starter fertilizer applied
- Burn (B) – all residues burnt (no starter fertilizer applied – common practice)

2. *Inter-row legumes (*Kayampoovam and Punnala*)*

- Three legumes planted as inter-crops and plots without legume served as control. The legumes used for inter-cropping were
  1. *Peuraria phaseoloides* (P) -Shade intolerant - raised in a nursery for 2 months and transplanted in the treatment plots during July 1998 and July 1999 (at 2 x 2 m spacing).
  2. *Stylosanthes hamata (*S) Shade intolerant – seeds sown in linear furrows across the plot areas @ 9 kg seeds ha^{-1} during July-August 1998.
  3. *Mucuna bracteata* (M) Shade tolerant- raised in a nursery for 2 months and transplanted in the treatment plots during July-August 1998
  4. Control (plots with no legumes, but regularly weeded)

An area around the base of the tree (0.5 x 0.5 m) was cleared of the weeds and legumes in all the treatments. Above ground biomass of legumes (oven-dried and weighed)was assessed by sampling 4 x 0.25 m^2 quadrats per plot at several times up to 42 months after establishment. Samples were oven-dried and weighed. The perennial legumes *Mucuna* and *Pueraria* are climbers and regular pruning was necessary to ensure that tree growth was not suppressed. *Stylosanthes* is an annual or short- lived herb which is semi-erect mostly and sometimes prostrate.

3. *Spacing trials (E. grandis* sites at Surianelli and Vattavada*)*

- Thinning at 2 yrs to 4 different stand densities
  800 (S08), 1200 (S12), 1600 (S16) and partially thinned/un-thinned at 2300 (S 23) stems ha^{-1}

The strategy for thinning was to ensure uniformity in the remaining stand and to retain approximately even spacing. The volume of timber removed in the thinning operation at the *E. grandis* plots was 3.2 m^3 ha^{-1} at Surianelli and 13.6 m^3 ha^{-1} at Vattavada.

4. *Weed management*

- Weeds retained except for a spot around tree base (NW)
  Weed biomass was approximately 6.7, 4.6, 3.3 and 2.3 t ha^{-1}, respectively at Kayampoovam, Punnala, Surianelli and Vattavda sites at 1 yr after establishment.
- 1 meter strip weed control along tree rows (SW) through sickle weeding
- Total weed control (CW): cutting off the weeds close to the soil surface atthree times a year (March-April, July-August and November – December).

Weed growth was reduced in the third year under *E. grandis*(due to canopy closure) and weeding was required only twice- a-year thereafter (July-Aug and November-December).

5. *Phosphorus additions* (with a basal dressing of N and K and other minor nutrients)

- 5 levels of P (as superphosphate) added at 4 split doses in the first and second year, total rates were
  P1 -0 kg Pha^{-1} ; P2 - 6.3 kg; P3- 21 kg; P4- 63 kgandP5 – 131 $kgha^{-1}$; S – starter fertilizer only (18.5 kgP ha^{-1}plus 42.4 kg Nha^{-1}). Basal dressing of N @ 187 $kgha^{-1}$ was applied in all the treatments. N was also applied at 4 years at a rate equivalent to half the initial basal N rate.

6. *Nitrogen additions* (with a basal dressing of P and K and other minor nutrients)

- 5 levels of N added (as urea) at 3 intervals annually for 2 years, rates were as follows
  N1- 0 kg; N2 – 18 kg; N3- 60; N4- 187 kg and N5- 375 kg N ha^{-1} $yr^{-1}$for 2 yrs; N0P0- neither N or P added. N was also applied at 50 % of the above rates in *E. tereticornis* plots and at 33% in *E. grandis* plots in the fourth year. Basal dressing of P in the N experiments was 63 kg ha^{-1}

7. *Soil trenching* (Punnala, Surianelli and Vattavada)

- Two levels of trenching –Staggered and contour trenches dug in replicate plots and plots not trenched served as control. Trench spacing was dependent on the topography of the site. In general, the trenches were 1 m long, 30 cm wide and 30-50 cm deep.

The contour trenches were spaced at vertical contour intervals depending on the slope of the site. The contour spacing at Punnala and Surianelli were 1m and it was 0.5 m at the steeper Vattavada. Staggered trenches were dug across the slope and their length was adjusted so that the area occupied by both types of trenches remained the same. Trench depth at Surianelli was increased to 1 m at 18 months after planting. Soil from the trenches was placed on the down slope side of each of the trenches.

5. Methods

5.1. Site nutrient pools

5.1.1. ***Biomass and nutrient content of forest floor*****:** Forest floor was sampled with twelve 0.5 x 0.5 m quadrats at each site. Litter was separated into components derived from eucalypt over storey (leaves, twigs and bark) and miscellaneous components derived from the under storey and finely comminuted organic matter. Sample dry weights were determined after oven drying at 70^0 C and subsamples from each of the 12 quadrats were ground and digested using the sulfuric acid/hydrogen peroxide digest of Heffernan (1985). Digests were analyzed for N and P on a flow injection analyzer, Ca and Mg on an atomic absorption spectrometer and K on a flame photometer.

5.1.2. ***Understory biomass and nutrient content:*** Understorey was sampled from twelve 2 x 2 m plots at each site. All understory material was harvested from each quadrat and separated into primary and secondary species. The primary understory species consisted mainly of *Chromolaena odorata* at the *E. tereticornis* sites, *Lantana camara* at Surianelli and *Ageratum conyzoides* at Vattavada. Other dominant understory species included *Glycosmis pentaphylla*, *Mallotus philippinensis* and *Vigna* sp. at Kayampoovam, *Alstonia scholaris*, *Calycopeteris floribunda* and *Macaranga peltata* at Punnala, and *Chrysopogon* and *Lava* sp. at Surianelli. Understory samples were separated into leaves plus small branches (< 1 cm), and larger branches and stems (> 1 cm diam). Fresh weights were determined in the field and subsamples were oven dried at 70^0 C to determine component dry weights. Dried sub-samples from each of the 12 quadrats were ground, digested in sulfuric acid/hydrogen peroxide and analyzed for N, P, K, Ca and Mg as discussed above.

5.1.3. ***Tree biomass and nutrient content****:* At each site, DBH (diameter at breast height - 137 cm) of all trees was measured. Six to eight trees representing the range in DBH were harvested at each site to determine tree biomass and nutrient content. Total height, height to the crown base and stem diameter at different heights (over and under bark) were measured and trees separated into leaves, branches (less than 1 cm, 1-3 cm and greater than 3 cm diameter), stem wood and stem bark. Each component was weighed in the field and subsamples were oven dried at 70^0C and weighed to determine biomass of various tree components. Sub-samples were ground and analyzed for N, P, K, Ca and Mg as detailed above. Biomass and nutrient content of the trees at each site was estimated on a dry weight basis by relating DBH of the destructively sampled trees to component dry weight dry weight or nutrient content using allometric functions of the form $In(y)= a \times In (x)+b$, where y was

biomass/nutrient content of the different components, x was diameter at breast height and the 'a' and 'b' parameters derived from the model fit to the empirical data. The values of the parameters for total biomass and nutrient content for each site/nutrient combination are shown in Table 2.

5.1.4. ***Soil sampling:*** Two pits (1 m deep) were dug at different positions in the landscape at each site (generally at an upslope and downslope position within each experimental site) to examine profile morphology and quantify the amount and distribution of major nutrients. Volumetric soil cores were taken sequentially with depth (0-10, 10-20, 20-30, 30-50, 50-70 and 70-100 cm), using stainless steel cores. Two replicate soil cores were taken 0.5 m from the face of each pit. Bulk density was calculated from the weights of material in each of the cores.

Table 2. Constants and R^2 for allometric equation to estimate total biomass and nutrient contents on a tree basis (prior to the experiment. The form of the equation was ln (y)=a x ln(x)+b, where y was biomass/nutrient content (kg tree^{-1}) and x was diameter at 137 cm height

Attribute (kg tree^{-1})	Kayampoovam *E. tereticornis*			Punnala *E. tereticornis*			Surianelli *E. grandis*			Vattavada *E. grandis*		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
Biomass	2.75	-2.87	0.999	2.75	-2.84	0.991	2.58	-2.65	0.998	2.37	-2.08	0.997
N content	2.62	-8.40	0.998	2.89	-8.99	0.984	2.11	-7.40	0.990	2.49	-8.83	0.990
P content	2.60	-9.79	0.991	2.58	-10.63	0.983	2.43	-9.82	0.998	2.36	-10.58	0.984
K content	2.48	-7.83	0.984	2.75	-8.79	0.973	2.31	-8.13	0.986	2.41	-8.47	0.977
Ca content	2.60	-7.57	0.984	2.24	-6.86	0.923	2.77	-7.86	0.976	2.65	-8.12	0.980
Mg content	2.39	-9.21	0.986	2.44	-9.35	0.950	2.43	-9.12	0.997	2.83	-10.84	0.997

Soils were analyzed for organic C by dry combustion (Leco™), total N and P by Kjeldahl digest and analysis on a flow injection analyzer, exchangeable K on a flame photometer and Ca and Mg on an atomic absorption spectrometer after exchange with an ammonium chloride solution (Rayment and Higginson, 1992). Soil nutrient concentration at each pit was calculated as the mean of the 2 cores. Surface soil samples (0-10 and 10-20 cm) were sampled within each experimental plot in May 1998 to provide base-line soil chemical characteristics of the applied harvest residue treatments. Annual sampling of soil was conducted in July-September each year to evaluate impacts of treatments.

5.2. Tree growth

Tree stem diameter and height were measured at 0.25, 0.5, 1, 1.5, 2, 3, 4, 5.3 and 6. 5 years after planting from all treatments at each of the sites. Stem volume (v) was calculated using the equation $v= 1/3\pi r^2 h$ where 'r' was the radius at the tree ground level (projected from the diameter measured at breast height) and 'h' was the height of the tree to the small end diameter of 1 cm. Standing volume was calculated as the sum of the stem volumes expressed per ha. A strong relationship was found between standing volume and recovered merchantable volume harvest (Fig 1a.).

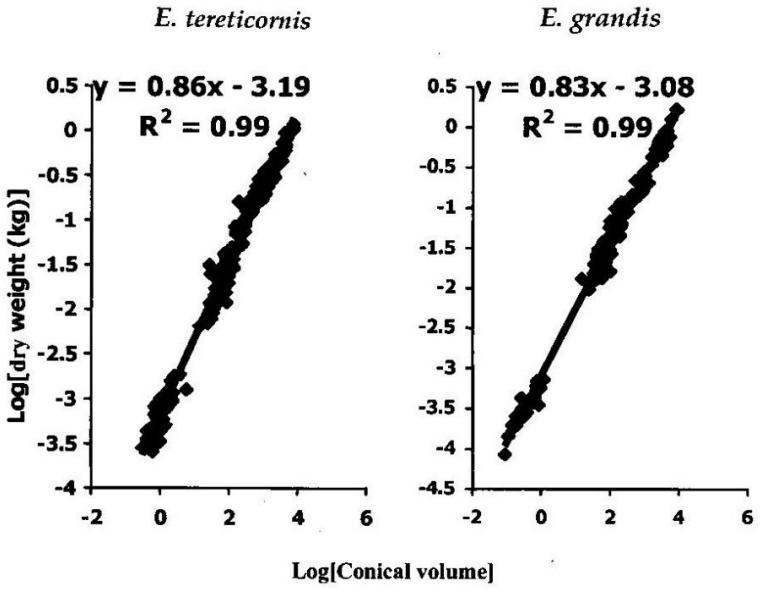


Fig 1a. Relationship between biomass and conical volume (0,3,6 and 12 months)

5.3. Nutrient cycling

5.3.1. Slash decomposition: Harvest residues were collected from freshly felled plantations, moisture content determined and air-dried. Fifty g of wood (approx. 15-20 cm size) each of 0.5, 2 and 4 cm diameter, 20 g of leaf litter and 20 g of bark were transferred to 25 x 25 nylon mesh bags (5 mm mesh) and laid in the experimental plot with single slash treatment at all four sites. There were four geographically diverse replicate plots (10 x 10m size) with 60 mesh bags laid in each (12 bags each of all fractions). Four replicate samples (one each from a single treatment plot) of each fraction were drawn at the interval of 1, 2, 3, 5, 7, 9, 12, 15, 18, 24, 30 and 36 months, dried at 70^0 C, cleaned free of soil and other particles and dry weight determined. All the samples were then analyzed for various nutrients as discussed above.

5.4. Soil properties

5.4.1. Nutrient recycling in slash management (OM) plots

Soils in slash management plots (zero residues, burn, single slash and double slash) were assessed for treatment effects on pH, exchangeable cations and available N at all sites. Soil samples were collected at 1 and 2 years after establishment of the plantations from the inner measure plots (10 x 10m). Sampling was carried out in the first half of September of the years 1999 and 2000, during the rainy season in Kerala. At this time of the year the soil moisture was at field capacity. A total of nine soil cores were collected from each plot from the 0-5, 5-10 and 10-20 cm depth ranges. The 9 soil samples were bulked within depths to produce a single sample for each depth range. Soil pH was measured in 1.5 water extracts (Rayment and Higginson, 1992). Exchangeable cations were assessed as solution Ca^{2+}, Mg^{2+} and K^{+} in filtrate after shaking 5 g dry soil (< 2mm) with 100 ml of 1 M ammonium chloride for 1 hour (Rayment and Higginson, 1992). N mineralization was assessed on the 1999 samples and other soil chemical parameters estimated on the samples collected in 2000.

5.4.1.1. **N mineralization studies:** In each plot, 18 soil cores (44 mm diameter) were pushed into the ground to 20 cm depth, removed and transported to the lab under cold conditions in insulated containers. For each plot, one set of 9 cores (the initial set) was extracted as soon as possible. The other set of 9 cores (the final set) was incubated aerobically for 14 days in the lab at 25^0 C at field moisture content (which was at or near field capacity) and then extracted. For extraction, the soil core was pushed out and split into the 0-5, 5-10 and 10-20 cm depth ranges. Soil from the 9 cores at each depth was mixed to form 3 composite samples (1 for each depth) to represent the plot. The sieved soil samples (from which 90 % soil was recovered) were stored for 2 days at 40^0 C until analysis for mineral N.

5.4.1.2. Laboratory measurements of Mineral- N: NH^{+}_{4}-N and NO^{-}_{3}-N forms: Mineral N in the initial and final soil samples was extracted with 1 M KCl (1:5 ratio) by shaking for 1 h on an end-to-end shaker. The soil KCl extracts were allowed to stand for 30 min and filtered through pre-washed filter (Whatman # 42). During the extraction utmost care was taken to complete the extraction within a short time period to avoid contamination from the atmospheric NH^{+}_{4}-N. NH^{+}_{4}-N was determined by salicylate–hypochlorite and NO^{-}_{3}-N content by reducing with copper-cadmium column by using a segmented flow auto analyzer (Technicon-II, USA). Mineral N concentrations in the soil were corrected for initial moisture content of soil samples and expressed on an over-dry weight basis. Net N mineralized during the incubation period was taken as the difference in mineral N between the initial and final samples and expressed on an oven-dry weight basis (Mendham et al., 2004).

5.4.1.3. Leaching (aerobic) experiment: This experiment was aimed to explore the long-term mineralization potential of soils and the effect of incorporation of Eucalyptus plant residues in a laboratory lysimeter leaching experiment maintained for 400 days. The incubators were constructed by removing the bottom from a 120 ml, screw-top plastic sample container (approx. 45 mm diam). About 30-45 holes (1/16' diam) were drilled in the lid of the container, which was inverted, so that the lid acted as the base of the incubator. The lid was fitted with a pre-filter (Millipore pre-filter, catalogue No. AP 15 04600) as the support pad for a polycarbonate membrane, the another pre-filter was placed on top to prevent clogging of the pores in the membrane. An O-ring above the pre-filter sealed the unit when the lid was screwed on firmly. Another pre-filter (Millipore pre-filter, catalogue No AP 25 04200) prevented silt from clogging the finer pre-filter below.

Soil (50 cm^3) was packed into the incubators at field bulk density. In the treatments with plant residues, leaf material was cut into small pieces and spread uniformly on top (equivalent 4 t (Mg) dry material ha^{-1} on a surface area basis). Another pre-filter (Millipore, AP 25 04200) was then placed on the top of the soil/plant residues to prevent the entry of leaching solution from the top displacing soil from the surface. A size 38 rubber bug sealed the top of the incubator. The rubber bug was fitted a tap (Baxter-Pharmaseal three-way stopcock, Cat No. K75) through which the leaching solution and compressed air was admitted. Compressed air was distributed from a pressure regulator (set at 25 k Pa) to the valve on each chamber via a network of hoses. This valve was closed when pressurized for leaching and opened when not leaching. To seal the incubator, the bug was firmly pressed in and taped down to withstand the pressure of a leaching cycle and stay in place during the incubation period. The entire experimental set-up was mounted on a stand with leachate collecting in a bottle below each incubator. Leachate solution, comprising 240-ml of 0.01 M $CaCl_2$/.01 M KCl, was slowly passed through the soil in the incubator by adding it to the top of the soil in the incubator (in several aliquots) and applying 25 kPa positive air pressure to the chamber. Leachate was suctioned into receiving container by applying a vacuum of 4-5 kPa for 1 to 2 s at 45 min intervals during the 8 hr cycle to ensure uniform leaching of the soil column.

After a complete leaching cycle, the volume of leachate was measured and a subs-sample was taken for the determination of NH^+_4-N and NO^-_3-N. Leachate subsamples were analyzed immediately or frozen until the analysis was completed (Mendham et al., 2000). Mineral nitrogen in leachate was determined as described above.

5.4.1.4. Potentially available nitrogen (anaerobic-N): Portions of moist soil (ca. 10-20 g dry soil) were weighed into 125 ml plastic vial and 30 ml of distilled water added, and incubated in a hot water bath at 40^0C for 7 days. After the incubation time, 30 ml of 2 M

KCl was added to the soil samples, and they were shaken end-over-end for 1 h. All the KCl extracts were extracted and analyzed using a Techicon II Auto Analyzer. Anaerobically mineralizable N was calculated from the difference in ammonium content of pre and post incubated samples.

5.4.1.5. Soil microbial biomass C: Soil microbial biomass C was estimated at 2 years after plantation establishment through the chloroform fumigation – extraction method (Brookes et al., 1985; Jenkinson and Powlson, 1976). Four replicate soil samples (field fresh) were fumigated with ethanol-free chloroform for 15 min. In brief, 2 sub-samples of moist soil (10-15 g approximating around 10 g on dry-weight basis) were weighed into a glass vial, one set was fumigated with ethanol-free chloroform in a desiccator by warming the chloroform and applying a vacuum to vaporize it. The wall of the desiccator was lined with wet tissue paper to maintain a humid soil atmosphere during repeat vacuum application. The vacuum was applied for 5 min after which the desiccators with soil samples were kept in dark conditions at 25^0C for 24h. A second, non-fumigated set was treated the same way. After 24 hrs, the samples were extracted with 0.5 M K_2SO_4 for 30 min by shaking on an end-to-end shaker. Microbial C and N was estimated as the difference in C and N concentrations between the fumigated and non-fumigated samples, multiplied by a *K*ec of 0.4 and *K*en of 0.45 (Sparling, 1992).

***5.4.2. Total C, N and P*:** Organic carbon was determined by the wet digestion method (Walkley and Black, 1934). Total N and P in soil were assessed by Micro-kjeldahl digestion of soil and chemical analysis of the extracts on an auto analyzer (Rayment and Higginson, 1992). All the values were expressed on an oven-dry-weight basis.

5.4.3. Nutrient cycling in plots inter-cropped with legumes

5.4.3.1. N mineralization in legume residue amended soils – lab incubation*:* Tensioned leaching micro-lysimeters (Aggangan et al., 1999) were used in a laboratory experiment to examine the influence of surface additions of legume and eucalypt materials on soil N supply over 392–day incubation. Unfertilized surface soil (0-10 cm) was collected from just outside the experimental areas at Kayampoovam and Punnala and air dried. Samples of mature (non- senesced) legume foliage and stem material and foliage of *E. tereticornis* were collected within the experimental plot at each site 20 months after establishment and air dried. *Eucalyptus, Mucuna* and *Stylosanthes* material was collected individually at each site, whilst *Pueraria* was collected only at Kayampoovam as biomass production was insufficient at Punnala. The *Stylosanthes* residues mostly consisted of stem material, whilst the other residues were predominantly leaf material. Plant material was cut into pieces approximately 15 mm (stems) or 12 x 12 mm area (foliage) prior to incubation.

The tensioned micro-lysimeters were packed to field bulk density (1.18 and 0.99 Mg m^3 at Kayampoovam and Punnala, respectively) with 50 cm 3 sieved (< 5 mm) soil. Seven residue treatments (four individual plant material types and 1:1 mixtures of each legume/*E. tereticornis* combination) and an un-amended control treatment were established on each of the two soils in a randomized block design with four replicate blocks. Cut plant residues were placed on the soil surface at a rate of 0.5 g dry weight per lysimeter (equivalent to 4 Mg ha^{-1} on dry plant material on a surface-area basis). A fiberglass filter was placed on top of the soil/residue in the lysimeter to prevent disturbance when the leaching solution was applied.

Incubators were maintained at a constant temperature of 25^0 C. Soils were leached with 240 ml of $CaCl_2$ /KCl solution (both at a concentration of 0.0.1 M) at the start of the experiment (day 0), and thereafter at day 10, 22, 36, 56, 77, 105, 133, 168, 225, 301 and 392. After leaching, the soil moisture was equilibrated to a constant matric tension by applying 25 kPa pressure to the headspace for 50 ha (equivalent to gravimetric moisture content of 28% and 38.9% at Kayampoovam and Punnala, respectively).The leachates were frozen until analysis for $NH4^+$ and $NO3^-$using calorimetric methods on a flow injection analyzer (Lachat QuikChem 8000). Net N immobilization or mineralization due to addition of plant residues was calculated as inorganic N leached from the corresponding un-amended soils. Cumulative N immobilized or mineralized was calculated by adding net N released at each leaching and expressed per gram of initially added C. Nitrogen released during the initial leaching d (day 0) was not included in the cumulative N release.

At the termination of the experiment, the oven- dry quantity of remaining surface residue material was assessed by weighing after cleaning it of loosely adhering soil particles.

5.4.3.2. Plant residue analysis*:* Plant residues were analyzed for C, N, and biochemical (soluble carbohydrates, holocellulose, soluble polyphenols and lignin) qualities. Total C was determined as CO_2 evolved after dry combustion at $1,200^0$ C on a carbon analyzer (Leco CR 41 TOC analyzer). Total N content was determined on a flow injection analyzer after Kjeldahl digestion with sulfuric acid/hydrogen peroxide (Heffernan, 1985). Biochemical qualities were determined using the proximate techniques of Allen (1974). Soluble carbohydrates were extracted in hot water (100^o C, 2 h) and analyzed calorimetrically using anthrone reagent. The holocellulose (cellulose + hemicellulose) fraction was determined as the mass remaining after de-lignifying the plant residue samples with sodium chlorite in acetic acid (10% v/v), following pre-

treatment with ether, water and dilute acid (H_2SO_4, 10% w/v) to remove fats, soluble carbohydrates and proteins, respectively. The holocellulose and lignin fractions were corrected for ash content. Soluble polyphenols were extracted in hot water (100^0 C, 1 h) and determined by colorimetry using the Folin-Denis reagent.

5.4.4. Nutrient cycling in plots which received nitrogen fertilizer:

Methods of collection of soil samples and determination of aerobically and anaerobically mineralizable N were as discussed under 'Nutrient recycling in slash management plots'.

5.4.4.1. Response of N mineralization to soil moisture: The effect of soil moisture on soil N mineralization was evaluated in a lab study using the soil samples collected as above. The soils were pushed out of the cores, dried, and re-packed into mini-cores suitable for adjusting soil moisture on a pressure plate. The mini-cores were placed on pressure plates and established at 10 different matric potentials (-10, -25,-50, -100, -400, -1500 Kpa, and at 4 levels of air drying), with 2 replicates. Two cores of each combination were set up, one for immediate extraction, and another for extraction after incubation. In total, 160 cores were established. Soil cores were equilibrated on pressure plates at 4^0C for 48 h to arrive at desired moisture contents. After equilibration, half of the cores were extracted immediately, and half were incubated at 25^0C and for 14 days prior to extraction. For the extraction, 20 g moist soil was extracted with 60 ml of 1-N KCl. The available N (NH_4-N and NO_3-N) content was determined and expressed on oven dry weight basis. The relationship between soil moisture and N mineralization was fitted to a sigmoidal function of the following form.

$$y = a + C/1+e^{-b(x-M}$$

where y is the N mineralization relative to that in non-water limited soil (unit-less scale of 0-1), x is the soil moisture content relative to that at -10kPa matric potential (also unit-less) and a, c and M are fitted co-efficients.

5.4.4.2. Response of N mineralization to soil temperature: A separate lab incubation experiment was conducted to study the response of N mineralization to a range of temperatures viz., 14, 20, 25, 30 and 35^0C. Soil samples were prepared as above and then equilibrated at 4^0 C on a pressure plate at matric potential of -25 kpa for 48 h. Two replicates of each site were incubated in each of the temperatures. In total, 40 cores

were incubated and another 16 (4 per site) were extracted immediately after equilibration for the baseline minerals N. The incubation were conducted at other variable times to account for the different rates of N mineralization, with the cores incubated at 35^0C for 7 days, the cores incubated at 25 and 30^0C for 14 days, and the remainder, were incubated for 28 days. At the end of incubation, 20 g moist soil was extracted with 60 ml of 1N KCl and analyzed colorimetrically for NH_4-N and NO_3-N. Net N mineralized during the incubation was calculated as the mineral N at the end of the incubation after subtracting the initial mineral N pool. The relationship between soil temperature and N mineralization was fitted to an exponential function of the following form.

$y = a + b X r^x$ where *y* is the N mineralization relative to that at 25 ^{0}C (unit-less), x is the soil temperature (^{0}C), and '*r*' are fitted coefficients.

5.4.4.3. Field temperature and moisture: Site environmental conditions were measured between July/August 1998 and Feb/March 2000 at each of the 4 sites. Hence, for modeling, the focus was on the 12 months of calendar year 1999. Soil cores were collected from the field at 28-day intervals to measure gravimetric moisture content and soil temperature was measured at depth of 5 cm at 9 am and 3 pm on a weekly basis.

5.4.4.4. Seasonal N mineralization modeling: Soil N mineralization (N_{min}) was predicted on a daily basis using the following equation

$N_{min} + N_{index} \times T \times M$, where N_{index} is the aerobic index of N mineralization described above. *T* is a temperature modifier, and *M* is a soil moisture modifier. The temperature and moisture modifiers mimic the conditions as in the field situations, which is incorporated in the equations described above.

Tree growth was measured as outlined above. Response of fertilizer (%) at each site was calculated based on the growth data in control and non-N-limited plots.

5.5. Measuring wood volume and growth in Et and Eg plantations in Kerala

Measurement of volume or weight is not difficult once the crop is harvested. However, it often becomes necessary to estimate the standing volume of the growing stock periodically and predict the volume at harvest. Except for some empirical methods or

thumb rules, no scientific method is available at present to estimate standing volume of trees. Work carried out under this title was intended to test the reliability of the conical method, which was used in the current study, in estimating the volume of standing trees of *E. tereticornis* and *E. grandis* under different intensities of management.

In Kerala, the pulpwood is usually made into 2 m billets and stacked to one meter height and convenient length soon after debarking. The payment for the pulpwood at the pulp mill is made by weight calculated at 50% moisture basis. Hence, a reliable conversion factor between stack volume and moisture content will be of high practical value. Although there are some conversion factors in use, a refinement of these is necessary based on data collected from different locations and different management intensities. This was the second objective of this study.

Sites at Punnala and Surianelli were used to conduct the proposed studies. At each site, prior to harvesting, the conical volume of trees in all the treatments was determined using the conventional method ($v = 1/3\pi r^2 h$). The trees were then harvested, measured for diameter over the bark and under bark at various heights, cut into 2 m billets, debarked and stalked at 1 m height within the plots. To assess the effect of stack position and log size on log moisture content, 12 stacks (made from the harvested trees) were used. The logs came from the N4 experiment (3 each from the 4 replicate treatments). Of these, one stack belonged to the measure trees and the other two were from the buffer rows. All stacks were oriented in the same direction in the plot.

5. 6. Plant Physiological studies

***5.6.1. Weather data*:** Weather data from the two experimental sites, namely, Punnala and Surianelli were collected using two separate automated weather stations. Atmospheric temperature, relative humidity, rainfall, wind velocity and solar radiation were the parameters measured. The raw data was processed in a computer and the data are presented. From Fig. 1b it may be noted that Surianelli is almost 7.5oC cooler compared to Punnala, which is due to the higher elevation of the former site. The maximum temperatures at both sites are seen during January to April. It may be seen from Fig. 1c that the humidity ranges between 25 and condensation at Punnala, whereas the lower range of humidity at Surianelli does not come below 50 %. Also, the Surianelli site shows much higher humidity during the pre-monsoon period. Fig. 1d shows that the vapor pressure deficit (vpd) at Punnala was much higher than that at Surianelli. The maximum vpd of 3 kPa was reported from Punnala during the pre-monsoon period.

Fig. 1b.

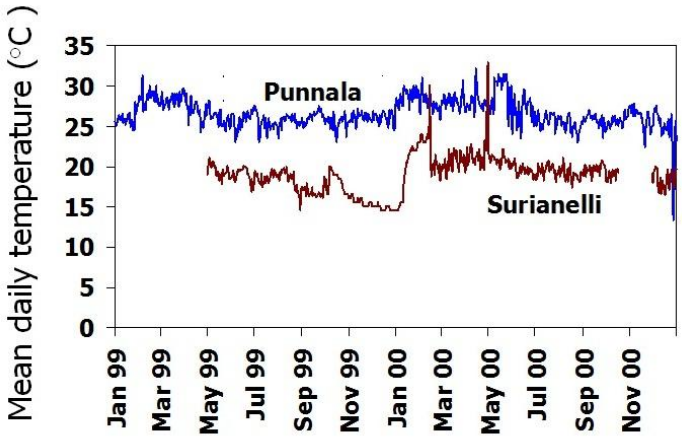


Fig. 1c.

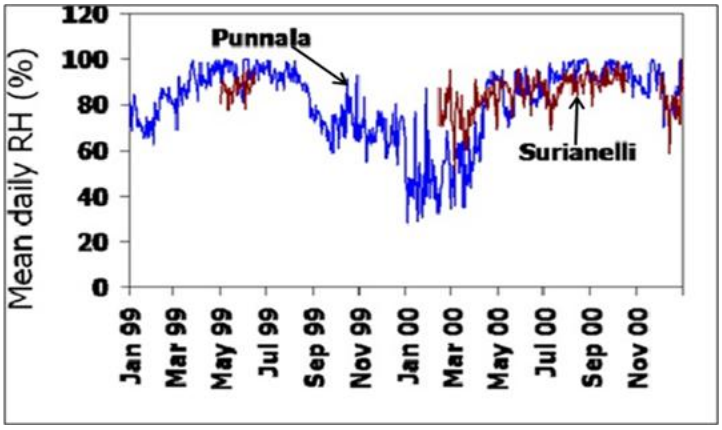


Fig. 1d.

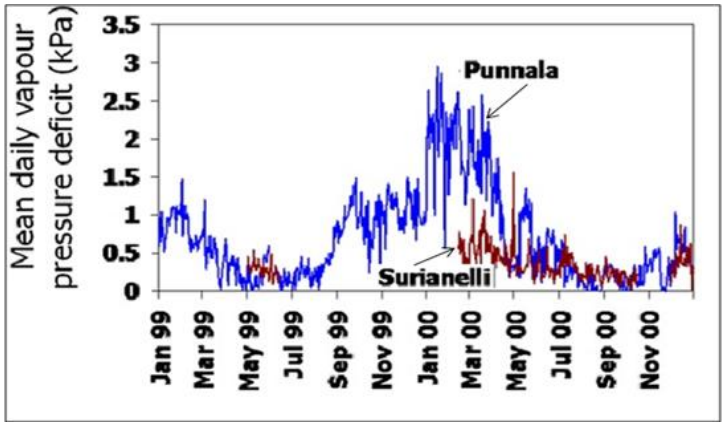


Fig 1b – d. Variations of (1b.) mean daily temperature (1c.) mean daily relative humidity and (1d.) mean daily vapour pressure deficit at the two experimental sites, Punnala and Surianelli

5.6.2. Impact of inter-rotation site management practices on tree water status in eucalypt plantations in Kerala.

The main objective of this experiment was to quantify monthly variation in leaf water potential (pre-dawn, midday) to assess seasonal effect of selected treatments on water availability to trees and maximum tree water stress. And, use water stress integral (Myers, 1988) to evaluate treatment effects on long-term tree and site water status.

Measurement of predawn and midday water potentials were done once every month at two sites, namely, Punnala and Surianelli, for *E.tereticornis* and *E. grandis*, respectively.

Sampling strategy: Two samples per plot were used for water potential measurement. This gives 2 samples x 4 plots = 8 replicates (N_0 and N_5) for each treatment (the treatment details are given elsewhere in this report).Well-exposed leaves from individual trees were collected before sunrise in a polythene bag and sealed. These samples were used for pressure chamber measurements later, taking all precautions. Similarly, the midday samples were collected and used for water potential determination in a pressure chamber. All the measurements were used to derive an integral water potential value.

5.6.3. Impact of inter-rotation site management practices on tree physiological function (stomatal conductance, leaf photosynthesis) and tree development (leaf area increment) in the experimental plots

The objective of this study was to determine the impact of selected silvicultural treatments on eucalypt physiological functions and development. Quantification of stomatal conductance (*gs*) using a porometer (measurements during pre- and post-monsoon periods) was done on selected treatments. Measurement of leaf photosynthesis (*Pn*) was done using a portable infrared gas analyser (LI-COR-6200) to evaluate the effect of silvicultural treatments (especially different levels of nitrogen availability) on carbon accretion. Measurement of Leaf Area Index (LAI) was done on a monthly basis on selected treatments using a LI-COR-2000 interception instrument. The instrument had been calibrated through destructive sampling. The LAI measurements were related to other tree characteristics (diameter at breast height, sap-wood area etc.) through allometric relationships. All the above measurements were done twice in a year, during pre-monsoon (when soil water was deficient) and during postmonsoon, when soil water was available in plenty. However, LAI was measured at plots once in two months. All plots in Punnala and Surianelli were subjected to measurements. Sampling strategy was as follows: three trees from the centre of each plot - two leaves from each tree sampled for stomatal conductance / photosynthesis.

5.6.4. Impact of inter-rotation site management practices on individual tree and whole stand water in the experimental plots

Estimating tree and stand water use by eucalypt plantations is a critical issue in many parts of the tropics and is a particularly a vexed issue in Kerala. Firstly, tree growth can be severely limited in strongly seasonal climates as it occurs in the State. This may be especially important in regions where shallow soil depths limit soil water storage and thus the availability of water for tree growth during the dry season. Secondly, impact of eucalypts on soil water storage and stream flow is an important social issue as it has been suggested that plantations have in some circumstances adversely affected other forms of land use as well as water supplies to urban and rural populations (Rajesh and Kallarackal, 1999). The provision of sound scientific data from well conducted experiments will help to resolve these issues.

In this background, this experiment was carried out to quantify tree water use by eucalypts at the leaf, tree and stand level and relate these estimates to alternative silvicultural practices for managing *E. tereticornis* and *E. grandis* plantations in Kerala.

Transpiration was determined on a unit leaf area basis from measurements of stomatal conductance using a porometer and related this to silvicultural treatments at two sites, namely, Punnala and Surianelli in Kerala. Transpiration at the leaf level will be simultaneously obtained in the LI-6200 measurements. The *gs* measurements which will also be obtained in LI-6200 will be used to establish a relation between *gs* and microclimate parameters. Transpiration was further determined on a tree stem basis from sap-flow measurements using a heat pulse instrument and related this to silvicultural treatments at the above two sites in Kerala. Sap flow measurements were monitored on selected plants at different plots using model SF-200 (Greenspan, Australia) for plants with <20 mm diameter and SF-300 for plants with >20 mm diameter. All treatments were monitored for sap flow using this method following the corrections given by Hatton et al. (1995). Sap velocity was measured at 10 and 20 mm depth by drilling holes into the wood. These measurements were done on N1 and N4 treatments on a number of trees at Punnala and Surianelli.

5.7. Statistical analysis

The Genstat statistical package (Lawes Agricultural Trust, Rothamsted, UK) was used for all analyses including analysis of variance (ANOVA) to assess the significance of difference on treatments on tree growth, the influence of slash management on C, N, P, N mineralization, microbial biomass and plant physiological studies. When treatment differences were significant, Duncan's multiple range test was applied to determine which means were different amongst the treatments. For the long-term incubation

study, a nested design was used to test treatment effects, with sites used as replicates. When treatments were compared across experiments and thus not statistically correct to analyze, the standard error of the means (SEM) of the observation is presented.

Regression analysis (Genstat) was used to test the relationship between residue quality and net N release and significance of productivity response to N indices. The effect of an interaction caused by mixing residues on net N mineralization was tested by comparing the observed N net mineralization in the mixed treatments with that expected if the mineralization from two residue types were contributing additively to the total net N mineralization. Significance of a deviation from the expected net N mineralization was examined using a paired t-test.

A single exponential decay model (Olson, 1963) was used to estimate the annual decomposition rate of litter - $x/x0 = e\text{-}kt$ where 'x' is the weight of litter remaining after time 't', 'x^0' is the initial weight of litter, 'e' is the base of natural logarithm and 'k', the decomposition rate constant. This exponential decay model was used to calculate the half- life of the litters. A summary of statistical analysis of tree growth in response to various treatments is given in Appendix 1.

6. Results

6.1. Pre-harvest stand characteristics: Selected properties of the study sites are provided in Table 1. Figure 2 shows the distribution of stem density and standing biomass with diameter class at each of the sites. The original stand density was the highest at Vattavada (3898 stems ha^{-1}) but most stems were relatively small with 2-4 cm the most populated class (Fig 2 d). The largest proportion of total tree biomass was in trees in the 14-16 cm diameter class. The other sites had much lower stand densities and the maximum proportion of trees was in the diameter class 8-10 cm diameter class at Kayampoovam and Punnala and 6-8 diameter class at Surianelli. Punnala had the lowest stand density and it also had fewer trees in the largest diameter class (16-18) compared to other sites. Maximum tree biomass was produced by trees in the diameter class 12-14 cm at both Kayampoovam and Punnala and by trees in the 16-18 cm group at Surianelli. The plantation productivity (Table 1) was comparable to the stem number at all sites with the Punnala site having the lowest productivity (6.1 m^3ha^{-1}) over a 7 yr rotation cycle. However, in terms of soil nutrient status, the site at Kayampoovam had the lowest total C and N compared to other sites. But, soil P was higher at Kayampoovam compared to Punnala and Surianelli. Vattavada site had the maximum concentration of total C, N and P (Table 1).

The productivity of the *E. tereticornis* plantation was 11.6 m^3 $ha^{-1}yr^{-1}$ at Kayampoovam and 6.1 m^3 at Punnala. In *E. grandis*, the productivity was 9 m^3 at Surianllei and 31.3 m^3 at Vattavada. The plantation density and basal area are provided n Table 1. The survival of trees (stems ha^{-1}) was very low at three sites (38.6, 42.2 and 54.2%, respectively, at Punnala, Surianelli and Kayampoovam.

6.2. Total above ground biomass and nutrients: The majority of the above-ground biomass was in the tree crop at each site (Fig. 3a) with 76, 66, 65 and 90% of the total above-ground biomass stored in the trees at Kayampoovam, Punnala (*E. tereticornis*), Surianelli and Vattavada (*E. grandis*), respectively. Due to differences in nutrient concentration in the different biomass fractions, the proportion of nutrients in the tree crop was lower than the proportion of biomass, with 30-66% of the N , 40-71% of the P, 42-73% of the K, 48-80% of the Ca and 30-72% of the Mg in the standing plantation pool (Fig 3b- 3f). The tree biomass differed significantly between sites (Table 3) with the Vattavada (*E. grandis*) site the most productive (143 t ha^{-1}). The standing biomass at Vattavada was more than double that of the *E. tereticornis* at Kayampoovam (63.8 t ha^{-1}) which was the second most productive site. Surianelli and Punnala were lower at 45.5 and 34.9 t ha^{-1}, respectively.

Most of the above ground nutrients were held in the eucalypt crop at Vattavada and Kayampoovam. Differences between sites in quantity of nutrients in the tree crop generally corresponded to differences in the above ground biomass with the exception of P at Kayampoovam which was higher than all of the other sites. The sites differed significantly in N and P content in the tree biomass (Table 3). However, the K content of tree biomass at Punnala and Surianelli and Ca and Mg content between Kayampoovam and Surianelli were almost similar. Of the 4 sites, Punnala had the lowest tree biomass and total above-ground nutrient pools.

Total above ground N pools (in trees, shrubs and the forest floor) at Kayampoovam, Surianelli and Vattavada were within 14 kg ha^{-1} of each other, with 357.8 , 343.5 and 347.5 kg ha^{-1} at Kayampoovam, Surianelli and Vattavada, respectively. Total above-ground-N at Punnala was approximately 70% of this value. The above-ground P content at Kayampoovam was highest at 55.9 kg ha^{-1} whilst Surianelli and Vattavada were close together at 39.1 and 38.1 kg, respectively. Punnala was the lowest with 19.7 kg ha-1. Vattavada had the highest K and Ca pools (362 and 886 kg ha^{-1} and Surianelli had the highest Magnesium pool (115 kg ha^{-1}) (Table 3).

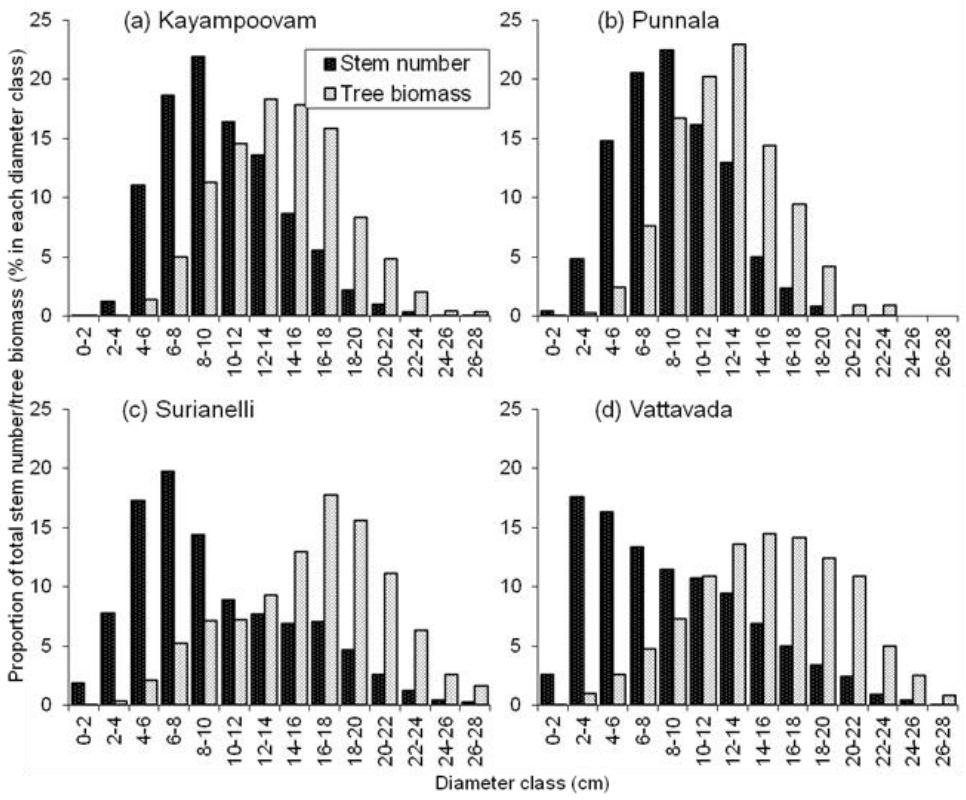


Fig. 2. Tree number and above ground biomass in relation to stem diameter class distribution at the four study sites

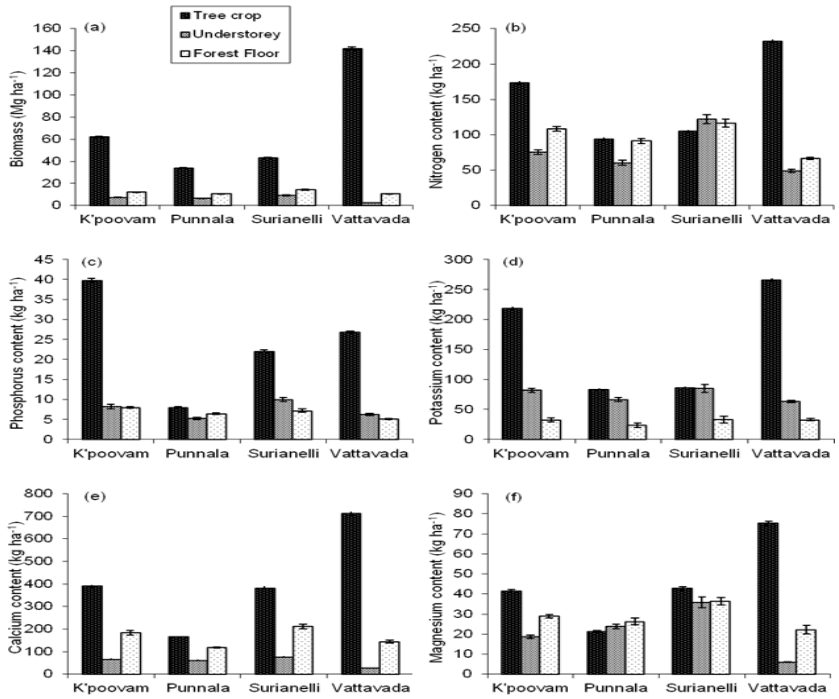


Fig. 3. Total above ground pools of (a) biomass, (b) nitrogen, (c) phosphorous, (d) potassium, (e) calcium, (f) magnesium at each of the four sites. Error bars show standard error of the mean.

Table 3. Total above ground pools of biomass (tha^{-1}) and major nutrients (kg ha^{-1})

Source/ nutrients	Tree crop				Understorey				Forest floor			
Sites	Kayam-poovam	Punnala	Surianelli	Vattavada	Kayam-poovam	Punnala	Surianelli	Vattavada	Kayam-poovam	Punnala	Surianelli	Vattavada
Biomass	63.76^{c*}	34.97^{a}	45.55^{b}	142.96^{d}	7.38^{b}	6.58^{b}	9.01^{c}	2.31^{a}	12.06^{b}	10.52^{a}	14.30^{c}	10.63^{a}
Nitrogen	173.75^{c}	94.21^{a}	104.97^{b}	232.91^{d}	75.51^{c}	60.37^{b}	121.97^{d}	48.88^{a}	108.52^{c}	91.21^{b}	116.58^{c}	66.48^{a}
Phosphorus	39.75^{d}	7.99^{a}	22.03^{b}	26.78^{c}	8.18^{b}	5.22^{a}	9.98^{b}	6.22^{a}	7.95^{c}	6.44^{b}	7.16^{bc}	5.07^{a}
Potassium	218.79^{b}	83.43^{a}	85.88^{a}	265.99^{c}	82.02^{b}	66.62^{a}	84.96^{b}	63.24^{a}	32.54^{b}	23.64^{a}	33.02^{b}	32.68^{b}
Calcium	390.92^{b}	166.08^{a}	382.26^{b}	712.08^{c}	66.77^{bc}	61.64^{b}	76.23^{c}	29.14^{a}	184.36^{c}	117.96^{a}	211.97^{c}	144.96^{b}
Magnesium	41.61^{b}	21.44^{a}	42.82^{b}	75.22^{c}	18.66^{b}	23.82^{c}	35.82^{d}	6.10^{a}	28.88^{a}	26.27^{a}	36.46^{b}	22.15^{a}

*Values with the same alphabet super-scribed are not statistically significant

6.3. Forest floor biomass and nutrients: Most of the forest floor biomass and nutrients at the lowland site *Et* sites (Kayampoovam and Punnala) was contained in the miscellaneous fraction which consisted of senesced understorey leaves and finally comminuted organic material (Figure 4 a-f). The miscellaneous fraction was a relatively low proportion of the total forest floor material at Vattavada. In general, the total forest floor biomass was significantly high at Surianelli (14.3 Mg ha^{-1}) compared to the other sites. Kayampoovam had more forest floor biomass than Vattavada and Punnala and the latter two sites contained almost the same amount of biomass (Fig 4 a).

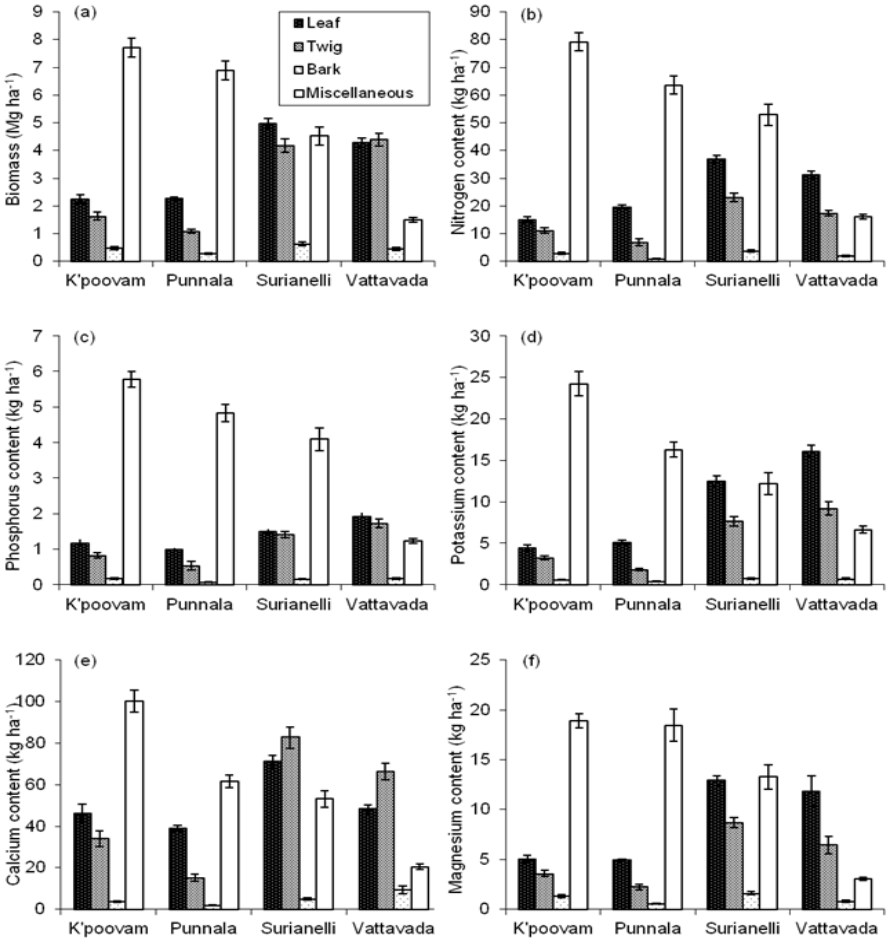


Fig. 4. Partioning of (a) biomass, (b) nitrogen, (c) phosphorous, (d) potassium, (e) calcium, (f) magnesium between the components of forest floor originating from the tree crop (leaves, twigs and bark) and the understorey at the study sites. Error bars show standard error of the mean.

Amongst the tree components, the biomass of the leaves on the forest floor was highest at all sites except at Vattavada where twigs were a slightly higher component. Leaf litter nutrient content was similar to, or higher than that for twigs at all sites, with the exception of calcium at *E. grandis* sites (Surianelli and Vattavada). The miscellaneous

fraction generally has higher N, P and K concentrations than leaves and twigs, so it made a larger relative contribution to the pools of those nutrients in the forest floor. The bark litter component contributed the least, with less than 5% of the total forest floor biomass and nutrients. The comparatively low biomass at Punnala and Vattavada corresponded to the low nutrient pools in the forest floor at these sites. The forest floor at Surainelli had significantly high Mg content than in other sites.

6.4. Understorey biomass and nutrients: The lowland *E. tereticornis* sites had a greater diversity of understory species than the highland *E. grandis* sites, and secondary species at those sites combined to have a similar or higher biomass than the primary under -storey species (Fig 5 a). The total biomass was significantly high at the Surianelli site (9 t ha^{-1}); both the *E. tereticornis* had almost similar biomass and the Vattavada site hadthe lowest biomass (2.3 t ha^{-1}) in contrast to the tree crop biomass. The content of N, P and Ca was relatively high in the secondary species at both the *E. tereticornis* sites, particularly at Punnala. Also, the content of K and Mg was almost similar in both secondary and primary species at Punnala. At each of the *E. grandis* sites, the understory was dominated by the primary species (*Lantana camara* at Surianelli and *Ageratum conyzoides* at Vattavada) in both biomass and nutrient content. The highest nutrient content in the biomass was at Surianelli which relates to the highest biomass. The secondary species at Surianelli contained about half the P, K and Ca in the primary species (Figs 5 b-f).

6.5. Tree crop biomass and nutrients: Biomass of the original stands varied four fold between the different sites partly due to differences in stocking rates of the coppiced regrowth and partly due to differences in soil fertility and competition from weeds (Table 1, Fig 6 a). Vattavada, which had the highest stocking, recorded the highest biomass followed by Kayampoovam, Surianelli and Punnala in that order. The stem wood was the major component of the tree biomass (81% at Vattavada, 71-73% at the other three sites) followed by bark, branches and leaves (Fig 6 a).

Leaves were a minor contributor representing only 3-7% of the biomass. Bark contributed to 9-14% of the total tree weight. However, nutrient concentrations in the stem wood were low compared to other components relative to dry weight. Stem wood comprised 22-47% of the tree N content, 38-54% of P, 38-44% of K and 15-27 % of tree Ca and Mg content. Leaves were the largest store of N at the highland sites while stem bark was the highest store of Ca and Mg across all the sites. The N and P content of the whole tree biomass differed significantly between sites (Table 3).

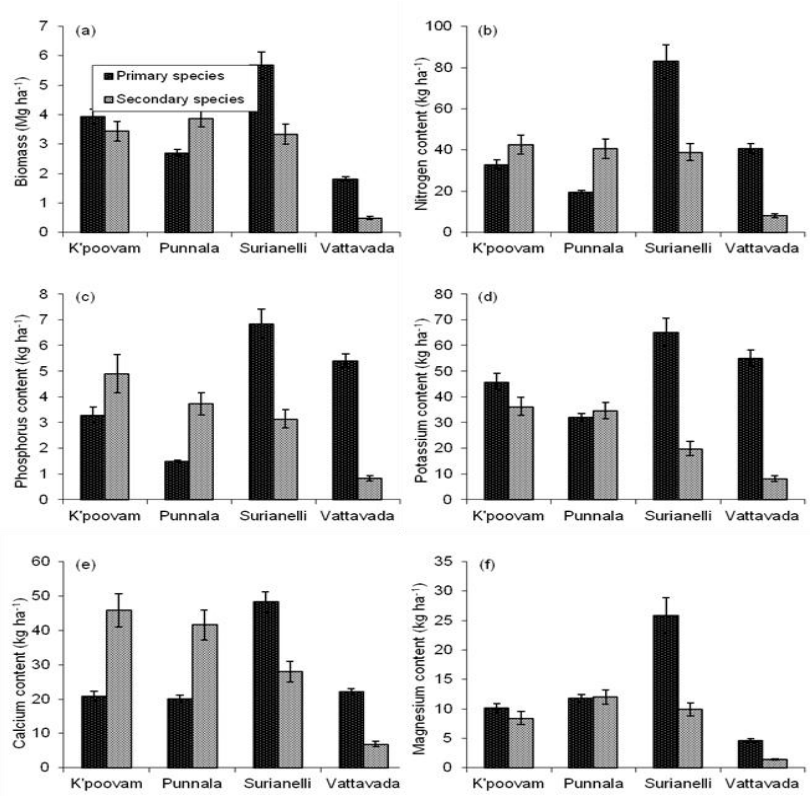


Fig. 5. Partioning of (a) biomass, (b) nitrogen, (c) phosphorous, (d) potassium, (e) calcium, (f) magnesium between the primary and secondary components of understorey at the study sites.

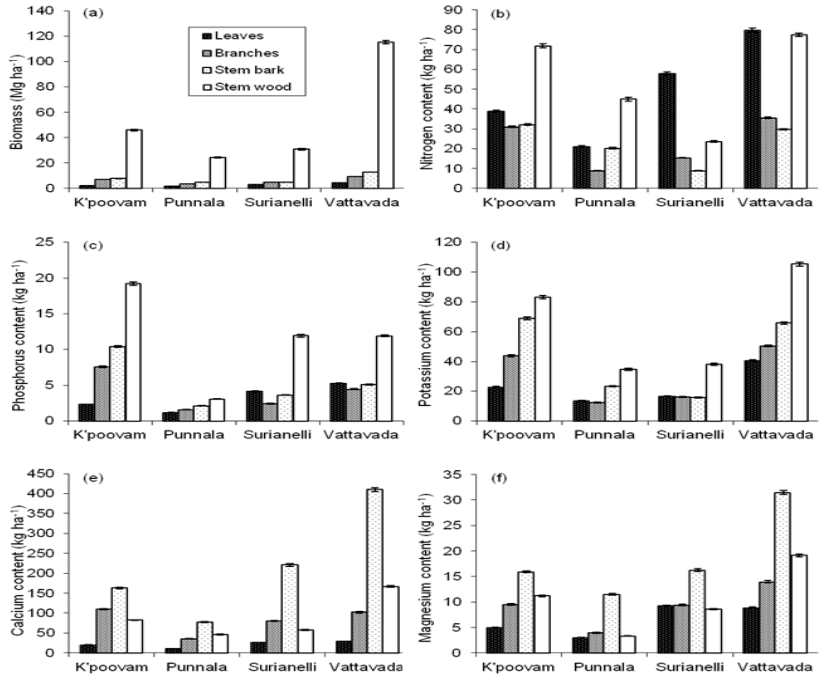


Fig. 6. Partioning of (a) biomass, (b) nitrogen, (c) phosphorous, (d) potassium, (e) calcium, (f) magnesium between the leaves, bark, branches and wood components of the tree crop. Error bars show standard error of the mean

The highest N content was recorded from Vattavada (232 kg ha^{-1}) and the highest P from Kayampoovam (39.7 kg ha^{-1}). Differences in nutrient distribution between stands reflected in part the different amounts of total biomass accumulated at the various sites and the amounts of nutrient-rich material such as leaves and small twigs present in each. The site at Punnala is a good example for this observation.

6.6. Harvest residue biomass: The amount of harvest residues (leaves, bark and branches) at each site partly reflected differences in site productivity and accumulated biomass at each site (Fig 6a). Smallest amount of residues were at Punnala nd Surianelli and greatest amounts at Kayampoovam and Vattavada. The amount of harvest residues at Vattavada was lower than expected and may reflect greater efficiency of wood extraction following logging. Total amount of harvest residues, the proportion of various slash fractions and differences between species in tissue nutrient concentration determined the quantities of nutrients deposited on the soil during logging operations. Here again, Punnala recorded the smallest amount of biomass and lowest amount of nutrients in slash. The harvest residues contained 1.6-3% of total site pools of N and the equivalent of up to 34, 60 and 38% of totalsite pools of K, Ca and Mg, respectively.

6.7. Soil organic carbon and nutrients: Quantities of carbon and nutrients in the soil were much higher than found above ground (Table 4, Fig. 7). The highland sites had higher organic C than the lowland sites. Vattavada had higher organic C in the 0-20 cm depth range, but was surpassed by Surianelli below 20 cm. Total cumulative N at the two highland sites (average 16 t ha^{-1}) was approximately double that at the lowland sites (average 9.8 t).Vattavada had high total N at all depths, but total N in the 0-10 cm depth range at Surianelli (2.34 t) was slightly lower that at Punnala (2.49 t). Surianelli and Vattavada also had similar total P to 1 m depth, but total P was higher in the top 70 cm at Vattavada. There was a marked difference in the 70-100 cm depth range such that cumulative total P was similar between the two sites at 1 m depth. Kayampoovam had much higher total P (8.8 t ha-^{1}) than the other sites and total P at Punnala was less than half of that at 3.8 t ha^{-1} to 1 m depth. Total P increased almost linearly with depth at each of the sites, with the exception of the lower depth range at Vattavada. Exchangeable K was lowest at Punnala and highest at Vattavada. Calcium and magnesium followed similar trends with depth (Fig 7e-f). Punnala and Surianelli both had relatively low cumulative exchangeable Ca (1.6 and 2.8 t ha^{-1} respectively to 1 m depth), whilst Vattavada and Kayampoovam had higher levels (7.9 and 8.7 t ha^{-1} respectively to 1 m depth).

Table 4. Total soil stores of organic C and nutrients (t ha^{-1}) to 1 m depth at each of the sites. Standard error of the mean is presented in parentheses

	Total C	Total N	Total P	Exchangeable K	Exchangeable Ca	Exchangeable Mg
K′ poovam	106 (4)	9.0 (0.4)	8.76 (0.92)	0.50 (0.04)	8.10 (0.40)	1.69 (0.09)
Punnala	141 (15)	9.3 (1.4)	2.91 (0.88)	0.45 (0.06)	0.76 (0.36)	0.42 (0.12)
Surianelli	296 (30)	15.9 (4.6)	5.22 (0.72)	0.29 (0.04)	0.31 (0.01)	0.07 (0.01)
Vattavada	215 (34)	16.2 (1.4)	8.58 (0.46)	2.68 (2.03)	10.47 (6.31)	1.83 (0.34)

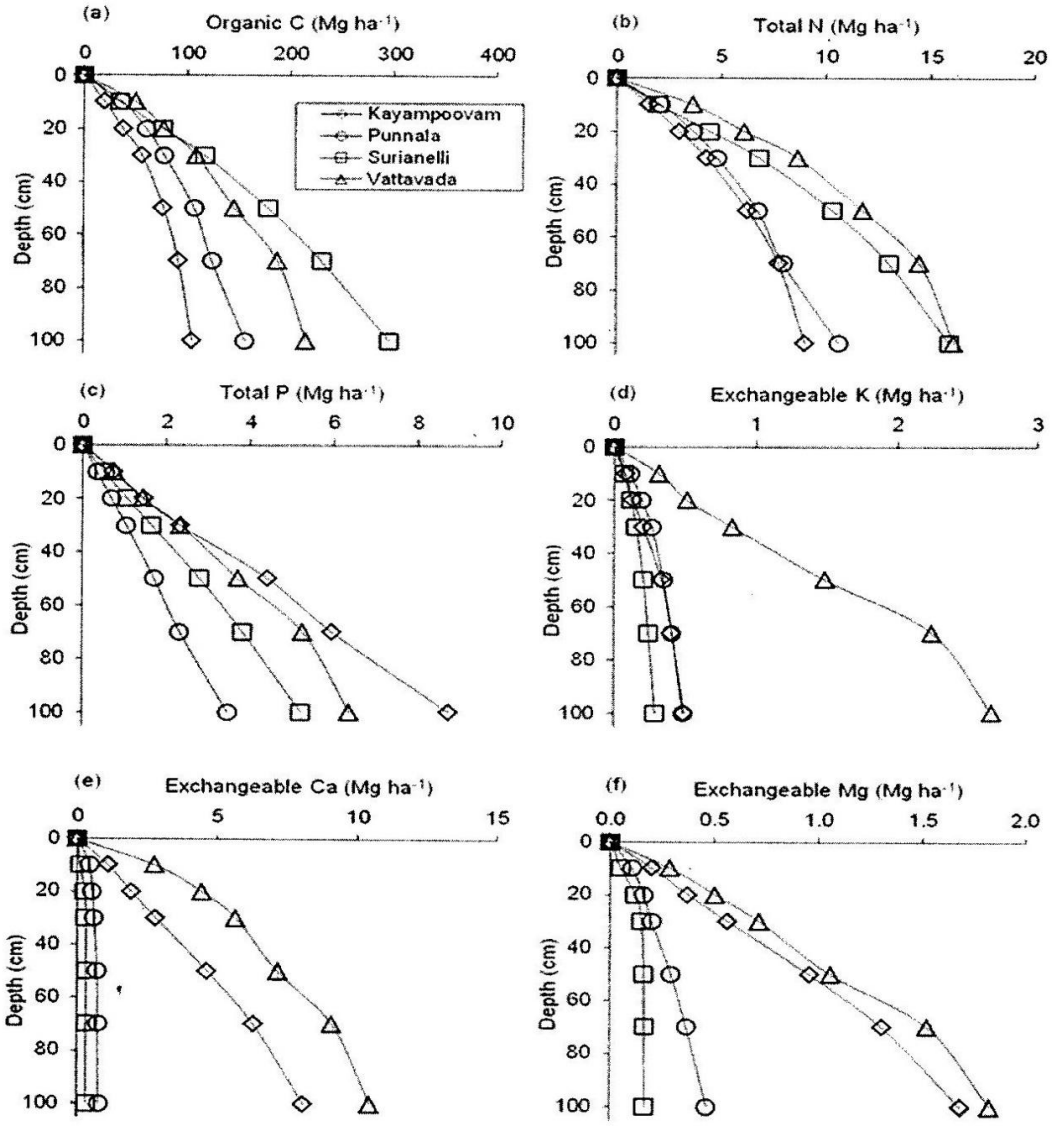


Fig. 7. Soil nutrient stores in relation to depth (t ha^{-1}) at the four experimental sites

6. 8. Predicted biomass and nutrient export following harvest: Potential exports of biomass and nutrients were examined for different biomass removal scenarios (Tables 5-7). These scenarios represent the extent to which materials are removed for pulpwood only, or for fuel and green manure requirements of the villagers. The most exploitative scenario is where all above-ground biomass was removed for fuel (which is relevant to all nutrients) or where the sites are burnt prior to replanting (where the main loss would be of biomass and N).

The quantity of biomass and nutrients that could be exported from the sites at harvest is dependent on the degree of removal of tree components. If stem wood only was removed at the end of 7 year rotation, 24-115 t ha^{-1} would be exported from the site, with a corresponding removal of 24-77 kg ha^{-1} of N (Table 5, 6). Nitrogen export increased on average by 116% (to 75-162 kg ha^{-1}) if all the tree components except leaves were removed, and by an average of 256% (to 142-225 kg ha^{-1}) if the under-storey was also removed. If all the above-ground biomass were removed, export of N increased by an average of 496% (to 247-358 kg ha^{-1}) over stem wood material removal alone. Export of P from the sites would have been between 3 and 19 kg ha^{-1} if only stem wood was removed from the site, but again, this increased markedly to 20-56 kg ha^{-1} if all the above-ground biomass were removed (Table 5, 6).

Table 5. Export of biomass (t ha^{-1}) (with percent increase over stem-only in parentheses) under different biomass removal scenarios at each of the 4 sites

Site/fractions	Stem only	Stem and branches[1]	Stem, Branches and bark[2]	Stem, branches, bark, and understorey	Stem, branches, bark, understorey and leaves[3]
Kayampoovam	46	54 (19%)	63 (37%)	70 (53%)	82 (79%)
Punnala	24	29 (18%)	34 (39%)	40 (67%)	51 (110%)
Surianelli	31	40 (29%)	45 (47%)	54 (76%)	67 (117%)
Vattavada	115	129 (12%)	142 (23%)	145 (25%)	155 (34%)
Mean	54	63 (20%)	71 (36%)	77 (55%)	89 (85%)

[1] Branches include twigs from forest floor and branches from the harvested eucalypt crop.

[2]Bark includes forest floor material as well as harvest residues.

[3]Leaves include forest floor material as well as harvest residues.

Stem bark was the single largest pool of Ca, with an average of 223 kg ha^{-1} of Ca (253% of that in the stem wood), but it represented a relatively low proportion of the biomass, with an average of 8 t ha^{-1} (15% of the stem wood biomass). Total quantities of C, N and P in the soil were much higher than found in the above-ground biomass (25 to 170 fold). Quantities of K, Ca and Mg in the above- ground biomass were a much higher proportion of site pools (Tables 6 & 7).

Table 6. Export of N, P and K (kg ha^{-1}) and proportion of total above and below-ground pools (% in parentheses) under different biomass removal scenarios at each of the 4 sites

Nutrients/ Fractions/ Site		Stem only	Stem and branches[1]	Stem, branches and bark[2]	Stem, branches, bark and understorey	Stem, branches, bark, understorey and leaves[3]
K'poovam	N	72 (0.57%)	114 (0.90%)	149 (1.18%)	225 (1.78%)	358 (2.83%)
	P	19 (0.22%)	28 (0.31%)	38 (0.43%)	46 (0.53%)	56 (0.63%)
	K	83 (2.65%)	130 (4.14%)	200 (6.35%)	282 (8.96%)	334 (10.60%)
Punnala	N	45 (0.44%)	61 (0.60%)	82 (0.81%)	142 (1.40%)	247 (2.43%)
	P	3 (0.10%)	5 (0.16%)	8 (0.23%)	13 (0.40%)	20 (0.62%)
	K	35 (2.21%)	49 (3.11%)	73 (4.62%)	139 (8.85%)	175 (11.08%)
Surianelli	N	24 (0.12%)	62 (0.32%)	75 (0.38%)	197 (1.01%)	344 (1.78%)
	P	12 (0.21%)	16 (0.28%)	20 (0.34%)	30 (0.52%)	39 (0.69%)
	K	38 (1.65%)	62 (2.68%)	79 (3.39%)	164 (7.06%)	205 (8.84%)
Vattavada	N	77 (0.36%)	130(0.61%)	162 (0.76%)	211 (0.99%)	338 (1.59%)
	P	12(0.21%)	18 (0.32%)	23 (0.41%)	30 (0.52%)	38 (0.67%)
	K	105 (1.13%)	165(1.78%)	232 (2.49%)	295 (3.17%)	358 (3.86%)
Mean	N	54 (0.37%)	92 (0.61%)	117 0.78%)	194 (1.29%)	322 (2.15%)
	P	12 (0.18%)	17 (0.27%)	22 (0.36%)	30 (0.49%)	38 (0.65%)
	K	65(1.91%)	102 (2.93%)	146 (4.22%)	220(7.01%)	268 (8.59%)

[1] Branches includes twigs on the forest floor and branches from the harvested eucalypt crop

[2] Bark includes forest floor material as well as harvest residues

[3]Leaves includes forest floor material as well as harvest residues

Potassium in the above-ground biomass was equivalent to 13-70% of the soil exchangeable K to 1 m depth across the 4 sites. Surianelli had the highest proportion of cations in the above-ground biomass with more than double the Ca present compared to that in the exchangeable pool in the top 1 m of soil. Punnala also had a relatively high proportion of cations in the above-ground biomass. Removal of all above-ground biomass led to potential exports increasing on average by 312% for K, 619% for Ca, and 764% for Mg compared with stem wood only removal.

Table 7. Export of Ca and Mg (kg ha^{-1}) and proportion of total above – and below-ground pools (% in parentheses) under different biomass removal scenarios at each of the 4 sites

Site	Nutrients	Stem only	Stem and branches[1]	Stem, branches and bark[2]	Stem, branches, bark and understorey	Stem, branches, bark, understory and leaves[3]
K'poovam	Ca	83 (0.89%)	227 (2.43%)	393 (4.22%)	460 (4.94%)	627 (6.73%)
	Mg	11(0.41%)	24 (0.90%)	42 (1.54%)	60 (2.23%)	89 (3.30%)
Punnala	Ca	46 (2.51%)	97 (5.25%)	176 (9.53%)	238 (12.87%)	349 (18.88%)
	Mg	3 (0.42%)	10 (1.21%)	22 (2.74%)	45 (5.75%)	72 (9.09%)
Surianelli	Ca	58 (1.69%)	221 (6.46%)	447 (13.06%)	523 (15.29%)	674 (19.69%)
	Mg	9 (1.61%)	27 (4.99%)	45 (8.31%)	80 (15.00%)	116(21.61%)
Vattavada	Ca	167 (2.15%)	335 (4.32%)	755 (9.72%)	784 (10.10%)	882 (11.37%)
	Mg	19 (0.62%)	40 (1.29%)	72 (2.33%)	78 (2.53%)	102(3.31%)
Mean	Ca	88(1.81%)	220 (4.62%)	443 (9.13%)	501 (10.80%)	633 (14.17%)
	Mg	11 (0.77%)	25 (2.09%)	45 (3.73%)	66 (6.38%)	95 (9.32%)

[1] Branches includes twigs from forest floor and branches from the harvested eucalypt crop

[2] Bark includes forest floor material as well as harvest residues

[3]Leaves includes forest floor material as well as harvest residues

6.9. Tree growth in response to silvicultural treatments

6.9.1. Organic matter manipulation

Harvest residue manipulation has had no impact on plantation productivity at any of the four sites during the rotation period although there were significant differences in productivity between the sites. The *E. tereticornis* sites (Kayampoovam and Punnala) had much lower productivity compared to the *E. grandis* sites. Vattavada had the highest productivity with around 2-fold of the standing volume at Surianelli and more than 3-fold at the *E. tereticornis* sites (Table 8). Of the six treatments, the burn without starter fertilizer (B) showed significantly less growth during the first 2 yrs at Punnala and Surianelli. However, these effects were due to differences in applied treatments (addition of starter fertilizer to other treatments) rather than single or double slash or

other manipulations. An early positive response to single slash treatment at Surianelli and BS at Punnala was not evident later in the growth cycle. The response to BS treatment suggests an early effect of burning and availability of ash (Fig. 8 & 9); (Appendix - 1).

Table 8. Tree parameters and productivity across OM treatments (mean) at 6.5 years compared to previous rotation

Site and species/ parameters	Current rotation		Basal area (m^2 ha^{-1})		Survival of trees (%)		MAI (m^3 ha^{-1} yr^{-1}) and total productivity (m^3 ha^{-1}) in brackets		Productivity increase over previous rotation (%)
	Tree height (m)	DBH (cm)	Previous rotation (PR)	Current rotation (CR)	PR	CR	PR	CR	
K-poovam *E. tereticornis*	14.6	10	12.9	16.6	54.2	82.2	11.6	17.08 (111)	47
Punnala *E. tereticornis*	13.6	8.9	7.3	13.4	38.6	81.0	6.1	13.40 (87)	119
Surianelli *E. grandis*	18.7	13.3	10.3	24.0	42.2	93.9	9.0	29.23 (190)	224
Vattavada *E. grandis*	23.7	16.9	33.7	39.0	100	95.6	31.3	55.40 (360)	77

The mean standing volume in harvest residue treatments were 111m^3 ha^{-1} at Kayampoovam, 87 m^3 ha^{-1} at Punnala (*E. tereticornis*) and 190 m^3 ha^{-1} at Surianelli and 360 m^3 ha^{-1} at Vattavada (Table 8). The productivity was significantly higher than the previous rotation across OM treatments at all sites. The productivity increase was in the range 47-119% at *E. tereticornis* sites and 77-224% at the *E.grandis* sites.The mean height of trees, diameter at breast height, basal area and survival (%) were also significantly higher in the OM plots in relation to the previous crop. These comparisons in productivity were made with the low input harvest residue treatments. Higher productivity was obtained in most of the other intensively managed treatments and thus the increase in productivity was up to 106% at Kayampoovam, 243% at Punnala, 380% at Surianelli and 101 % at Vattavada across treatments compared to the previous rotation (Table 9).

8 a. 8 b.

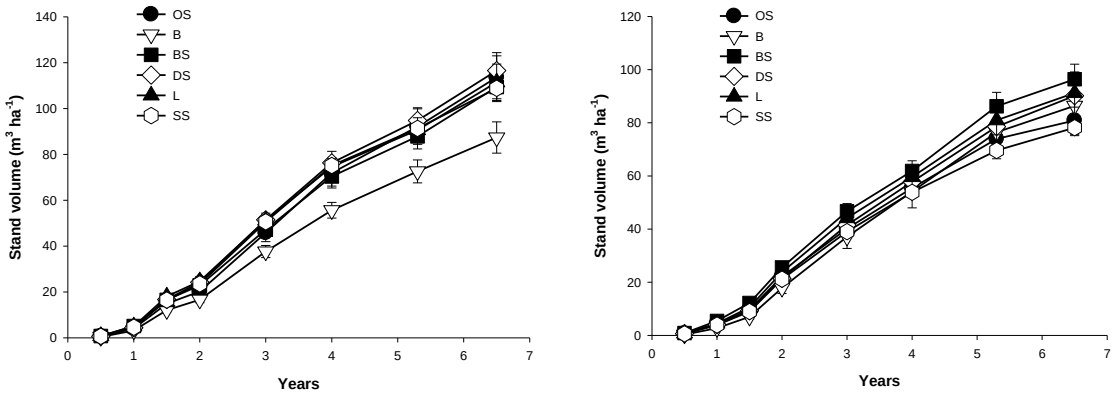


Fig. 8. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in organic matter experimental plots – *E. tereticornis* sites at (a) Kayampoovam and (b) Punnala.

9 a. 9 b.

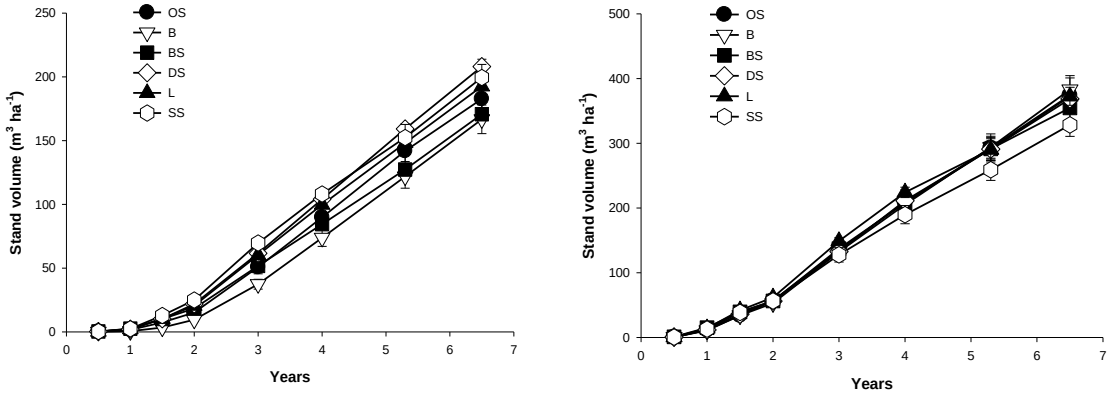


Fig. 9. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in organic matter experimental plots – *E. grandis* sites at (a) Surianelli and (b) Vattavada.

Table 9. Highest stand volume (m^3 ha^{-1}) across treatments at 6.5 years at the 4 sites.

Site/treatments	K'poovam	Punnala	Surianelli	Vattavada
OM treatment	116.5	96.4	208.1	372.6
N addition	127.1	130.3	269.5	371.0
P addition	155.4	132.4	281.1	350.0
Weed control	113.6	87.0	197.0	314.2
Legume intercropping	105.1	97.7	ne	ne
Thinning	ne	ne	255.0	409.0
Trenching	ne	136.4	180.0	303.0
Productivity of the previous crop (at 6.5 yrs)	75.4	39.7	58.5	203.5
ne – No experiment				

6.9.2. Legume intercropping

6.9.2.1. Legume establishment and biomass: Legume biomass varied seasonally with the maximum of 6.1, 4.6 and 1.8 t ha^{-1} respectively for *Stylosanthes*, *Peuraria* and *Mucuna*at Kayampoovam at 15 months after establishment. At Punnala, the corresponding figures were 6.3, 2.8 t ha^{-1} respectively, for *Stylosanthes* and *Mucuna*. Values for maximum biomass of *Stylosanthes* and *Mucuna* were recorded at 15 months, but *Pueraria* developed more slowly at that site, reaching a maximum biomass at 36 months after establishment. *Stylosanthes* and *Mucuna* grew well from the start of the experiment at both sites, but establishment of *Pueraria* was initially poor with significant biomass only produced after replanting in May 1999 (12 months after establishment). Dry matter production peaked after the main monsoon (June –August) and was at its lowest during dry period prior to monsoon (Fig10). *Stylosanthes* produced the highest biomass with a peak of approx. 6 t ha^{-1} at both the sites in the first two years. *Mucuna* had lower biomass with a maximum of 2 t ha^{-1} at both sites. The response of *Pueraria* differed between the sites with a relatively high biomass at Kayampoovam at 15 months (4.6 Mg ha^{-1}), but a lower biomass at Punnala until after 24 months. Although the eucalypt overstorey had reached near maximum leaf area by 24 months, as *E. tereticornis* has a relatively open canopy there was adequate light for continued growth of legumes (Fig 10).

6.9.2.2. Tree growth in response to legume treatment: The open canopy of *E. tereticornis* promoted growth of all legumes up to 3 years. Thereafter, except for *Mucuna* at Punnala and *Pueraria* at Kayampoovam, other species did not persist and no attempt was made to replant them. Legume cover crops induced an initial decline in productivity of the plantations (significant at Punnala at 18 months). The decline in growth of eucalypts in plots planted with *Mucuna* and *Stylosanthes* was 29 and 20%, respectively compared to controls. After 18 months, the absolute differences between treatments and control reduced and were minimal at 4 years.

A significant increase ($P<0.05$) in productivity of eucalypts over control was observed in plots intercropped with *Pueraria* and *Stylosanthes* at 5 years at Punnala. There was further improvement in growth of the trees at the end of the rotation (6.5 years) with an increase of 20% in tree volume in the above plots ($P< 0.01$) against plots without legumes. The *Mucuna* cover crop caused approximately 20% mortality in standing volume of trees at Punnala by smothering them. This resulted in no difference in productivity between these and control plots although individual trees were larger in the *Mucuna* plots which compensated the loss of tree numbers. Legume cover cropping

had no significant effect on planation productivity at Kayampoovam during the rotation. However, the productivity of trees was comparatively higher in the *Mucuna* plots at Kayampoovam from 3 years till the end of the rotation (Fig 11).

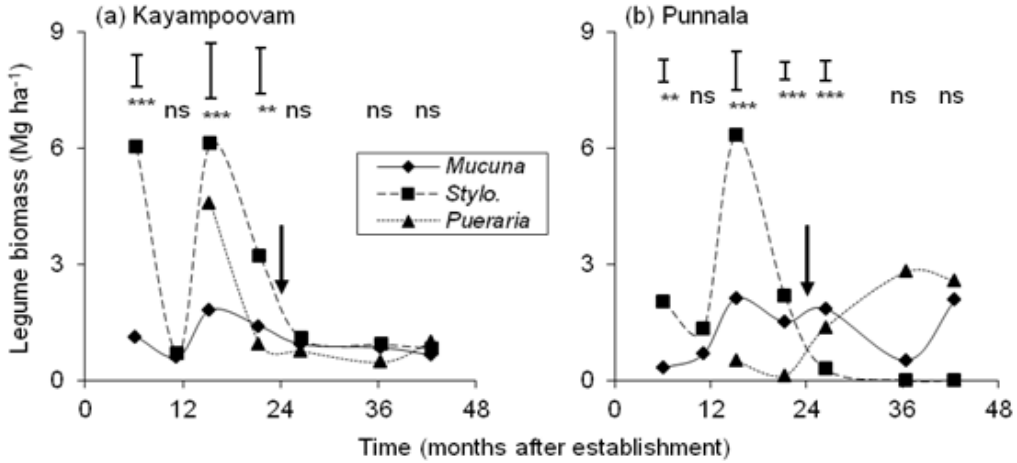


Fig. 10. Time course of above ground legume biomass at (a) Kayampoovam and (b) Punnala. ns – not significant, ** $p < 0.01$; bars show LSD ($\alpha = 0.05$) where differences were apparent; arrows indicate the time of sampling for field N availability measures.

11 a. 11 b.

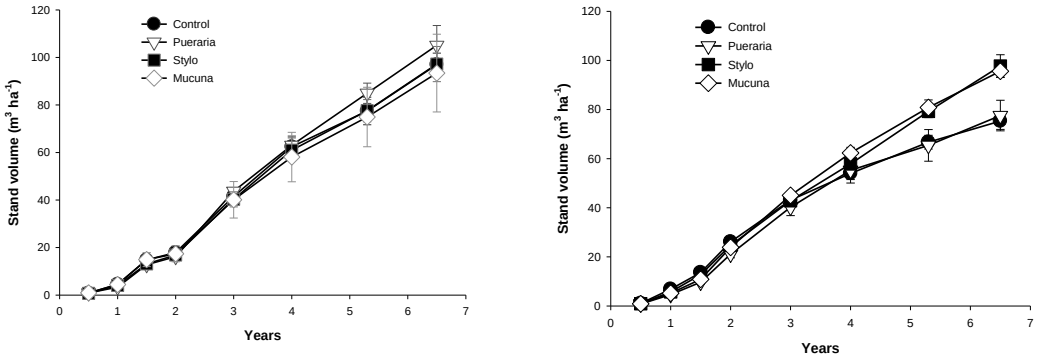


Fig.11. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in legume experimental plots at at (a) Kayampoovam and (b) Punnala

6.9.3. Tree growth in response to spacing (thinning) trials in *E. grandis*: Trees in the highest density plot (2360 stems ha^{-1}) showed significantly high tree volume from 3 years of growth until the end of the rotation compared to the low density plots (833, 1250 and 1667 stems ha^{-1}) However, trees in the low density plots showed a positive trend in volume at 5 and 6.5 yrs (Fig. 12). A comparison of CAI-MAI values in the S 08 plot showed the potential for continued growth in volume of trees compared to the other plots.

12 a. 12 b.

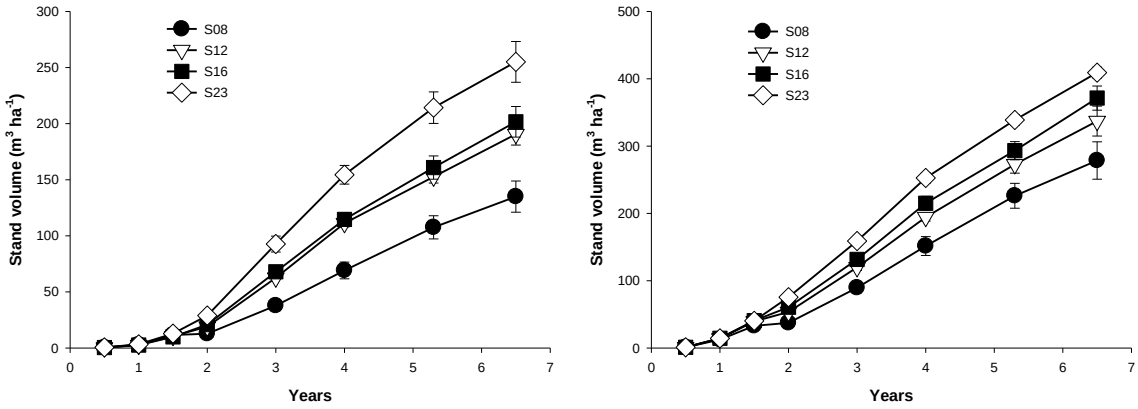


Fig.12. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in thinning experimental plots at (a) Surianelli and (b) Vattavada

6.9.4. Weed control: Tree growth was significantly higher in complete weeded treatments at the *Et* sites during all the measurement times till the end of the rotation ($P<0.05$ at 6.5 years at both the sites (Fig. 13). The productivity in complete weeded treatment was increased by 77% at Kayampoovam and 150% at Punnala, over non-weeded treatment at the time of harvest. Though strip weeding had a positive trend for higher growth especially at *Et* sites, the standing volume was not significantly improved over control at any of the sites. At Vattavada, the initial positive influence of complete weeding on productivity (up to 1.5 years) was not observed later in the rotation (Fig. 14) Weeding had no significant effect on tree growth at Surianelli at any of the measurement times although the CW treatment had 33m^3 ha^{-1} more volume at 6.5 yrs (Fig. 14).

6. 9.5. Trenching: Responses to trenching were not significant at all the three sites tested at any of the measure times till the end of the rotation. However, a trend for consistent higher productivity in plots with contour trenching compared to staggered trenching and control was observed at Punnala. At Surianelli this trend was apparent in plots with staggered trenching with an increase in productivity of 33.9 m^3 ha^{-1} over control at the end of the rotation. No clear trends were visible at Vattavada and the differences between treatments were minimal (Table 10 a). The mean stand volume at 6.5 years in the trenching experiment plots was 129.8, 158.7 and 294 m^3 ha^{-1} at Punnala, Surianelli and Vattavada, respectively. In general, the productivity achieved was significantly higher compared to the previous rotation.

13 a. 13 b.

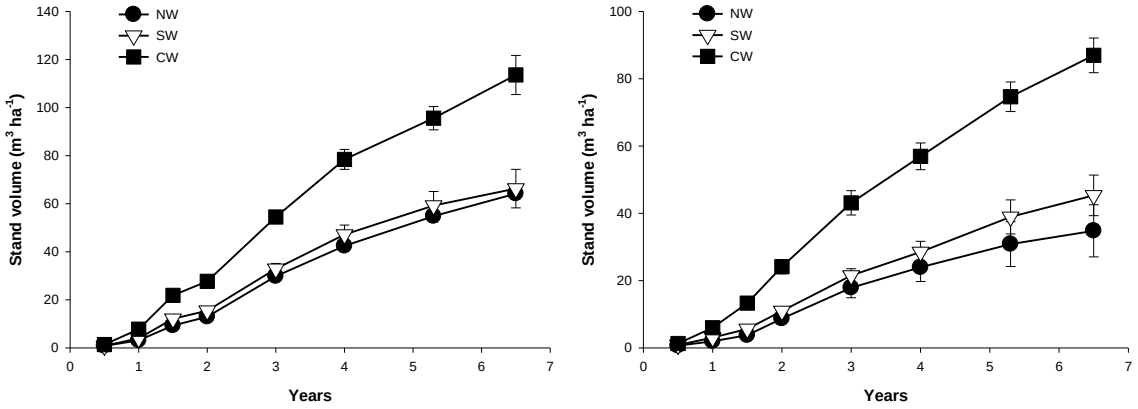


Fig. 13. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in weeding experimental plots– *E. tereticornis* sites at (a) Kayampoovam and (b) Punnala

14 a. 14 b.

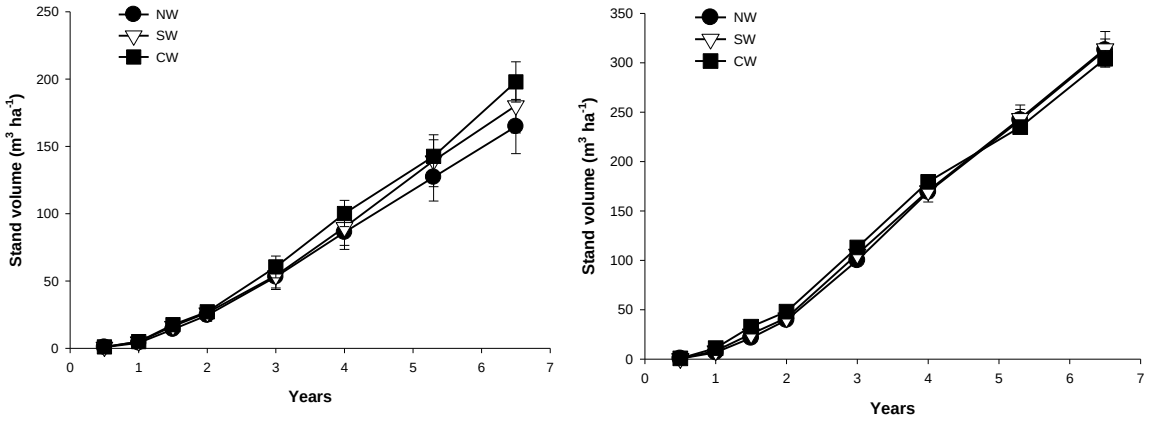


Fig. 14. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in weeding experimental plots– *E. grandis* sites at (a) Surianelli and (b) Vattavada

6.9.6. Tree growth in response to Nitrogen addition: There was a trend for higher productivity with N fertilizer application at all 4 sites (Fig 15 a - e). However, treatment differences were significant only for Punnala till the end of the rotation. The large and significant response at Surianelli up to 5 years was not significant at 6.5 years though the magnitude of the volume gain was to the tune of 64 m^3 ha^{-1} in the highest treatment (N5). Significant improvement in tree growth was observed at Vattavada only up to 3 yrs. Kayampoovam was the least responsive to N application with significant improvement in tree growth observed only at 3 and 6 months. At the Et site, 187 kg N ha^{-1} gave the maximum response (55% increase over zero nitrogen input) and the corresponding N rate for Eg was 375 kg N ha^{-1} (31% increase over control).

Table 10a. Mean tree volume (m^3ha^{-1}) in trenching experiments at the experimental sites

Site/yr of measurement/ Trenching mode	0.5 year		1 year		1.5 year		2 years		3 years		4years		5.3 years		6.5 years	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Punnala NT	**0.97**	0.13	**6.50**	0.54	**15.37**	1.39	**28.00**	2.75	**55.11**	5.92	**78.64**	8.84	**112.45**	20.13	**126.39**	20.81
CT	**1.19**	0.49	**6.95**	1.85	**16.71**	4.74	**30.89**	7.00	**58.19**	10.94	**84.27**	14.55	**117.37**	21.28	**136.41**	25.79
ST	**1.06**	0.11	**6.72**	0.29	**16.25**	1.67	**29.75**	2.93	**57.93**	10.40	**80.55**	16.03	**110.53**	23.55	**126.65**	28.71
Surianelli NT	**0.18**	0.04	**1.12**	0.17	**3.74**	0.65	**7.15**	1.01	**27.02**	4.25	**59.45**	7.42	**104.23**	7.71	**146.98**	7.09
CT	**0.24**	0.09	**1.54**	0.29	**4.95**	1.30	**9.84**	2.35	**33.91**	7.08	**66.29**	8.23	**101.50**	14.07	**148.21**	20.54
ST	**0.22**	0.08	**1.27**	0.41	**5.58**	2.09	**11.88**	4.75	**42.68**	14.91	**83.08**	20.28	**128.11**	28.82	**180.85**	40.74
Vattavada NT	**0.94**	0.19	**11.89**	1.09	**31.13**	2.57	**43.30**	1.55	**115.13**	4.67	**179.25**	5.34	**238.38**	5.53	**258.86**	13.80
CT	**1.01**	0.14	**13.38**	0.83	**35.90**	2.10	**46.11**	3.02	**116.61**	7.80	**184.11**	9.91	**240.95**	37.53	**303.17**	31.41
ST	**1.00**	0.21	**13.46**	1.94	**34.40**	4.45	**47.39**	4.13	**120.40**	12.24	**189.05**	15.94	**235.18**	22.79	**294.00**	32.23

NT – No trenching ; CT – Contour trenching; ST – Staggered trenching

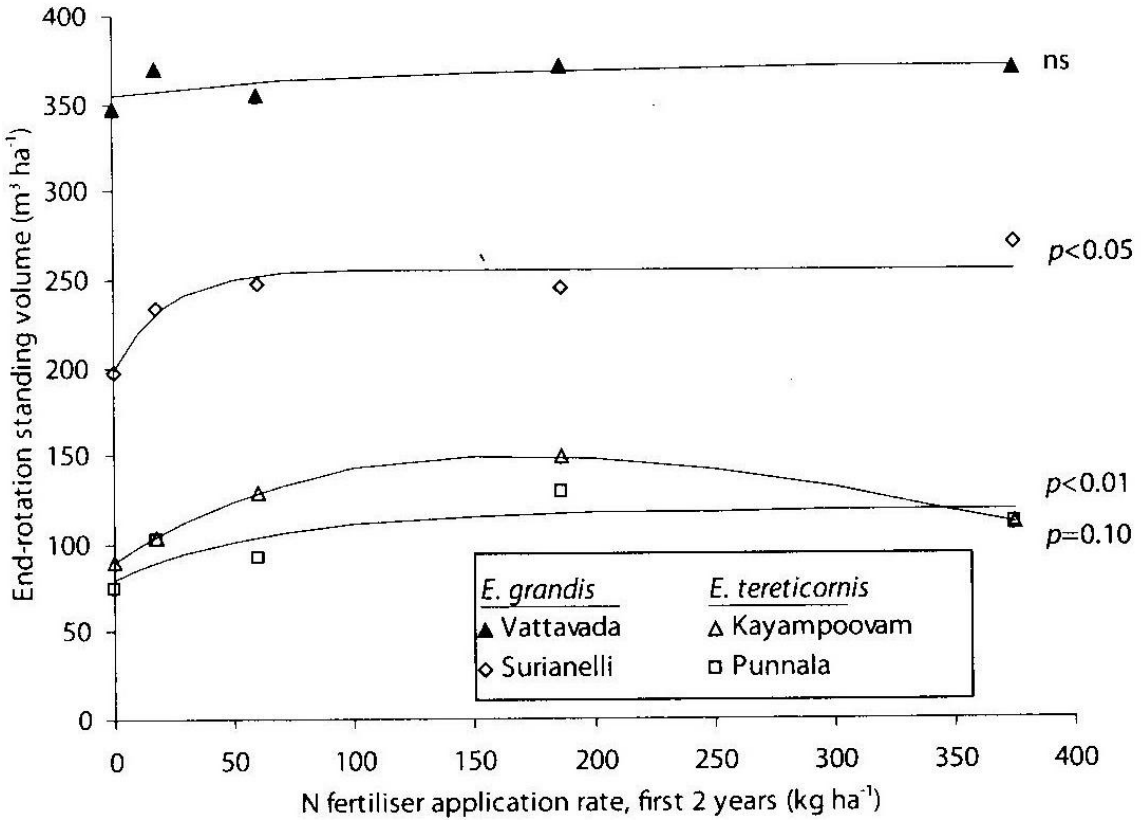
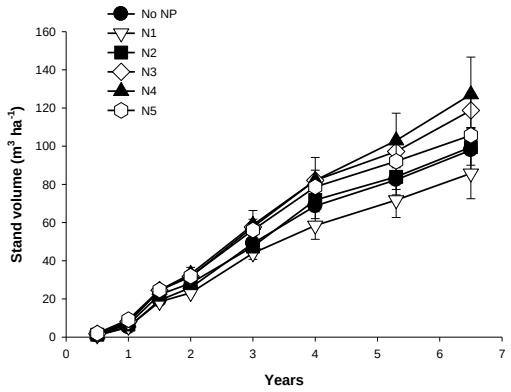


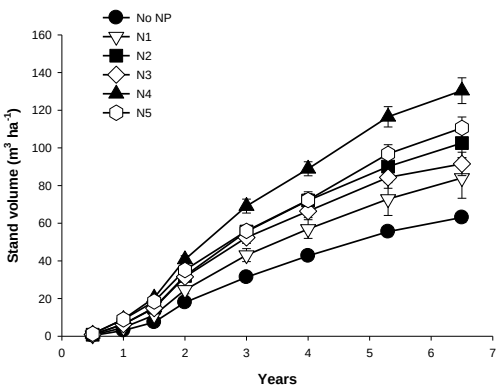
Fig. 15a. Standing volume response to N fertilizer at the end of the rotation. p values represent the significance of the exponential regression.

6.9.7. Impact of Phosphorous addition: A significant increase in standing volume in plots applied with 131 kg ha^{-1} was observed at Punnala throughout the rotation (35 % increase in volume compared to zero P input at 6.5 yrs). A similar response was also evident at Surainelli until 4 years but the highest volume was recorded for P1 treatment at 5 and 6.5 years. (Fig. 15 f-i). The response at Vattavada site was minimal and not apparent later in the rotation. The Kayampoovam site did not respond to P application but curiously a significant increase in growth was observed in P1 plots at 5 and 6.5 years of growth. Results such as this are difficult to interpret since the response was not in any logical order. The mean tree volume (m^3 ha^{-1}) in various treatments at the time f harvest (6.5 years) at various sites is given in Appendix 3.

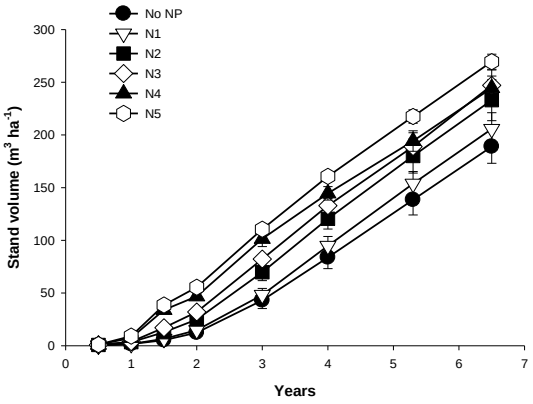
15 b.



15 c.



15 d.



15 e.

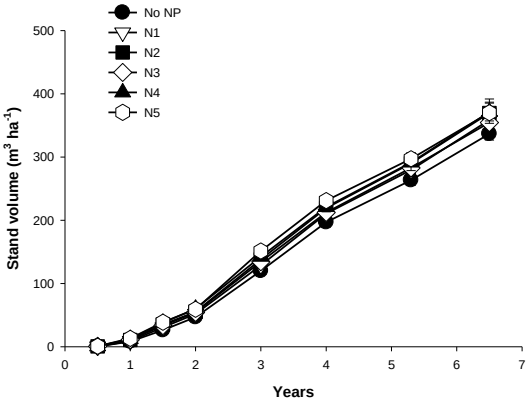
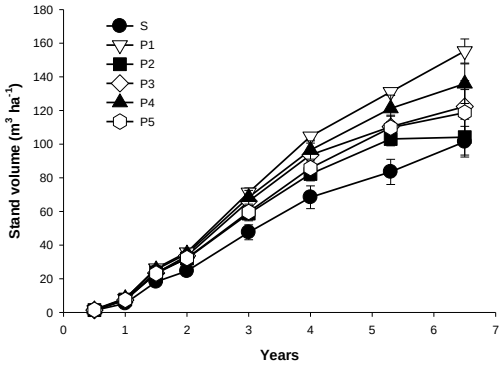


Fig. 15 b - e. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in N experimental plots at (b) Kayampoovam (c) Punnala (d) Surianelli and (e) Vattavada.

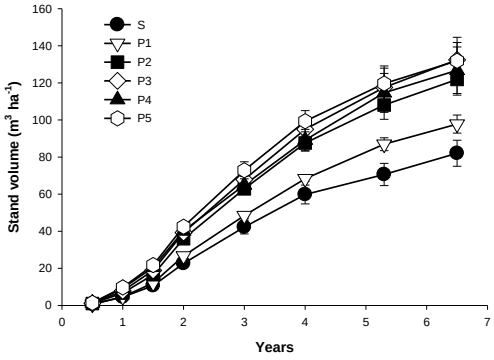
6. 9. 8. Soil nutrient dynamics in OM plots

6.9.8.1. Soil C, N and P: Retention or removal of slash did not have any significant effect on soil C at any of the 4 sites (Fig.16) but significantly influenced total soil N (Fig.17) at only Punnala (both at 0-5 and 5-10 cm depths). Similarly soil P (Fig.18) was influenced by harvest residue retention at Surianelli (significant for 0-5 cm depth). When tested across sites, only P was significantly influenced by treatment.

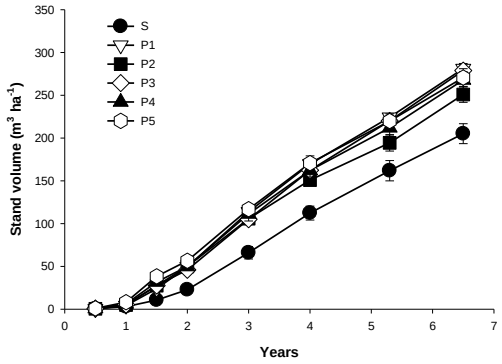
15 f.



15 g.



15 h.



15 i.

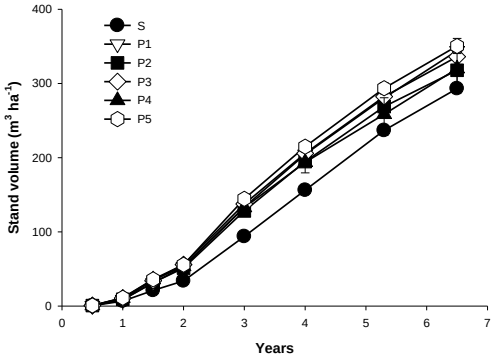


Fig. 15 f - i. Tree volume (m^3 ha^{-1}) changes with plantation age (years) in P experimental plots at (f) Kayampoovam (g) Punnala (h) Surianelli and (i) Vattavada.

6. 9.8.2. Cations: Effects of slash manipulation on soil cations were assessed in 2000 (at the age of 2 years). There were no significant effects of residue treatment on K, Ca or Mg at any of the depths (0-5, 5-10 and 10-20 cm). So, only mean values are presented in Table 10a. Vattavada had the highest concentration of each of the cations. Punnala and Surianelli had relatively low Ca concentration (Table 10b). The time course of soil cations were examined in more detail at Punnala where residue retention resulted in a significant increase in surface (0.5 cm) exchangeable potassium when the experiment was established (Fig. 19). There were no other significant treatment effects on exchangeable cations. The time course of exchangeable potassium showed a steady decline at all 3 depths over the 6 years since establishment, but a trend for Calcium and Magnesium over time was not as evident (Fig. 19). Soil content of K was in the order Double Slash>Burnt with starter fertilizer >Single Slash>Zero Slash.

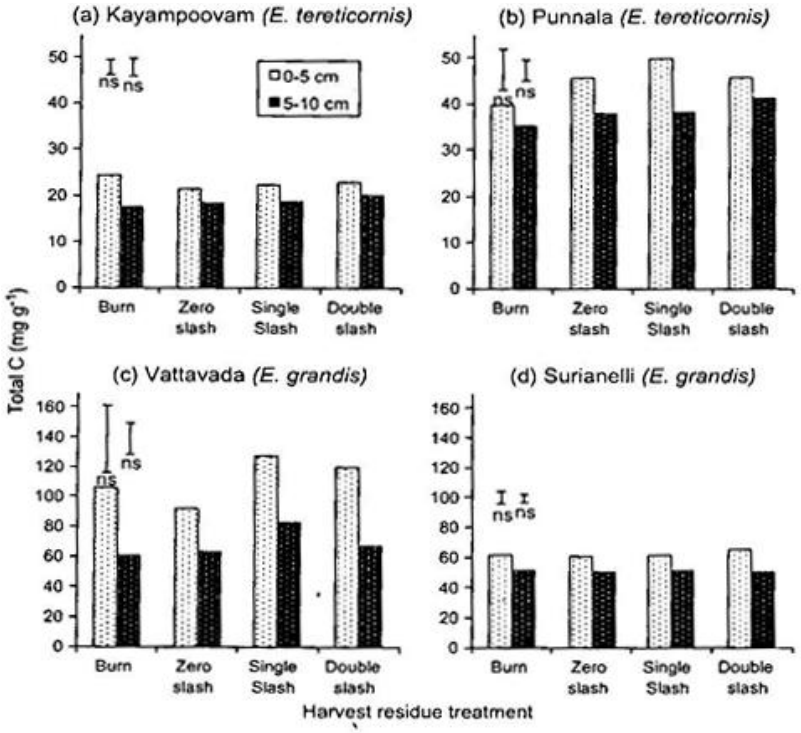


Fig. 16 a - d. Influence of harvest residue management on total organic carbon (0 -5 and 5 -10 cm) two years after establishment at (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site

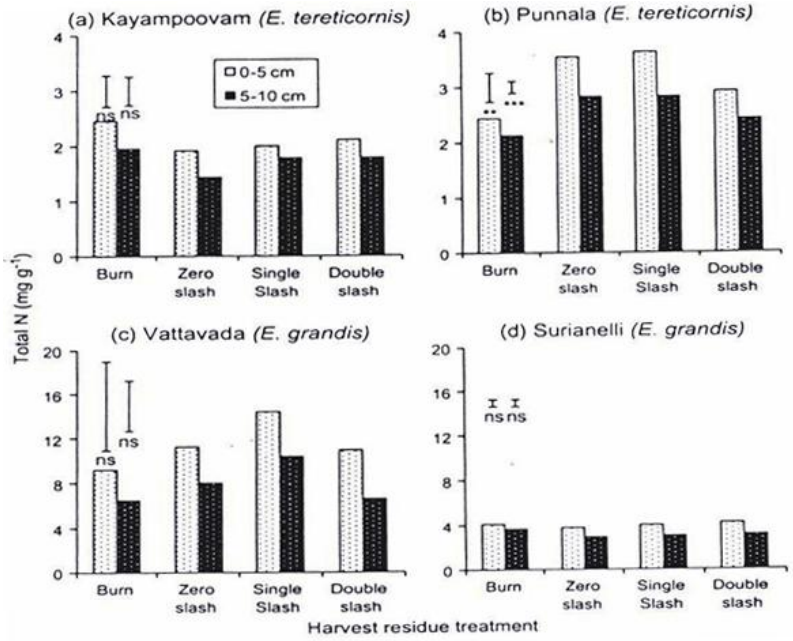


Fig. 17 a - d. Influence of harvest residue management on total soil N (0 -5 and 5 -10 cm) two years after establishment at (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site

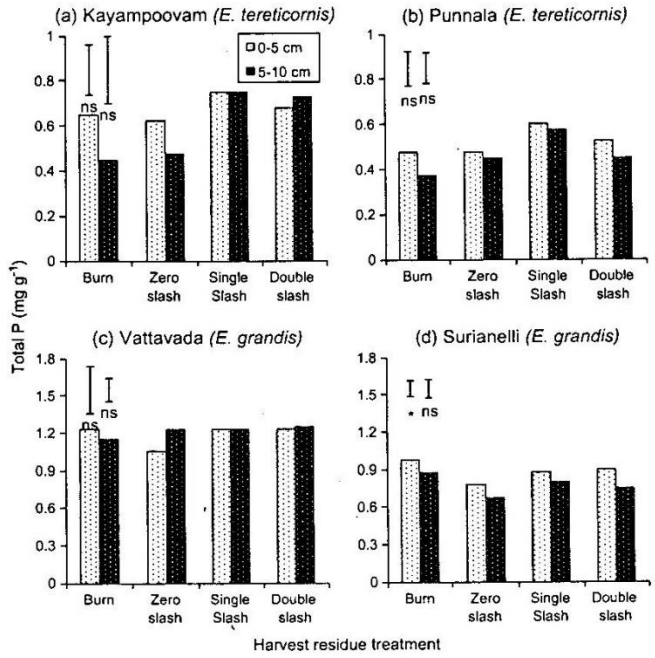


Fig. 18 a - d. Influence of harvest residue management on total soil P (0 -5 and 5 -10 cm) two years after establishment at (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site.

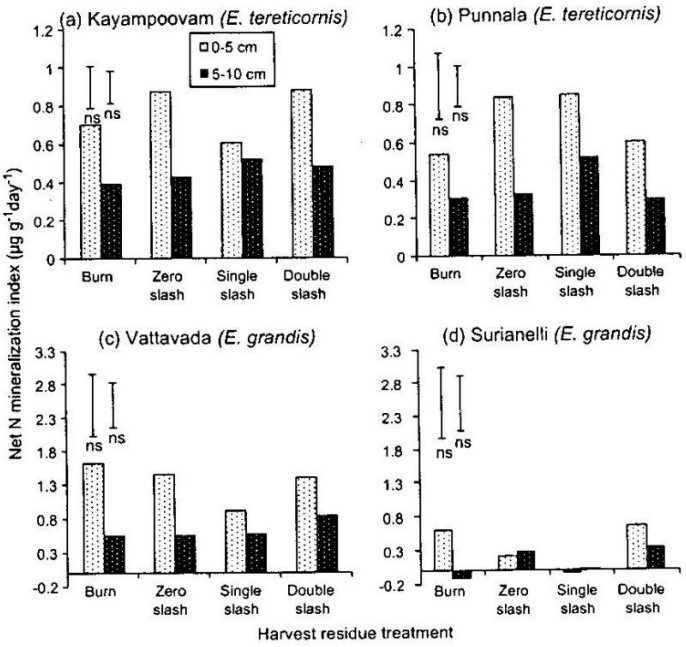


Fig. 20 a - d. Influence of harvest residue management on *in situ* N mineralization (0 -5 and 5 -10 cm) two years after establishment at (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site. Pooling the data and analyzing across sites did not improve the significance of treatment differences

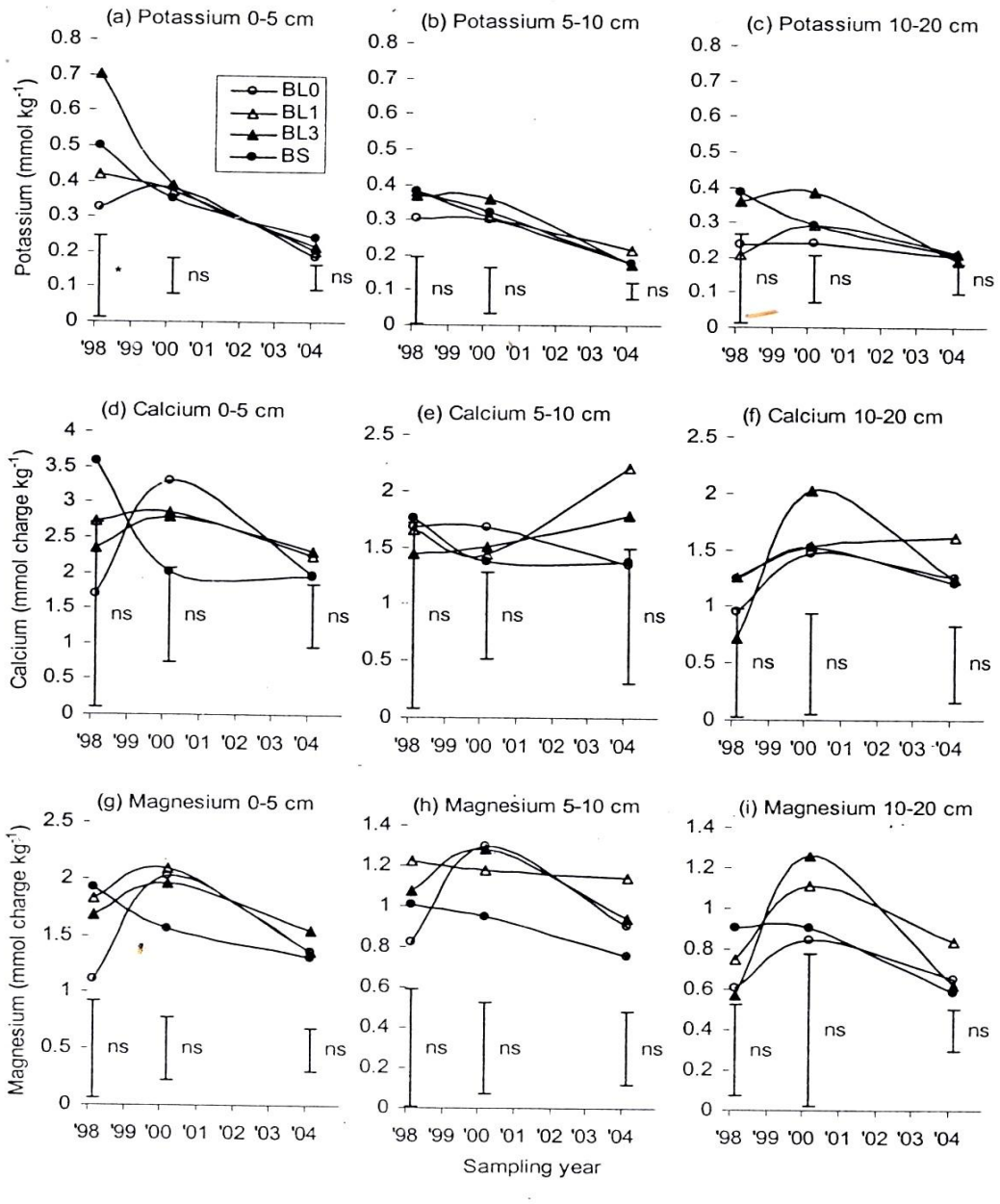


Fig 19. Impact of treatment on soil exchangeable K (a- c), Ca (d – f) and Mg (g- i) concentration over time at Punnala.

Table 10 b. Soil exchangeable cation concentration (cmol (p^+)kg^{-1})

Sites	K		Ca		Mg	
	0-10cm	10-20cm	0-10cm	10-20cm	0-10cm	10-20cm
Kayampoovam	0.47	0.55	9.83	8.60	2.51	2.78
Punnala	0.35	0.30	2.08	1.64	1.52	1.03
Surianelli	0.51	0.33	3.21	0.83	2.58	1.02
Vattavada	1.13	1.03	24.30	13.20	7.13	3.71

6.9.8.4. Pattern of N mineralization:

Field experiments: Harvest residue manipulation in the field did not have any significant effect on N mineralization at age 2 years (Fig.20). Whilst there were no significant treatment effects, there were large differences across sites and between soil depths. The upper layer (0-5 cm) tended to have higher mineralization rates. At 3 of the sites, (Kayampoovam, Punnala and Vattavada) significant quantities of N were released over the course of the incubation in all treatments. However, the Surianelli site did not release as much N and immobilization of N occurred in some of the samples.

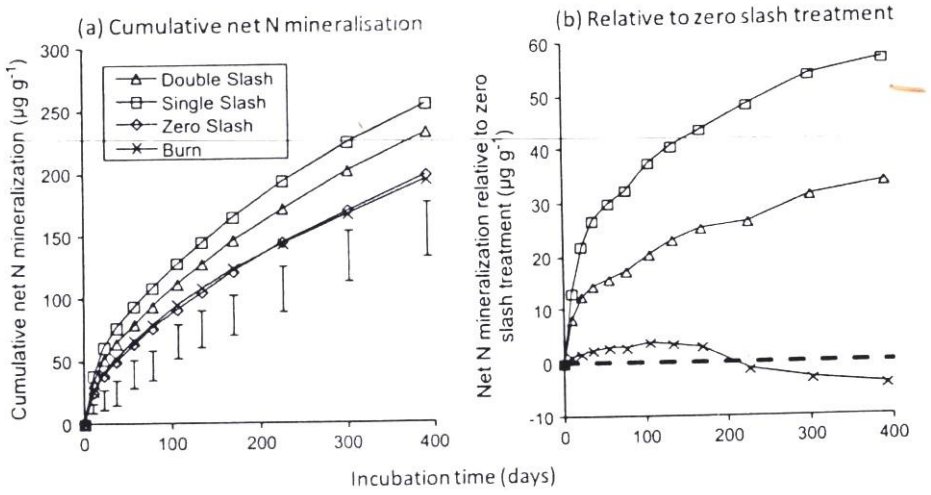


Fig. 21. Cumulative N mineralization (µg g^{-1}) after 3 years of establishment of plantation in a lab leaching experiment for each treatment (a) and relative to zero slash treatment (b). Treatment effects were not significant at individual sites. When data from all sites were pooled, treatment effects were significant ($p < 0.05$). Bars show LSD ($p = 0.05$).

6.9.8.4. Long-term lab incubation: As with the *in situ* measures of N mineralization, the N released during the laboratory incubation was subject to high variability and when the individual sites were considered, treatment trends were apparent but not significant. However, when data were pooled across sites, there were significant treatment effects on the pattern of N mineralization (Fig. 21a, b). The rate of release of N was higher initially, and declined over time, but even after 400 days under the ideal temperature and moisture conditions of incubation, the treatments with added slash (DS and SS) were still leaching more N than the zero slash treatment.

6.9.8.5. Anaerobically mineralizable N: Harvest residue retention tended to increase the anaerobically mineralizable-N, and these trends were significant at 2 of the 4 sites (Kayampoovam and Surianelli) (Fig.22). Again, the surface 0-5 cm layer tended to have

higher amounts of anaerobically mineralizable-N compared to the 5-10 cm layer, but in contrast to the aerobic N mineralization index, the highland sites (Vattavada and Surianelli) had substantially higher rates of anaerobically mineralizable-N. When compared across sites, the residue-retained sites had significantly higher anaerobically mineralizable-N than the slash removed or burnt treatments.

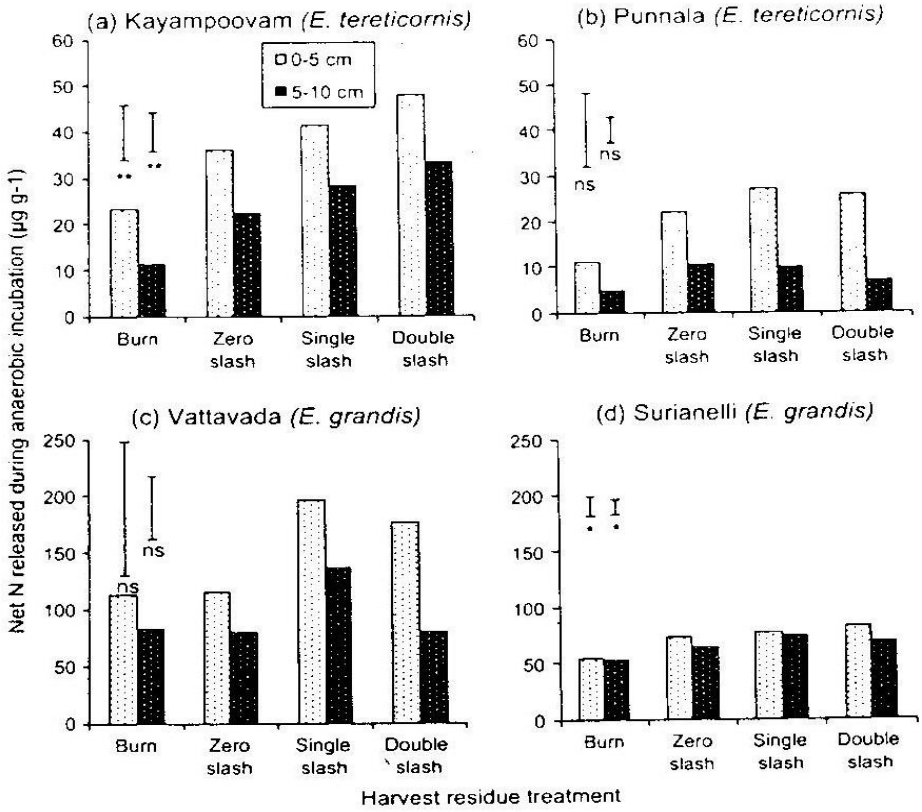


Fig. 22. Influence of harvest residue management on soil N mineralized (µg g^{-1}) during an aerobic incubation (0 – 5 and 5 – 10 cm) 2 years after establishment of plantation (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site. Treatment effects were significant for both soil depth ranges when compared across sites (p = 0.03 for 0 -5 cm and p = 0.01 for 5 – 10 cm).

6.9.8.6. Microbial biomass-C: As with other *in situ* measures, microbial biomass carbon tended to be higher under the residue-retained treatments at most sites, but at a site level, this was only significant at Punnala (5-10 cm depth range) and at Vattavada (0-5 cm depth range). When all sites were considered in the analysis, there were significant treatment influences on microbial biomass carbon, with highest values in the residue-retained treatments and lowest in the residue–removed treatments. The ratio of microbial biomass C to anaerobically mineralizable N was also significantly affected by treatment P< 0.001 in the 0-5 cm depth range) at Kayampoovam site with 16.4 mg

biomass C μg^{-1} anaerobically mineralizable N, compared to an average of 9.96 mg biomass C μg^{-1} anaerobically mineralizable N for all other treatments (range 9.6 -10.2 mg μg^{-1}). The other sites and soil depths did not show a significant trend in this ratio, but a similar (non-significant) trend was found at the Punnala site (Fig. 23).

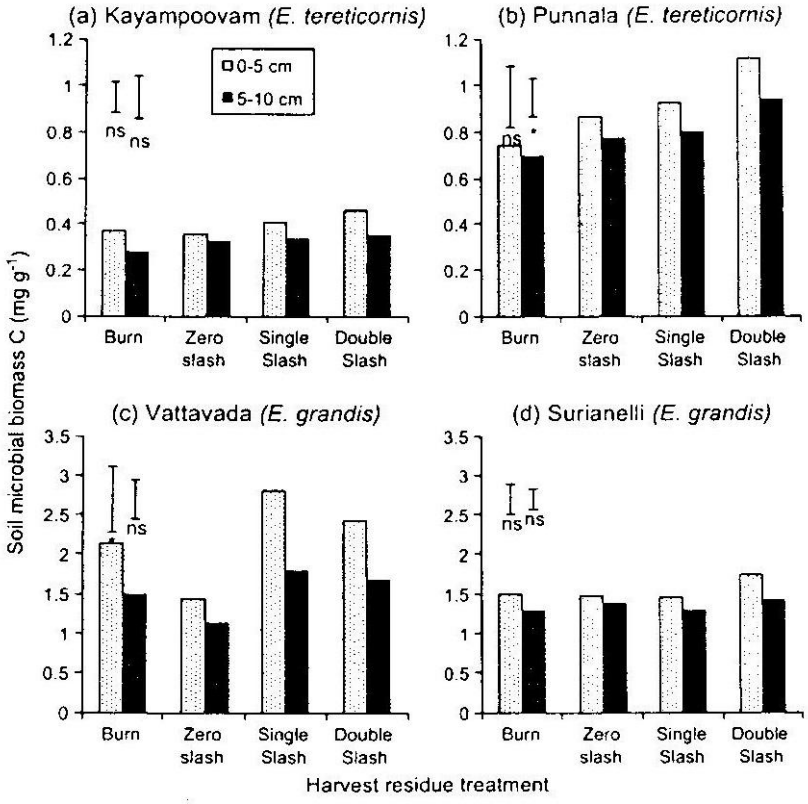


Fig. 23. Influence of harvest residue management on soil microbial biomass at 2 years after establishment of plantation (a) Kayampoovam (b) Punnala (c) Surianelli and (d) Vattavada. Bars show LSD (p = 0.05) for each depth range at each site. Treatment effects were significant for both soil depth ranges when compared across sites (p = 0.01 for 0 -5 cm and p = 0.04 for 5 – 10 cm).

6.10. Nutrient dynamics in legume plots

6.10.1. Chemical quality of residues: The residues of *Mucuna*, *Stylosanthes, Pueraria* and *Eucalyptus tereticornis* used in this study had contrasting characteristics with largest differences in concentrations of total N, soluble carbohydrates and soluble polyphenols (Table 11). There was a consistent trend for lower N concentrations in plant material from Kayampoovam compared to Punnala. The range in lignin content between species was small. In general, the *Mucuna* residues had higher chemical quality (lowest C:N, lignin: N and soluble polyphenol : N ratios) compared to the other residues

followed by *Pueraria. Stylosanthes* had a relatively low chemical quality with the highest C:N and lignin : N ratios. Eucalypt leaves had higher concentrations of soluble polyphenols and carbohydrates than the legume residues but somewhat lower lignin content. Eucalypt leaves also had the highest soluble polyphenol : N ratio.

6.10.2. N release from eucalypt and legume residues during laboratory incubation: N leaching during the initial leaching (day 0) was significantly different between treatments (Table 12) with relatively high net release of N from *Mucuna* followed by *Stylosanthes* and *Pueraria*. The treatments from eucalypt and eucalypt + *Pueraria* residues caused N immobilization during the initial leaching in the Kayampoovam soil. N mineralization from the un-amended (control) soils was rapid during the initial stage (day 0-10) of the experiment (Fig 24) but after 36 days, rates had dropped to low values (<0.3 mg N kg^{-1} soil day^{-1}) and declined only marginally with each leaching. Punnala had higher N mineralization than Kayampoovam although the difference between sites was only apparent up to about the 56th day of leaching.

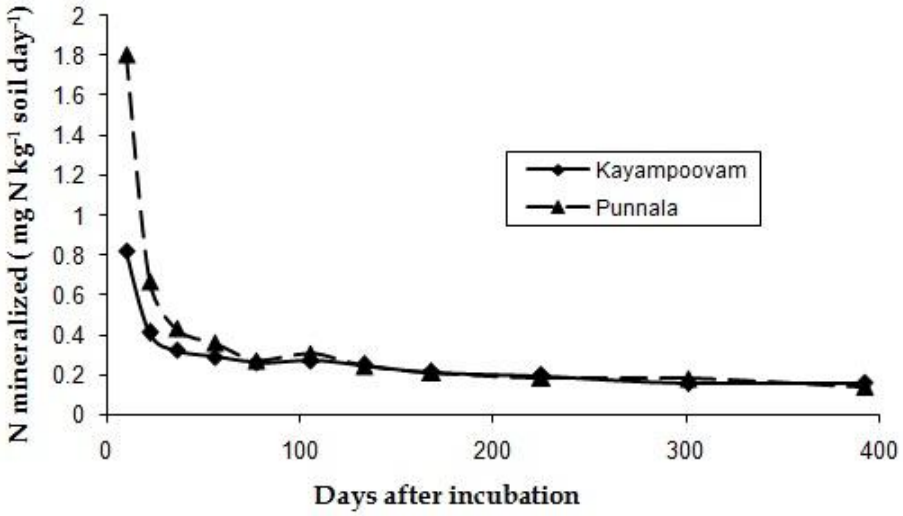


Fig. 24. Net N mineralization from the control (un amended) treatment in the lab incubation for both soils (mean of four replicates).

Net N immobilization/mineralization in residue–amended soils was strongly influenced by the types of residues applied, with similar patterns across both soils (Fig 25). *Mucuna* produced the highest amounts of N mineralized in both soils, with *Pueraria* residues giving the next highest net N mineralization. Eucalypt residues initially immobilized N, but net release of N commenced after 22 and 10 days for Kayampoovam and Punnala soils, respectively. Cumulative net N release from

euclaypt residues was positive 77 and 36 days in Kayampoovam and Punnala soils, respectively. N immobilization was greatest in *Stylosanthes* residues, with net N release only occurring after 225 in Kayampoovam and 301 days in Punnala soils.

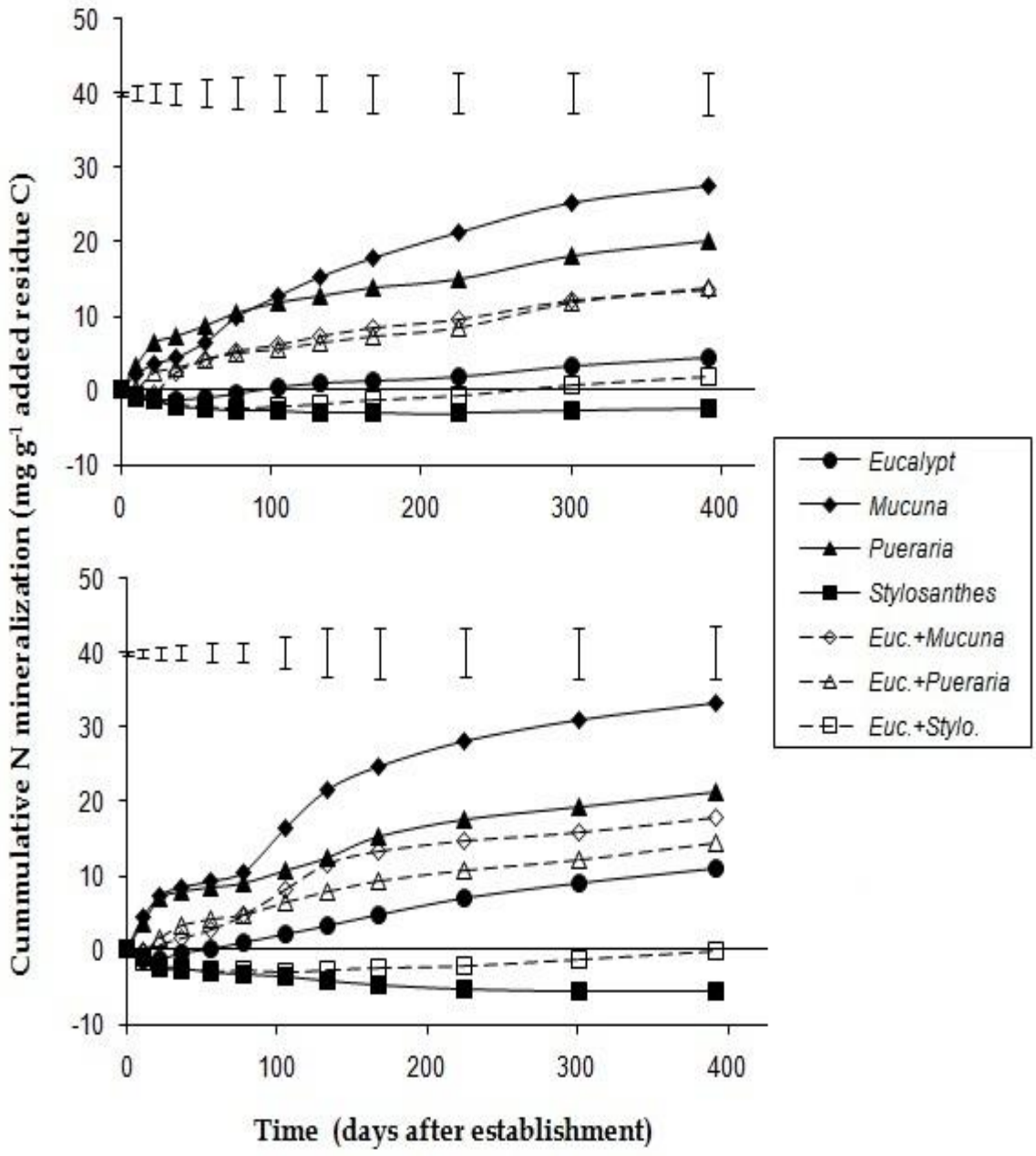


Fig. 25. Cumulative net N mineralization over 392 days from the treatments with the residues added (difference in control) at Kayampoovam (top) and Punnala (bottom). Bars show LSD for means at each sampling time for soils from each site. Differences between treatments were highly significant ($p < 0.001$) at each sampling time at each site

Table 11. Chemical characteristics of the legume (intercropped) and eucalypt residues used in the laboratory incubation with the Kayampoovam (Kay.) and Punnala (Pun.) soils

Residue	*Eucalyputus*		*Mucuna*		*Pueraria**	*Stylosanthes*	
	Kay.	Pun.	Kay.	Pun.	Kay.	Kay.	Pun.
Total C (mg g^{-1})	496.0	503.0	471.0	487.0	451.0	465.0	469.0
Total N (mg g^{-1})	12.5	15.3	35.3	46.3	25.8	6.48	7.16
Inorganic N (mg g^{-1})	0.249	0.285	1.27	1.51	0.539	0.100	0.093
Soluble carbohydrates (mg g^{-1})	111.0	89.6	31.4	33.0	27.4	20.9	21.2
Holocellulose (mg g^{-1})	401.0	359.0	428.0	401.0	421.0	683.0	615.0
Lignin (mg g^{-1})	156.0	165.0	230.0	168.0	217.0	182.0	172.0
Soluble polyphenols (mg g^{-1})	122.0	114.0	19.4	16.5	26.3	12.1	10.9
C:N ratio	39.8	33.0	13.3	10.5	17.5	71.8	65.5
Lignin :N ratio	12.5	10.8	6.53	3.63	8.40	28.1	24.0
Soluble polyphenol : N ratio	9.79	7.45	0.548	0.356	1.02	1.87	1.52
(Lignin + soluble polyphenol): N ratio	22.3	18.3	7.08	3.98	9.42	30.0	25.5

**Pueraria* residue was collected from Kayampoovam only as insufficient material was available at Punnala

Over the complete incubation period (392 days), *Stylosanthes* residues caused net cumulative N immobilization in both soils. There were significant differences ($P<0.01$) between residue types in the proportions of C and N remaining in residues recovered after incubation with a similar pattern for both the sites (Fig. 26). *Pueraria* had the highest rate of loss of both C and N with approximately 20% of the residue C, and 30% of the residue N remaining. The strong N immobilization observed in the *Stylosanthes* treatment was confirmed by an increase in residue N for the Punnala soil (125% recovery), and a small decrease in residue N in the Kayampoovam soil (84% recovery).

Net N mineralization/immobilization due to legume residue addition was strongly correlated with several of the residue quality indices, including total N concentration (Fig 27 b; $P<0.001$), C:N ratio (Fig 27c; $P<0.001$), lignin: N ratio (Fig 27d; $P =0.002$) and the lignin+soluble polyphenol: N ratio(Fig 27f; $P< 0.001$).

Table 12. Nitrogen released from added residues (i.e. difference from control) in initial leaching of laboratory incubation (mg N g^{-1} added residue C)

Residues and combinations	Kayampoovam	Punnala
Eucalyptus	-0.189	0.069
Mucuna	2.77	2.793
Stylosanthes	1.43	1.29
Pueraria	0.192	0.574
Eucalyptus +Mucuna	1.10	1.49
Eucalyptus +Stylosanthes	0.467	0.478
Eucalyptus + Pueraria	-0.288	0.117
P value	<0.001	<0.001
LSD	0.674	0.543

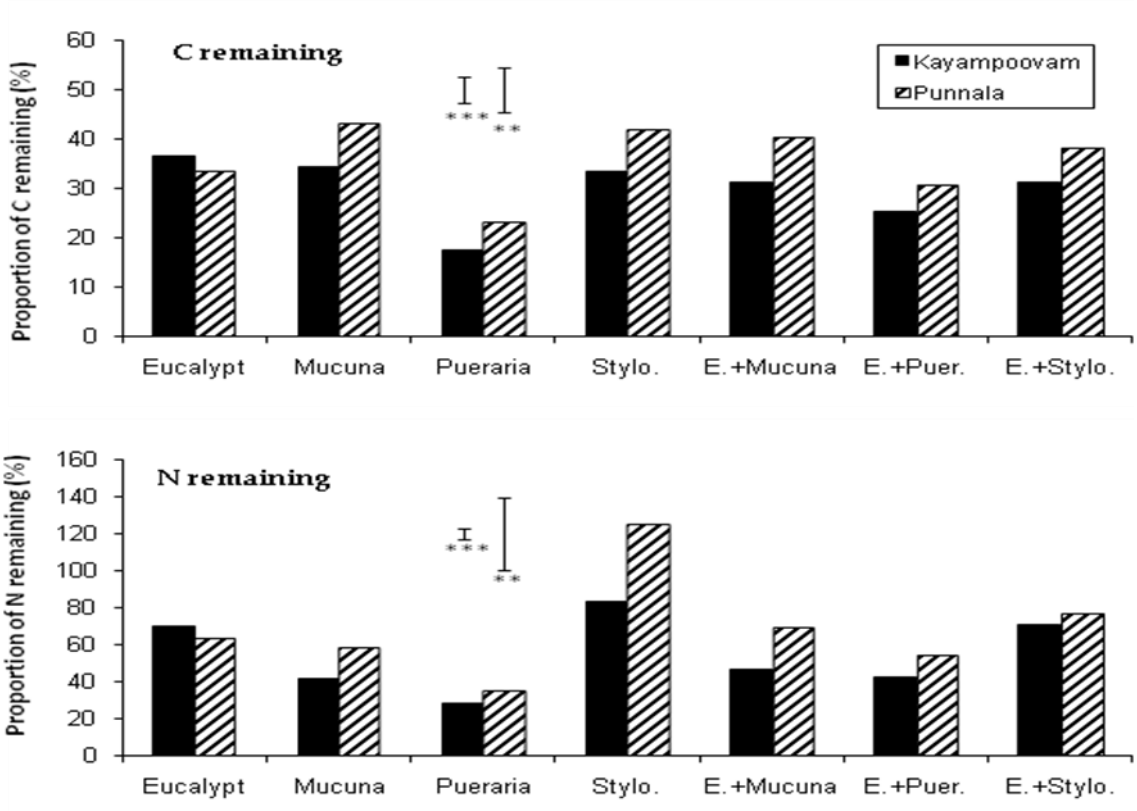


Fig. 26. Properties of residues C (a) and N (b) remaining on the soil surface after 392 – day incubation. Bars show LSD for comparing treatments at each site. Significance of comparison is indiacted by ** p <0.01, *** p < 0.001

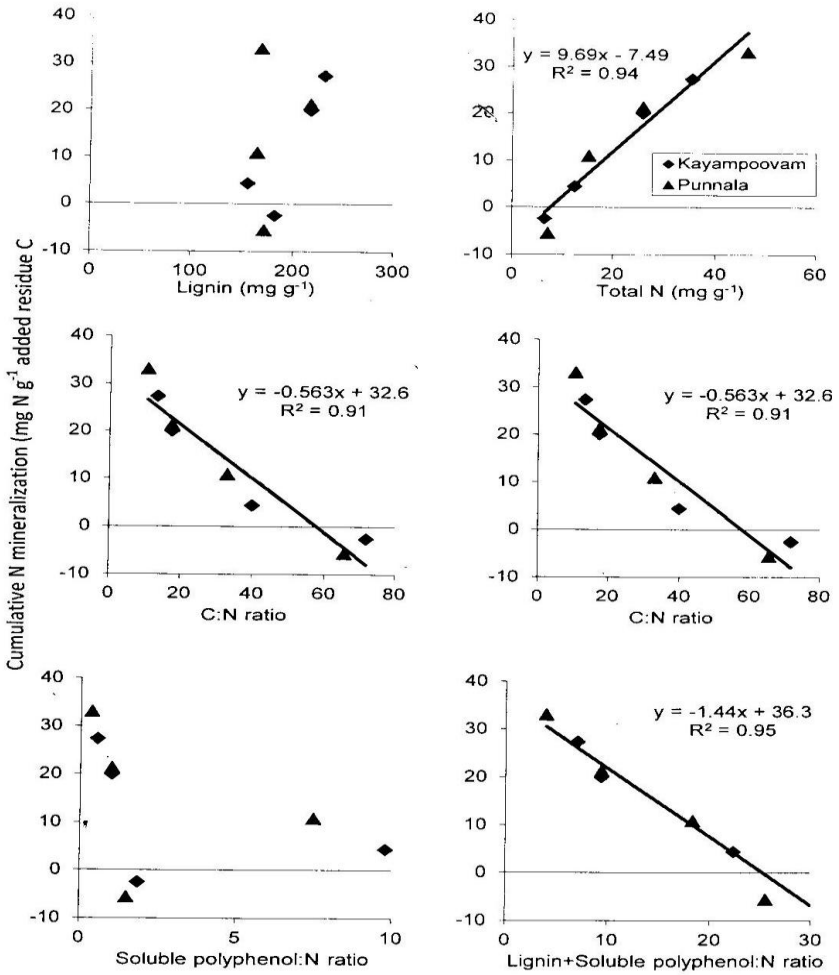


Fig. 27. Relation between cumulative N mineralization/ immobilization in treatments with pure residue additions (difference from control) and residue biochemical quality attributes: lignin (a), total N concentration (b), C:N ratio (c), lignin: N ratio (d), soluble polyphenol: N ratio (e), and (lignin + soluble polyphenol): N ratio (f).

Net N release for mixtures of eucalypt and legume residues generally followed similar patterns to rates predicted from the additive effects of individual residues (Fig 28). However, most of the differences between observed and predicted N mineralization-immobilization occurred for the *Mucuna* and *Stylosanthes* residues in the Kayampoovam soil up to 150 days into the experiment. The combination of eucalypt and *Mucuna* or *Stylosanthes* (Kayampoovam) or eucalypt and *Pueraria* (Punnala) residues at the second leaching day (day 10) resulted in stronger N immobilization than that predicted from the treatments with residue incubated alone, but this effect was reversed at leaching at day 36 for Mucuna in the Kayampoovam soil.

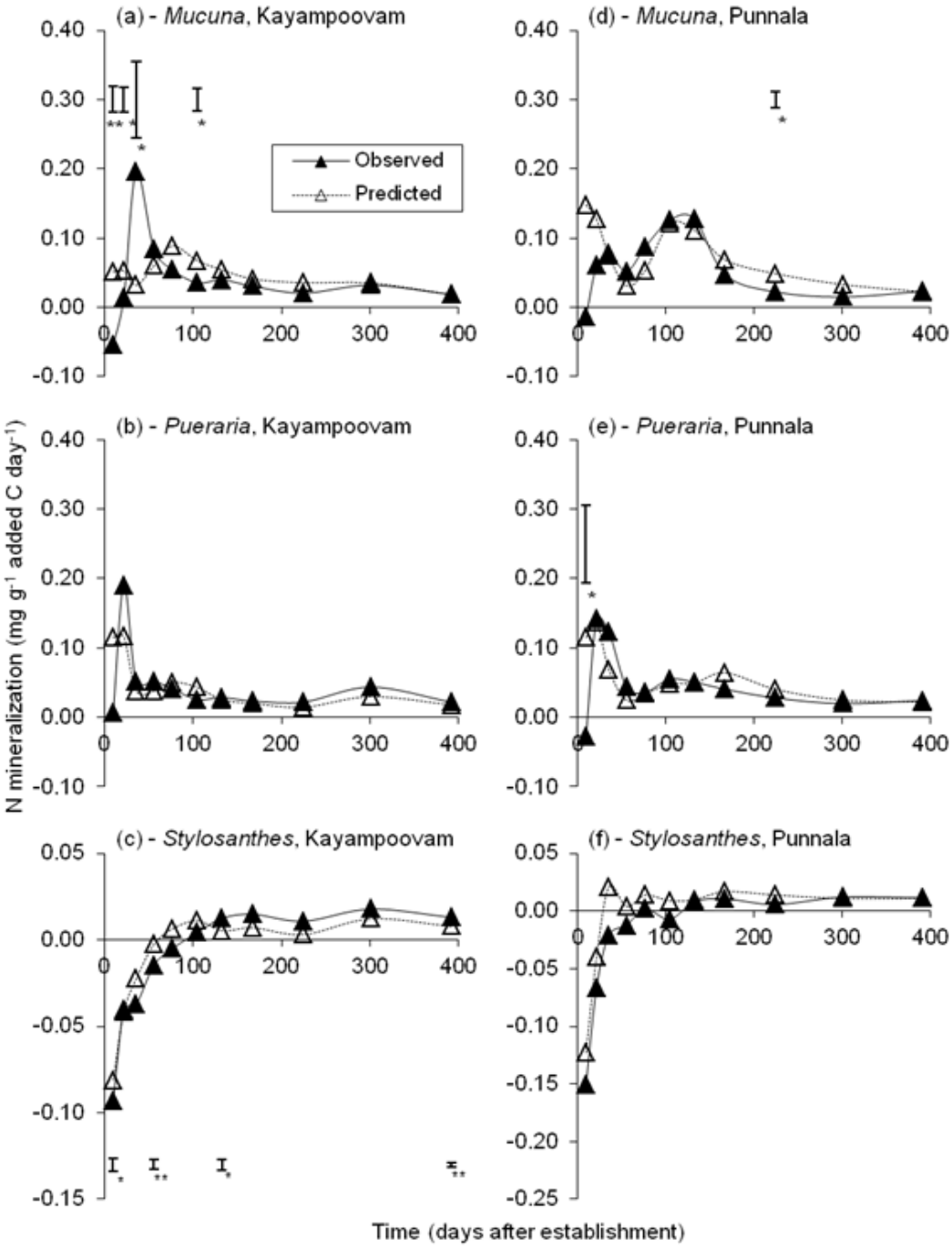


Fig.28. Observed N mineralization / immobilization at each leaching time in treatments with mixed Eucalypt/ legume residues compared to that predicted (assuming equal contribution of residues from treatments where residues were incubated alone) for eucalypt with *Mucuna* (a, d), *Peuraria* (b,e), *Stylosanthes* (c, f) residue in the Kayampoovam (a – c) and Punnala (d – f) soils. Bars represent LSD. Significance of difference between predicted and observed N mineralization at each sampling time is indicated by* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6.11. Nutrient cycling in plots applied with N fertilizer

6.11.1. Indices of soil N mineralization: The aerobic and anaerobic indices of N availability showed different trends across sites (Table 13). The aerobic N index was lowest at Surianelli and highest at Vattavada and intermediate at the two *Et* sites. Vattavada also had the highest anaerobic N index followed by Surianelli. Fig. 29 shows the relationship between N mineralization and soil moisture and temperature under lab conditions with soils across the 4 sites. A sigmoidal function was fitted to the moisture response across all sites (R2 of 0.83 Fig. 29 a). The shape of the curve suggests that N mineralization continued to increase with increasing soil water content above -25 k Pa.

Table 13. Soil N indices across the 4 sites

Site	Aerobic N (µg g^{-1} $a^{-1)}$	Anaerobic (µg g^{-1} $a^{-1)}$
Kayampoovam	277.4	13505.0
Punnala	255.5	7774.3
Surianelli	129.6	26097.5
Vattavada	489.1	54859.5

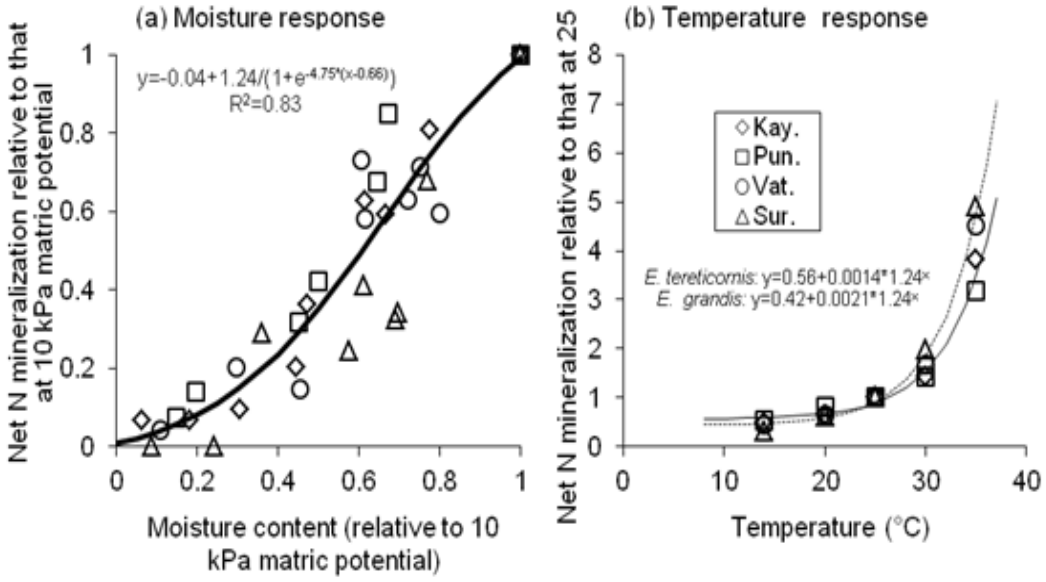


Fig. 29. Response of relative N mineralization to (a) soil moisture content (relative to that at matric potential of -10 kPa), and (b) temperature in a lab incubation (relative to that at 25°C).

The experiment on response of N mineralization to temperature showed that N mineralization dropped below 25^0 C, doubled between 25-35^0 C and continued to increase exponentially up to 35^0C at all the sites. The response varied significantly between Et and Eg soils. Therefore, separate non-linear parameters were fitted (overall $R^2$was 0.983, Fig. 29b). These moisture and temperature response functions were used with measured soil moisture and temperature data to model N mineralization.

6.11.2. Modeled net N mineralization: The seasonal and rate of predicted net N mineralization varied across sites for calendar year 1999 (Fig.30) with maximum N mineralization response at Kayampoovam(118 kg $ha^{-1}a^{-1}$) followed by Vattavada (112 kg) and Punnala (107 kg) and the lowest N mineralization was predicted for Surianelli for 26 kg. The south-west monsoon (from June to September) had a large impact on N mineralization at Kayampoovam and Punnala while at Vattavada it was greater during the north-east monsoon (October –January) and both monsoons had a significant impact on predicted N mineralization at Surianelli. There was a distinct seasonal variation in N mineralization across sites which was mostly due to the changes in soil moisture content over the year.

The range of responses to N fertilizer across sites was useful for testing the potential generality of relationships between soil N indices and response of growth of eucalyptus to N fertilizer although it is recognized that 4 sites are insufficient for developing a practical diagnostic tool. However, this framework was used to screen a range of possible N indices for their potential application to a large response dataset.

6.11.3. Relationship between response to N fertilizer and indices of soil N supply: Several measures of soil N availability were significantly related to fertilizer response across the 4 sites (Fig. 31). The C : N ratio (Fig. 31 a) and total soil N (Fig. 31 b) were broadly related to fertilizer response although the Et sites had similar fertilizer response to differing C: N ratios. The aerobic N mineralization index (Fig. 31c) was highly correlated with response to fertilizer (R^2 = 0.927), whilst anaerobically mineralizable N was not related to fertilizer response across the 4 sites (Fig. 31d). The Vattavada site had an N mineralization index of 1.34 µg g^{-1} $d^{-1}$and a minimal response to N fertilizer, suggesting that this level of basal N mineralization was adequate to sustain maximum site potential. Of the 4 chemical/biological indices of N availability that were assessed, anaerobic N was the least well correlated with response to N fertilizer.

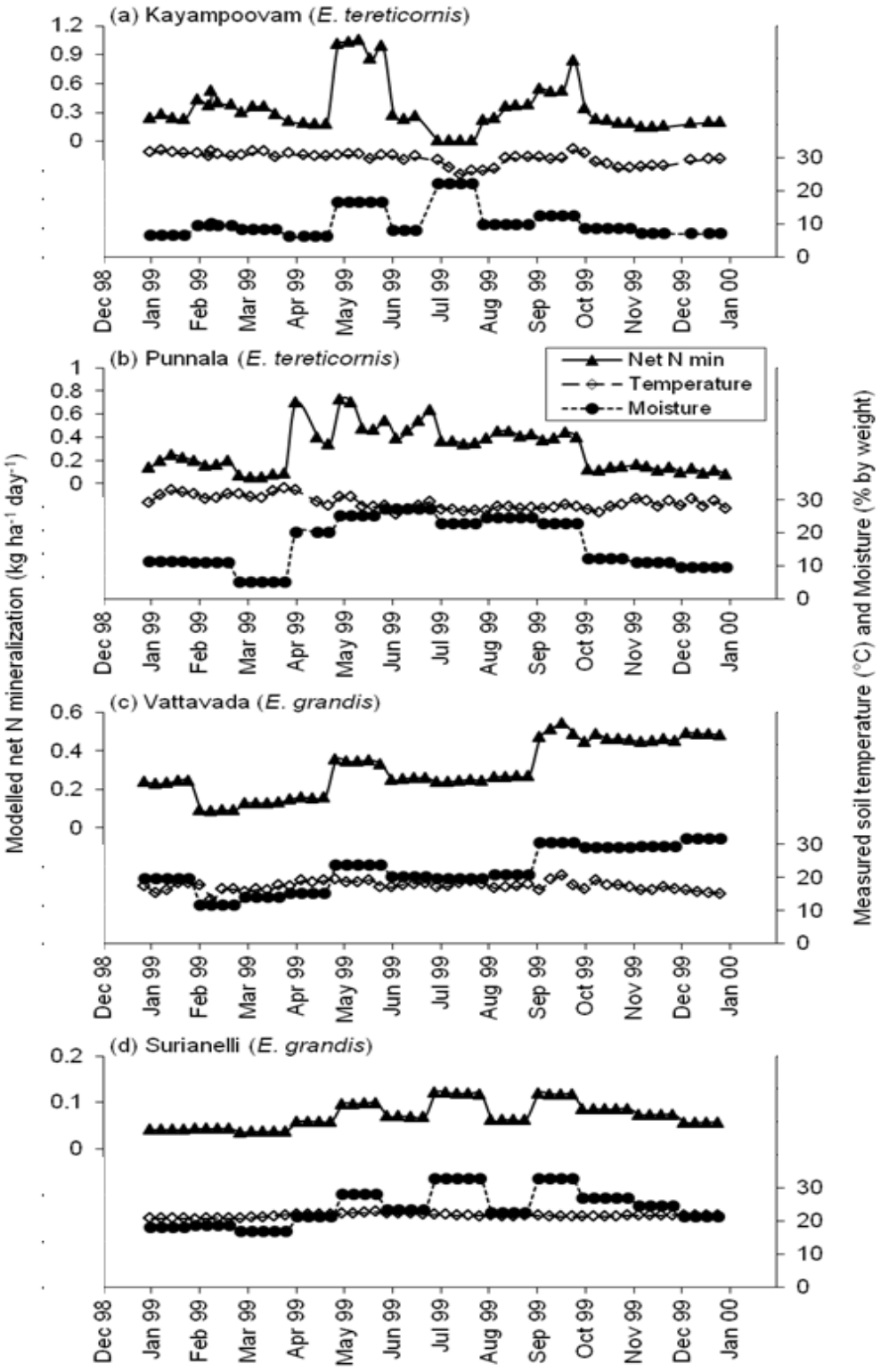


Fig. 30. Modeled N mineralization rates (0 – 10 cm) at (a) Kayampoovam, (b) Punnala, (c) Vattavada and (d) Surianelli, in relation to measured soil temperature and moisture during the course of a calendar year.

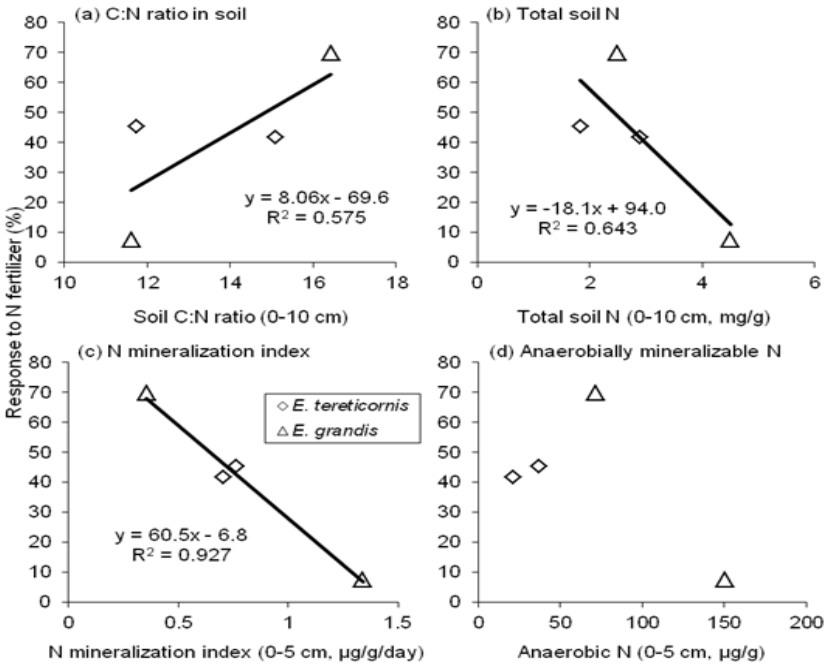


Fig. 31. Relationship between response to N fertilizers (a), soil C:N ratio, (b) total soil N, (c) N mineralization index in the surface (0–5 cm) soil and (d) N released during anaerobic incubation of the surface (0–5 cm) soil.

6.11.4. Modeled net N mineralization and response to fertilizer N: Modeling net soil N mineralization on an annual basis did not improve the diagnosis of fertilizer response, compared to the other soil indicators (Fig. 32). Results of the Surianelli site were consistent with low predicted annual net mineralization. However, the other 3 sites had similar predicted annual net N mineralization but widely variable response to added fertilizer N but it had by far the largest demand and the high growth rate (Table 14). But, *E. tereticornis* had much lower demand (slower growing plantation) and were responsive to N fertilizer.

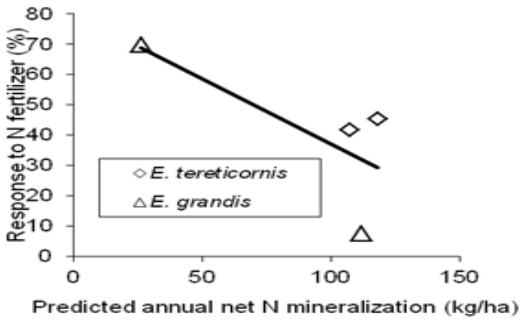


Fig. 32. Relationship between response to N fertilization across the 4 sites and predicted annual net N mineralization

Table 14. Comparison of predicted N supply and above-ground internal requirement (kg ha^{-1} a^{-1}) in low and high contents of N fertilizer

Eucalyptus species/Sites	Predicted net N mineralization [a] (kg ha^{-1} a^{-1})	Annual N internal requirement (kg ha^{-1} a^{-1})[b]	
		Nil N	Sufficient N
E. tereticornis			
Kayampoovam	118.2	27.0	39.2
Punnala	107.2	25.9	36.3
E. grandis			
Surianelli	26.2	47.9	62.4
Vattavada	111.8	87.6	89.5
[a] Calculated for the 1999 Calendar year in the 0-10cm depth range [b]Average for years 2,3 and 4			

6.12. Decay of harvest residues and nutrient release: Weight loss over time differed significantly between residue fractions and species. Among the various slash residues, leaves decomposed fastest at all sites compared to other fractions (Fig. 33). Decay rate of bark was slower than that of leaves but faster compared to twigs. Decay rate of slash residues was highest at *Et* sites compared to *Eg* sites with the slowest rates at Vattavada. For example, almost 95% of the leaves decomposed by 12 months at the Et sites while 21-34% of the leaf residues remained at *Eg* sites. At Surianelli, 97.5% of the leaves decomposed by 15 months where as it took 24 months to achieve this decay rate at Vattavada. Bark decomposition was faster at Kayampoovam than Punnala with 94 and 85% loss at 18 months, respectively. Bark decay rate at Surianelli was almost similar to Punnala but it was much slower at Vattavada (90% loss at 30 months). Interestingly, decay rate of twigs was faster at Punnala in relation to Kayampoovam. There was no significant difference between decay rates of different twigs at the *Et* sites, 80-95% of which were lost by 24 months. At the *Eg* site, the loss was 50-75%by the same time.

Table 15. Calculated half-life (months) and decay constants yr^{-1} (k value) of the different residue fractions(dry weight) at each site

Residue fraction	K-poovam		Punnala		Surianelli		Vattavada	
	Half life	k	Half life	k	Half life	k	Half life	k
Leaf	2.5	3.555	2.8	2.931	5.4	1.548	7.8	1.062
Bark	5.2	1.589	7.0	1.19	10.7	0.775	13.9	0.60
Twig 0.5 cm	11.4	0.73	6.4	1.295	17.8	0.467	20.7	0.401
Branch 2 cm	12.0	0.694	9.1	0.918	15.8	0.526	18.4	0.453
Branch 4 cm	12.3	0.677	9.9	0.838	19.4	0.478	30.7	0.271

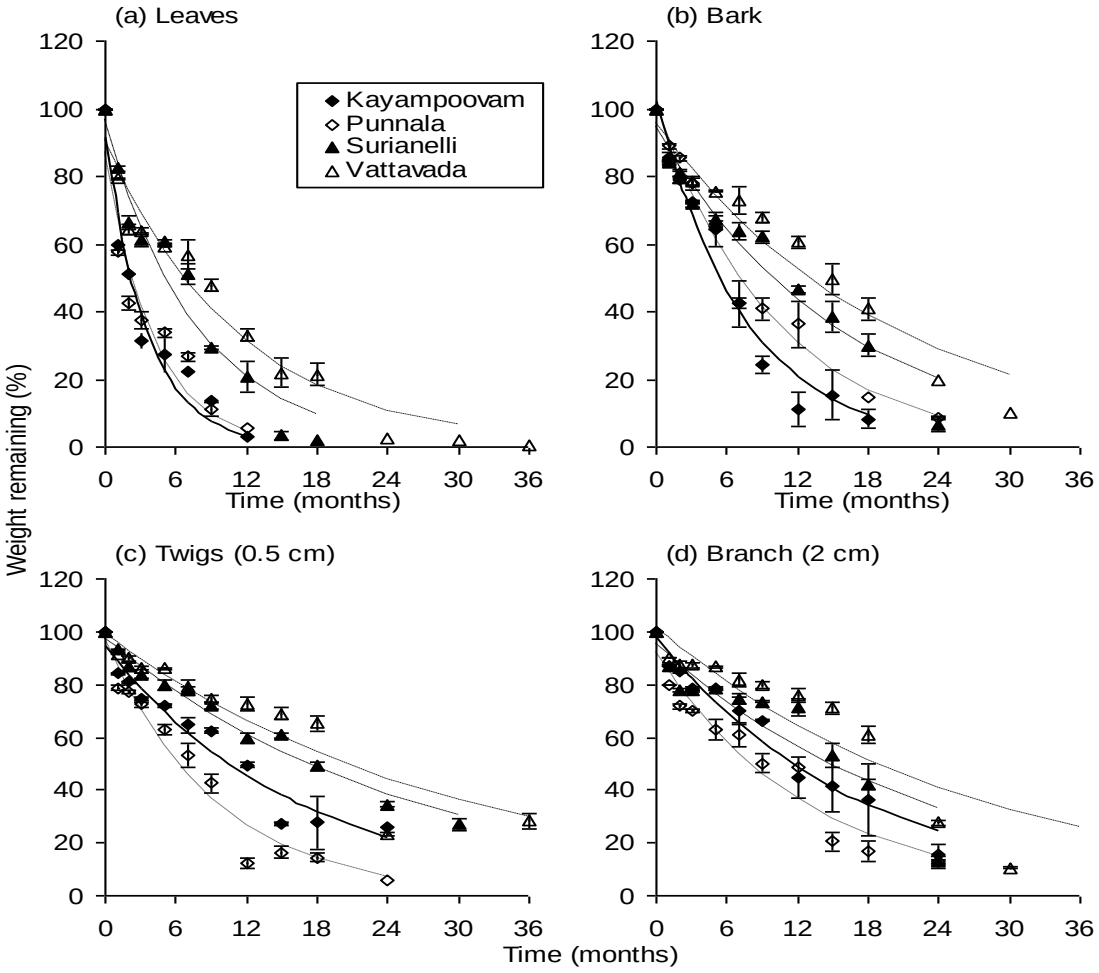


Fig. 33. Proportion of (a) leaf, (b) bark, (c) twig (0.5 cm) and (d) branch (2 cm) material remaining (dry weight basis) at each of the experimental sites over the duration of the experiment. Bars represent the SEM for each point. The fitted lines are single exponential regressions, from which the half-life of each component at each site was derived (solid line for Kayampoovam, dotted line for Punnala, dashed line for Surinaelli, dotted and dashed line for Vattavada.

Decay was initially faster for leaves, almost 50% of which were lost by 2 and 7 months respectively, at the *Et* and *Eg* sites presumably influenced by the rainy season. However, the decay rate was much slower for twigs during the initial months; 40-75% of the residues were still remaining at the end of 12 months, across sites. The half-life of different litters and the decay constant (k) determined from fitted first order decay functions (Olson, 1963) reflect these differences in decay rates between residues and sites (Table 15). In general, the half-lives of all residues were 2-3 folds greater for *Eg* sites compared to *Et* sites. The half-life was the shortest for leaves (2.5–2.8 months for *Et* and 5.4-7.8 months for *Eg*) followed by bark and twigs.

Table 16. Quantity of harvest residues (t ha^{-1}) deposited at each of the four experimental sites. The standard error of the mean is presented in parentheses

Site	Kayampoovam	Punnala	Surianelli	Vattavada
Leaf	2.07 (0.06)	1.46 (0.05)	3.09 (0.08)	4.20 (0.11)
Bark	7.71 (0.2)	4.81 (0.17)	4.79 (0.16)	12.72 (0.28)
Twig <1cm	1.80 (0.05)	1.10 (0.04)	1.92 (0.05)	4.58 (0.11)
Branch 1-3 cm	3.50 (0.1)	1.63 (0.07)	1.99 (0.07)	4.84 (0.13)
Branch >3 cm	1.08 (0.07)	0.47 (0.02)	0.55 (0.09)	0.52 (0.04)

Release of nutrients from decomposing harvest residues also differed significantly between sites and fractions analyzed (Fig. 34). Table 16 shows quantity of harvest residues deposited at each of the four experimental sites and Table 17 gives initial nutrient concentration for each of the harvest residues at each site.

For both the species, release of K during decomposition was rapid with most of K lost from residues in the first month of exposure in the field (around 80% for Et sites and 65-75% for Eg sites). Release of other nutrients was slower with P followed by Mg most rapid at all sites except Vattavada. N was relatively slow to release at most sites and it was the slowest at Kayampoovam until 5 months compared to Punnala and Surianelli. Ca was comparatively immobile with 22% (Surianelli) and 40% (Punnala) release at 1months. In contrast, at Kayamapoovam, 90% of the Ca was released by 18 months. P (-24%) and Ca (-21%) exhibited immobility or accumulation in residues at Vattavada with only K (83%), Mg (55%) and N (34%) released by 18 months. In general, an initial rapid release, an immobilization phase and a later release was noticed for most nutrients. Except for K, release of all nutrients was the slowest at Vattavada.

In summary, but for Vattavada, 80-90% of N, P, K and Mg were released from harvest residues by 18 months at all sites (Fig. 34). Release of all nutrients was generally most rapid from leaf residues. The difference between species in nutrient release rates reflected the difference in decay rates. Barring K and P, more rapid release of nutrients was recorded from *E. tereticornis* than *E. grandis* residues.

Table 17. Initial nutrient concentrations (mg g^{-1}) for each of the harvest residue components at each site - SEM presented in parentheses

Site	N	P	K	Ca	Mg
Kayampoovam					
Leaf	13.33 (0.38)	1.20 (0.00)	10.4 (0.2)	11.6 (0.2)	2.03 (0.02)
Bark	2.76 (0.09)	1.40 (0.00)	7.1 (0.1)	68.3 (2.0)	2.64 (0.04)
Twig <1cm	4.75 (0.12)	0.84 (0.03)	6.7 (0.3)	15.3 (3.8)	1.57 (0.04)
Branch 1-3cm	3.20 (0.25)	1.02 (0.07)	4.9 (0.4)	26.8 (2.3)	2.13 (0.15)
Branch >3cm	1.52 (0.07)	0.85 (0.04)	4.3 (0.2)	7.2 (1.9)	0.59 (0.02)
Punnala					
Leaf	14.19 (0.72)	0.71 (0.02)	11.3 (0.6)	10.0 (0.7)	2.49 (0.14)
Bark	2.83 (0.16)	0.38 (0.08)	3.6 (1.0)	18.9 (6.1)	2.29 (0.21)
Twig <1cm	4.56 (0.98)	0.36 (0.06)	6.1 (0.7)	6.1 (1.5)	1.12 (0.07)
Branch 1-3cm	4.01 (0.89)	0.43 (0.11)	5.4(1.1)	7.0(1.3)	1.15 (0.37)
Branch >3cm	2.79 (0.18)	1.10 (0.06)	3.1(0.1)	8.0 (2.3)	1.54 (0.04)
Surianelli					
Leaf	16.48 (0.61)	1.40 (0.00)	9.1 (0.3)	10.9 (0.4)	2.90 (0.10)
Bark	1.71 (0.20)	0.80 (0.00)	7.5 (0.5)	19.6 (5.0)	2.10(0.40)
Twig <1cm	4.49 (0.94)	1.10 (0.02)	7.2 (0.6)	9.9 (4.9)	1.42 (0.27)
Branch 1-3cm	1.63 (0.47)	0.68 (0.25)	3.2 (0.8)	4.4 (1.0)	0.77(0.17)
Branch >3cm	1.33 (0.31)	0.54 (0.05)	2.9 (0.4)	4.5 (1.0)	0.78 (0.21)
Vattavada					
Leaf	17.36 (1.65)	1.28 (0.11)	10.4 (0.6)	8.1 (0.4)	2.92 (0.23)
Bark	2.08 (0.10)	0.26 (0.09)	6.8 (0.5)	15.2(4.3)	2.51 (0.65)
Twig <1cm	3.37 (0.53)	0.23 (0.05)	3.5 (1.0)	9.2 (3.8)	1.45 (0.23)
Branch 1-3cm	2.03 (0.61)	0.23 (0.09)	3.2 (0.6)	3.9 (2.4)	0.96 (0.28)
Branch >3cm	1.85 (0.45)	0.29 (0.20)	2.7 (0.7)	2.3 (1.2)	0.76 (0.35)

Table 18. Slash contributions to various nutrients (kg ha^{-1}) at 12 months after planting

Residues and Nutrients		Sites			
		K-poovam	Punnala	Surianelli	Vattavada
N	Bark	37.56	11.57	-3.78	-13.73
	Leaf	27.52	20.01	43.80	44.20
	Twigs	11.91	6.76	2.33	-0.60
P	Bark	10.18	1.24	2.54	-1.77
	Leaf	2.28	1.15	3.61	3.83
	Twigs	5.83	1.17	1.50	-0.87
K	Bark	67.69	17.51	14.03	47.92
	Leaf	22.75	13.51	15.73	37.50
	Twigs	36.58	9.92	10.99	29.45
Ca	Bark	147.94	- 16.13	-122.93	-351.96
	Leaf	19.36	9.90	17.58	14.66
	Twigs	105.56	30.61	-11.92	-61.59
Mg	Bark	15.29	6.42	7.06	20.61
	Leaf	4.96	2.98	8.21	7.21
	Twigs	5.50	2.87	0.71	2.99

Fig. 34 a.

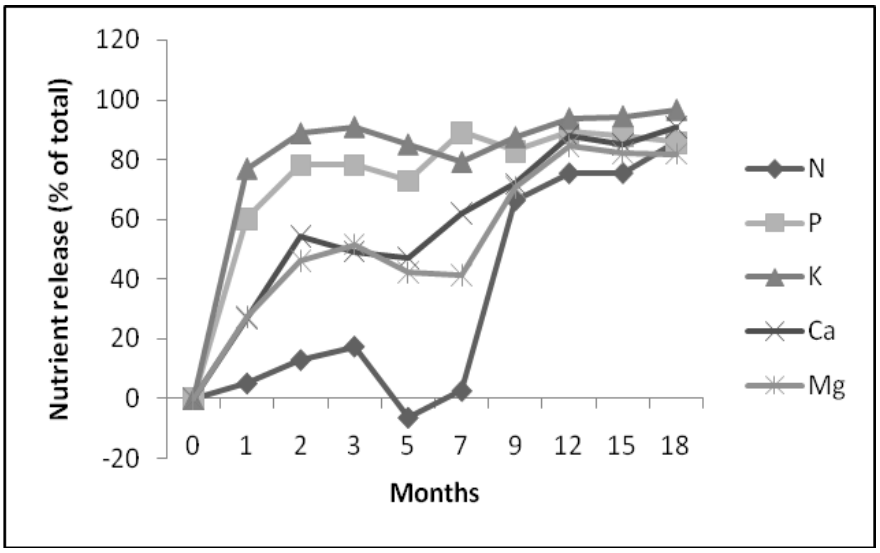


Fig. 34 b.

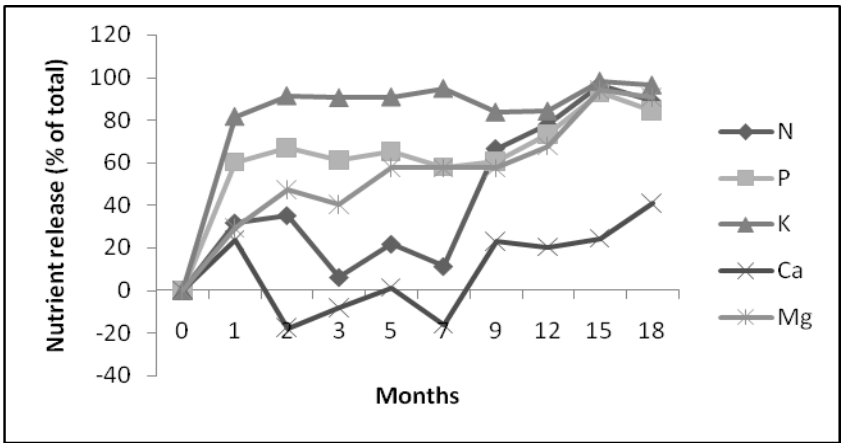
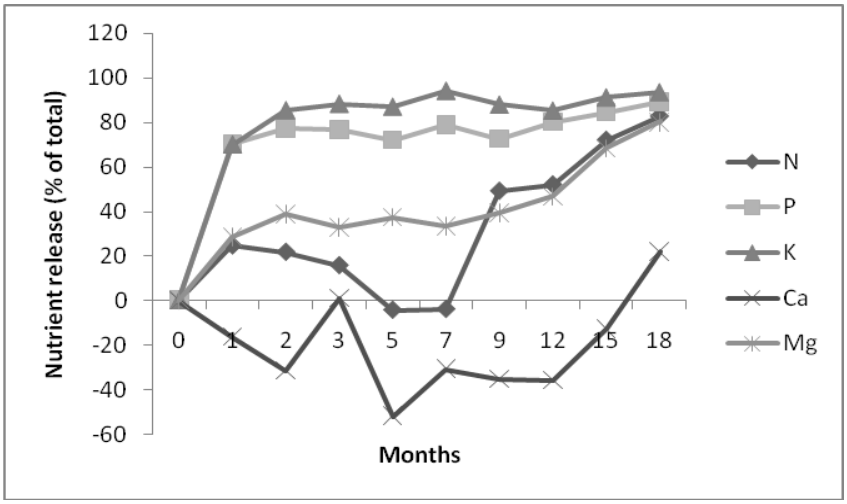


Fig. 34 c.



34 d.

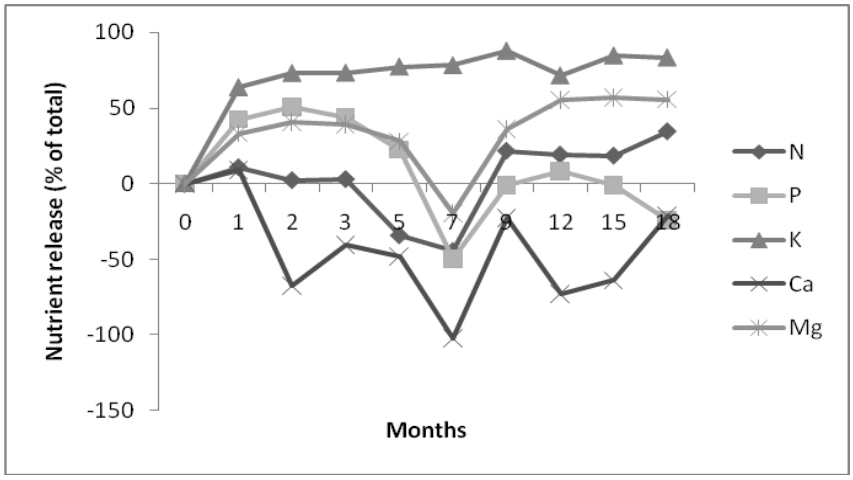


Fig. 34. Cumulative nutrient release from harvest residues till 18 months after planting (a) Kayampoovam, (b) Punnala, (c) Surianelli and (d) Vattavada

Table 18 shows nutrient contributions by decaying slash at 12 months. The bark contributed to the highest amount of N, P, K Ca and Mg at Kayampoovam compared to other sites. This site also had highest amount of all nutrients released by slash residues except for N in leaves which was the highest at Surianelli. The bark released 148 kgha^{-1} of Ca at Kayampoovam whereas accumulation of Ca in the bark and twigs was recorded from Surianelli and Vattavada. Vattavada site also showed accumulation of N and P in the bark and twigs. Residues at Punnala contributed to lower amounts of all nutrients compared to Kayampoovam and P at Surianelli. In general, the data show that the bark of Et is a storehouse of nutrients at fertile sites. Residues of Eg are less rich in nutrients (except K) and N, P and Ca are getting accumulated in the bark and twigs at fertile sites.

6.13. Measuring wood volume and growth in Et and Eg plantations

6.13.1.Conical volume approximation: The diameter over bark (dob) and diameter under bark (dub) measurements approximates with that of a cone with a common bottom cut diameter. This holds valid for both the species irrespective of the treatments.The dob and dub approximations are reflected well in corresponding volume (Fig 35).

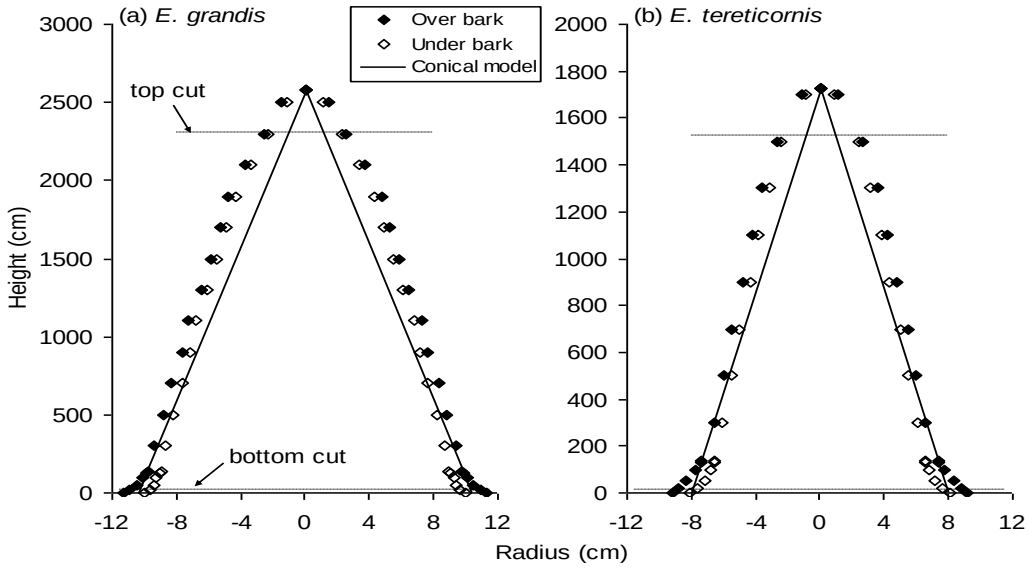


Fig. 35. Closeness of fit of the conical approximation to 6-year old *E.grandis* and *E.tereticornis* stems. The points represent measured over and under bark diameters for a single example tree from each species.

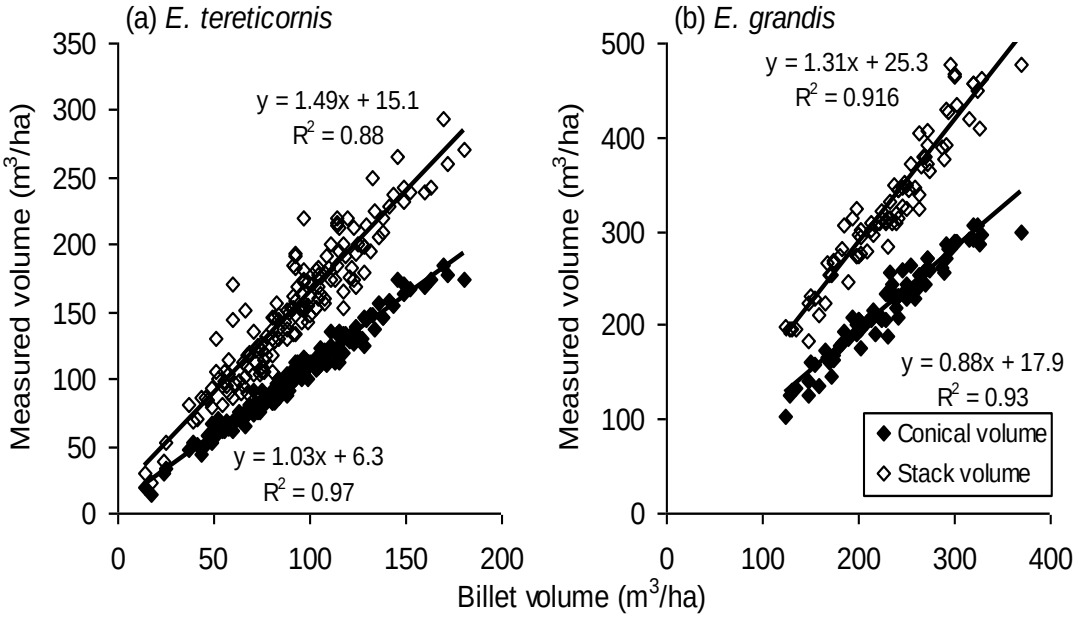


Fig. 36. Relationships between recovered log volume (volume of billets) and standing volume (measured using the conical approximation) and stacked volume for *E.tereticornis* (a) and *E.grandis* (b). All relationships are highly significant.

6.13.2. Volume inter-correlations: For conical volume and stack volume, there is a strong relationship between log (billet) volume and measured conical volume, in *E. tereticornis* (R^2 = 0.88 for conical volume, 0.97 for stack volume) and *E. grandis* (R^2=0.82, 0.93) (Fig. 36).

6.13.2. Log moisture loss

6.13.2.1. Stack position effect: Mean size and diameter of heartwood logs used in the moisture loss study is given in Table 19. The initial moisture content of *E. grandis* billets (85-100%) dropped to 38 to 50% within a week after stacking followed by harvest. For *E. tereticornis*, the drop was from an initial moisture content of 80 - 82 % to 25-38 % within a week. There was only negligible further drying in *E. grandis* during weeks 4 and 6. However, *E. tereticornis* further dried to 20 -39 % by fourth week, and an increase in moisture content occurred by the fourth week due to intermittent showers. The rate of drying in Et was upper billets > side billets > middle billets > bottom billets (P=0.01 at second week and P=0.05 at fourth week), but in *E. grandis* it was side billets > upper billets > bottom billets > middle billets(P= 0.05 at second and fourth week) (Fig. 37).

Table 19. Mean size and heartwood diameter of logs used in moisture loss study. Standard error of the mean is presented in parentheses

Site	Log size	Log diameter	Heartwood diam.
Punnala	Large	8.55 (0.06)	4.56 (0.10)
	Small	6.17 (0.06)	2.88 (0.07)
Surianelli	Large	10.20 (0.09)	3.38 (0.33)
	Small	7.42 (0.07)	2.31 (0.17)

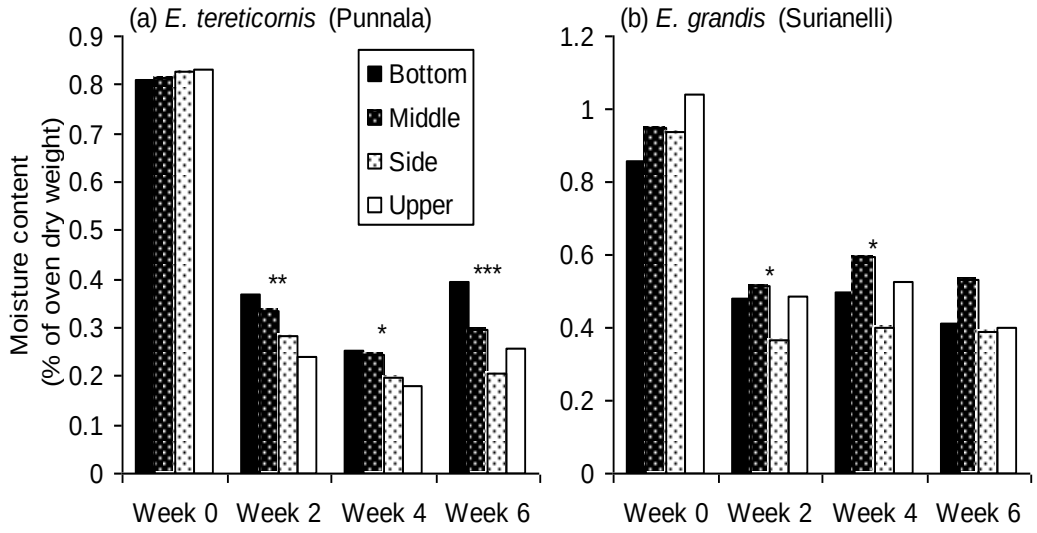


Fig. 37. Effect of stack position and time on log moisture content in *E.tereticornis* (a) and *E.grandis* (b). Asterisks indicate significance of log stack position on log moisture content at each sampling time: *:P<0.05, **:P<0.01, ***:P<0.001.

6.13.2.2. Log size effect: Small logs had slightly higher initial moisture content than large logs, but the values were not significantly different. In *E. tereticornis* and *E. grandis*, the rate of drying was significantly faster in smaller logs as expected. The drying was faster during the initial week dropping just more than half of the moisture (Fig 38). Logs dried further by 4 weeks but gained some moisture at 6 weeks for Et. There was no significant moisture loss at 4 and 6 weeks for Eg. However, the moisture content of large and small logs differed significantly at all measuring periods for both the species (Fig. 38).

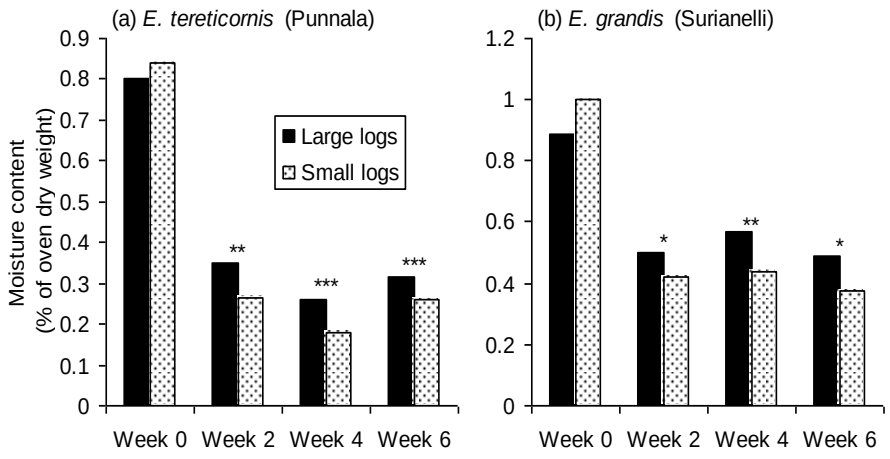


Fig. 38. Effect of log size and time on stacked log moisture content in *E.tereticornis* (a) and *E.grandis* (b). Asterisks indicate significance of log stack position on log moisture content at each sampling time: *:P<0.05, **:P<0.01, ***:P<0.001

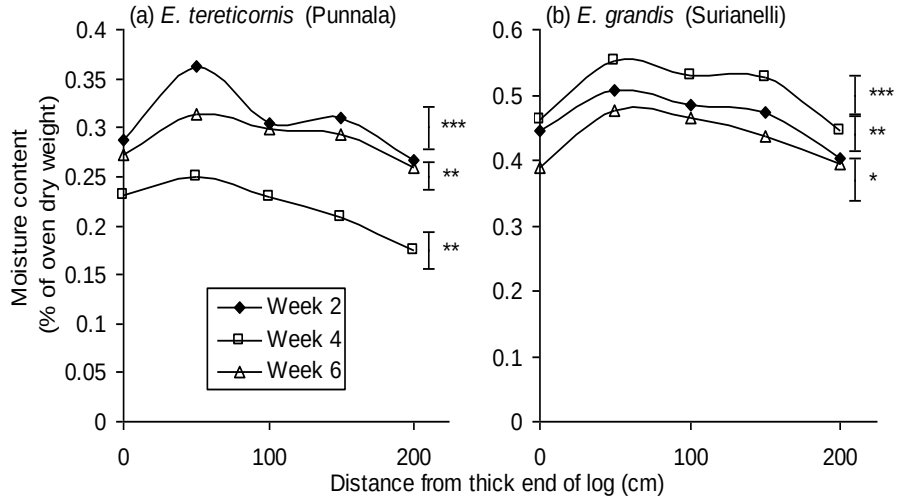


Fig. 39. Main effect of distance from end of log on moisture content in *E.tereticornis* (a) and *E.grandis* (b). The thick end of the billet is at 0 cm, and the thin end of the billet is at 200 cm. Bars represent the LSD (α=0.05). Asterisks indicate significance of distance on log moisture content at each sampling time: *:P<0.05, **:P<0.01, ***:P<0.001.

6.13.2.3. Intra-log drying: The drying rate significantly varied with distance from thick end for both the species. The drying was faster at the thin end followed by thick end (Fig 39). The drying rate in other log positions showed decrease with increase in distance from thin end.There was no significant interaction between distance from thick end of the log and position in stack on moisture content, except for *E. tereticornis* logs at Punnala (Fig. 40) at the six weeks measure when the thin end of bottom logs lost moisture faster than the thick end.

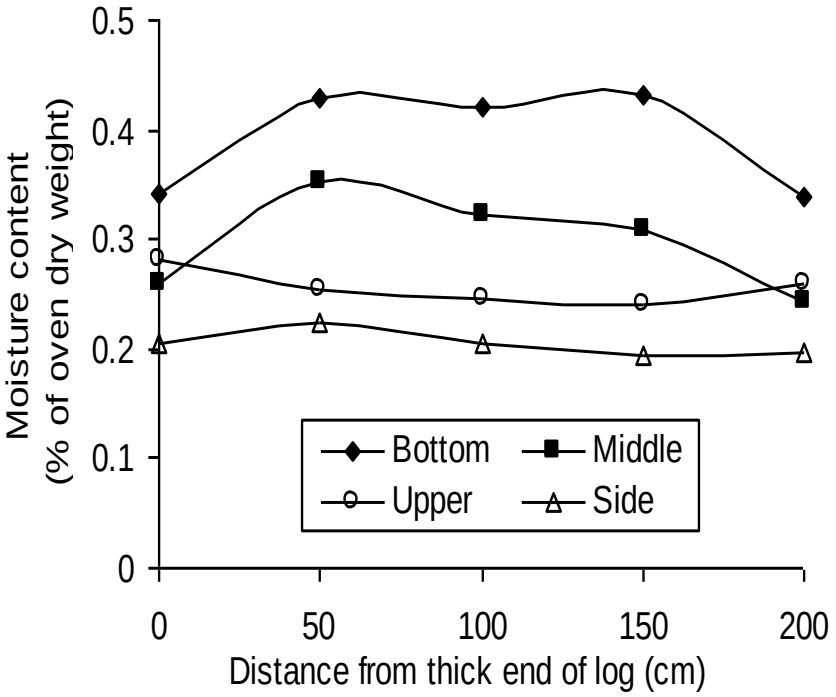


Fig. 40. Significant interaction (P=0.017) between distance from thick end of log and position in stack on moisture content of *E.tereticornis* logs at Punnala at the 6 week measure. This was the only significant interaction involving the intra-log drying.

6.14. Plant Physiological studies

6.14.1. Impact of inter-rotation site management practices on tree water status in eucalypt plantations in Kerala: Pressure chamber measurements on water potential shows that the predawn water potentials at Punnala reached -0.8 MPa and -1 MPa at Surianelli. The nitrogen addition seems to have helped the trees to maintain higher water potentials at least for *E. grandis*. The water potentials reached their lowest peaks before the monsoon rains started (Fig 41).

An examination of the predawn water potential over time for the different treatments, namely, N5, N0NP, P5 and S, shows that the differences in the water potential values are not significant. Also, very rarely the predawn values reached below -0.5 MPa showing that the water stress is not severe to affect the growth of eucalypts at least during the measurement period, which is the first three years of planting (Fig. 42, 43).

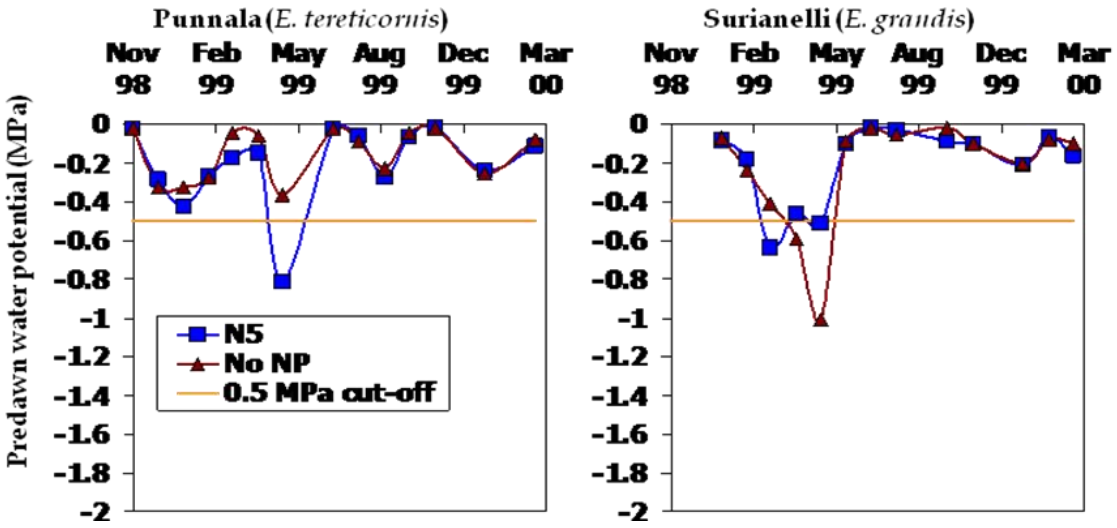


Fig. 41. Predawn water potentials measured at two sites for two treatments, N0 and N5, at Punnala and Surianelli for *E. tereticornis* and *E. grandis* respectively during 1998-2000.

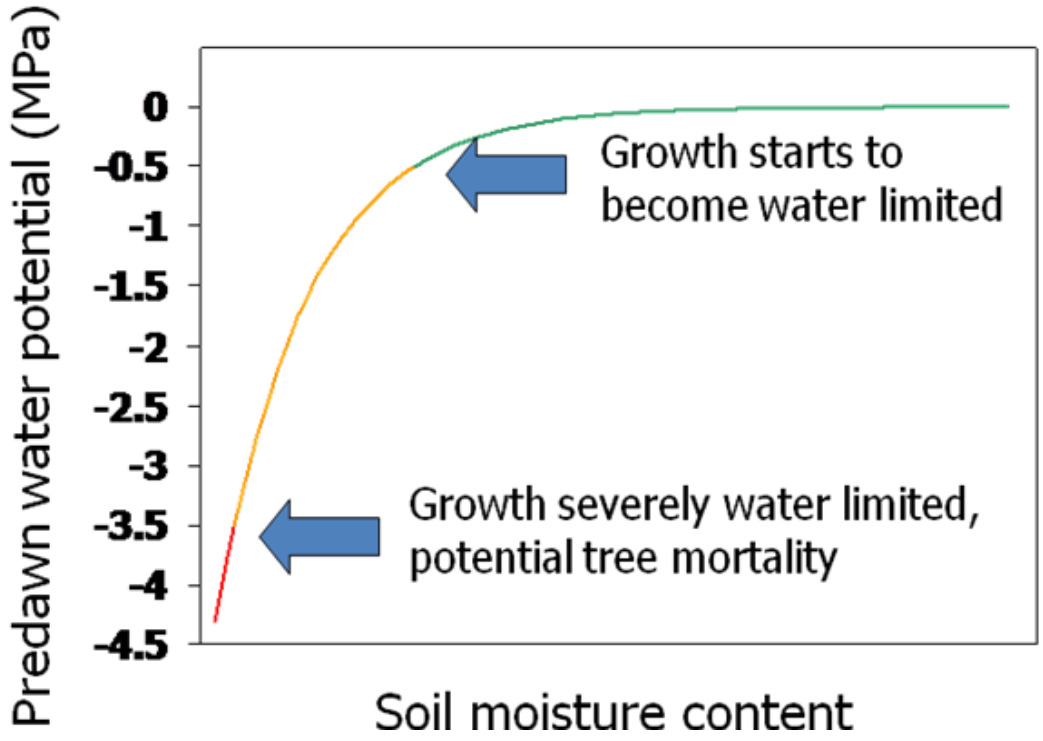


Fig. 42. Predawn water potentials and the way it affects the growth of the plant as shown in *E. globulus*. It may be noted that when the predawn water potentials of the tree reached -0.5 MPa, the growth became water limited. Potential tree mortality occurs when the water potential reaches -3.5 MPa (after White et al. 1999).

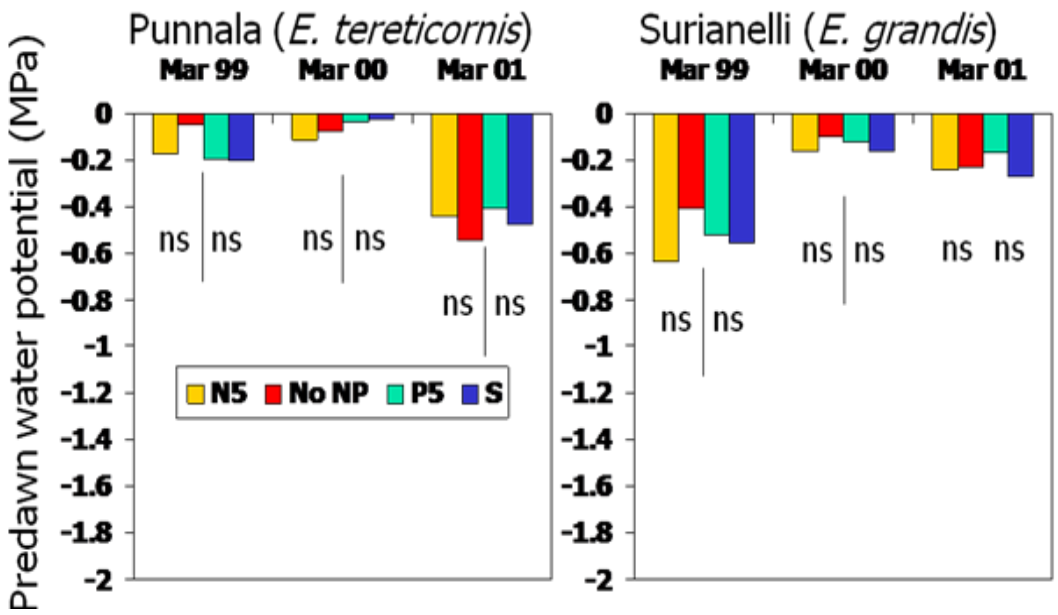


Fig. 43. Predawn water potentials over time for the different treatments, namely, N5, N0NP, P5 and S. It may be noted that the the differences in water potential for each treatment is not significant.

This does not mean that there is no water stress for eucalypt plantations in Kerala. Although not originally planned in the project, we monitored the predawn water potentials of the *E. tereticornis* plantation at Kayampoovam, another experimental site in the same project, not meant for physiological studies. The figure shows that predawn water potentials reached much lower levels than that of Punnala or Surianelli at this site. In some of the treatments the values reached almost -2.5 MPa predawn (Fig 44). The soil depth at this site is much lower compared to Punnala or Surianelli.

6.14.2. Impact of inter-rotation site management practices on tree physiological functions and tree development (leaf area increment) at the experimental sites: Fig. 45 shows the photosynthesis maximum obtained at different light irradiances at the two experimental sites, Punnala and Surianelli for the two species, *E. tereticornis* and *E. grandis*. The regression line shows that the A_{max} value comes to 14.4 µmol m^{-2} s^{-1} without much significant difference for the two species located at two different locations.

Photosynthesis measurements corrected for light taken at the two experimental sites in the N and P experiments are shown in Fig 46. No significant differences were found in photosynthesis between treatments, although *E. tereticornis* always showed less photosynthetic rate at the leaf level. Also, there were no significant differences in photosynthesis over time.

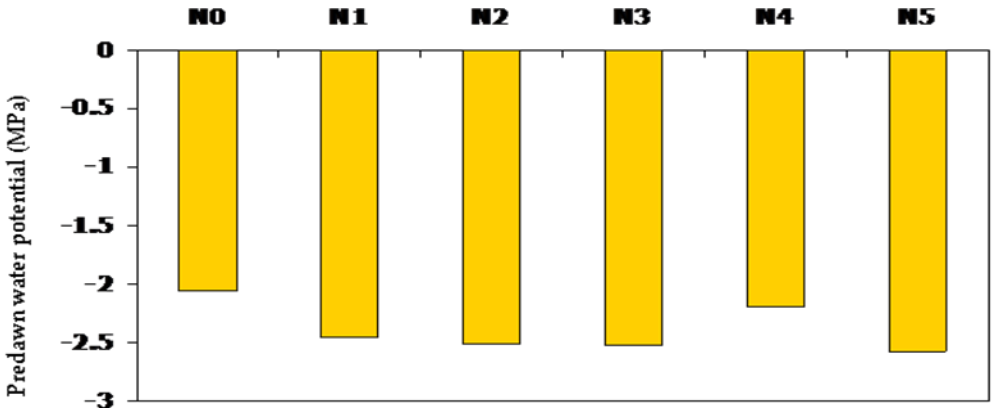


Fig. 44. Predawn water potentials determined for *E. tereticornis* at Kayampoovam during the summer of 1999 in the different Nitrogen treated plots. The differences between treatments are not significant

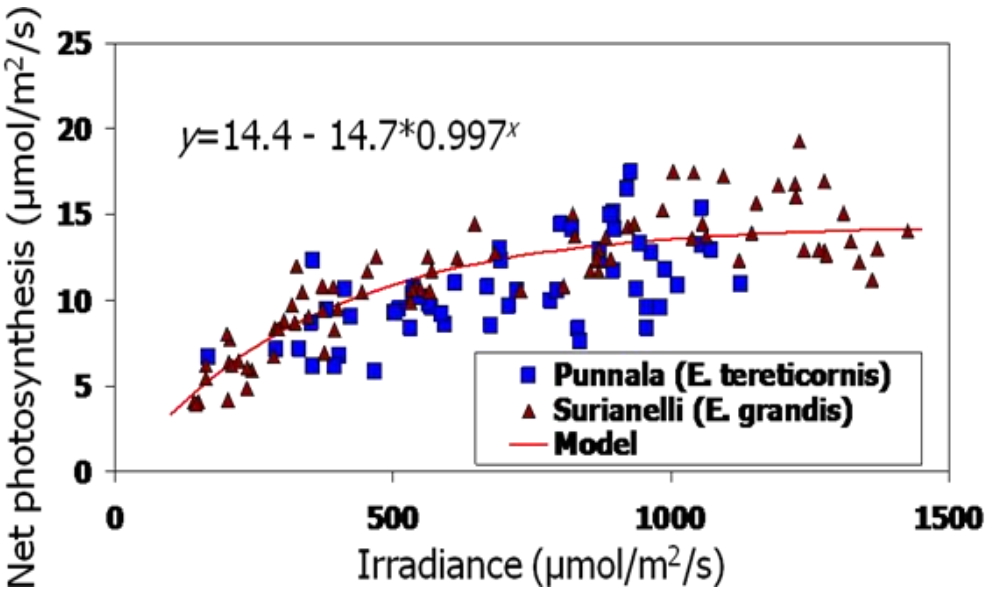


Fig.45. Net photosynthesis measurements using the infrared gas analyser on *E. tereticonrnis* and *E. grandis* at the two experimental sites, Punnala and Surianelli. The maximum photosynthetic values obtained for each irradiance was plotted to obtain the A_{max}. The regression line shows the A_{max} obtained.

LAI measurements done at the two experimental sites show mostly significant differences in N application, with higher LAI for more nitrogen (N5) applied to the plants. This certainly shows that the effect of nitrogen application is very effective in eucalypt plantations in Kerala, which is somewhat deficient in Nitrogen. The effect of P application is also found very effective at Punnala, although it was not so in Surianelli during the early stages (Fig 47). The LAI was certainly much higher in *E. grandis* compared to *E. tereticornis*.

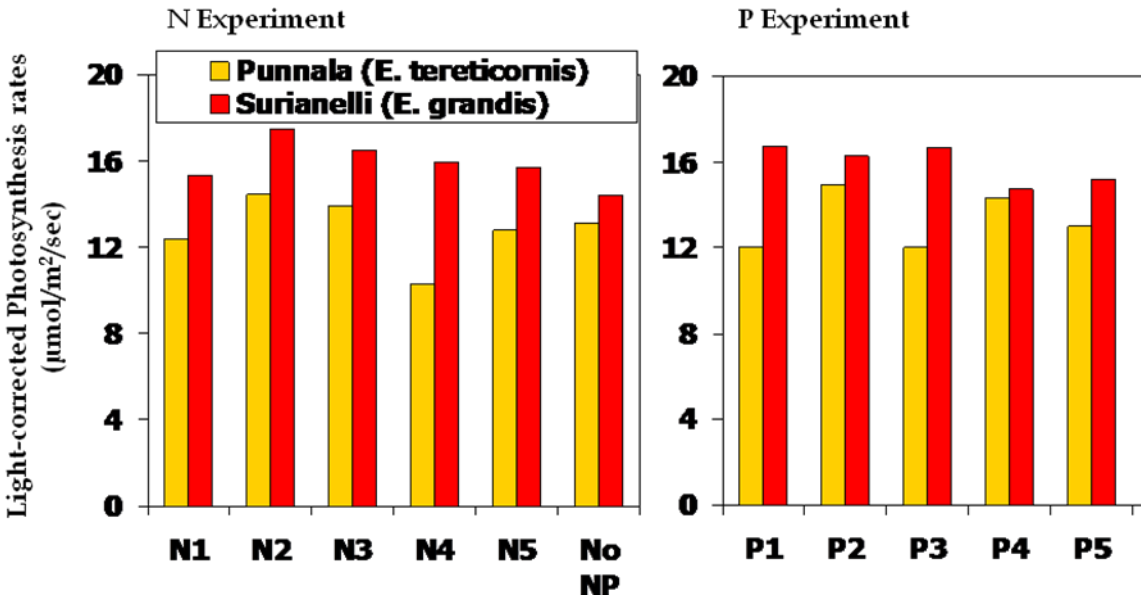


Fig.46. Treatment effects of N and P on photosynthesis at the two experimental sites in *E. tereticornis* and *E. grandis*

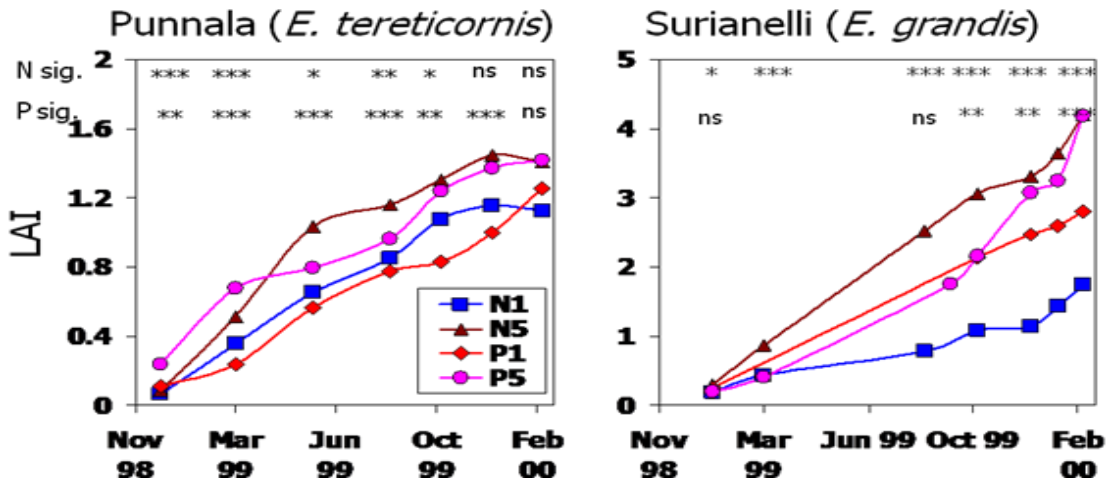


Fig. 47. Treatment effects on leaf area index (LAI) during the first 18 months of plantation at the two experimental sites in Punnala and Surianelli for *E. tereticornis* and *E. grandis*.The significance test for each set of points in each treatment, that is N1 and N5 and P1 and P5 are shown on the graph (ns= not significant).

The stand volume at 3 years age was related to the LAI as shown in Fig 48. There was significant (common) relationship between LAI and stand volume in both N and P treatments. The photosynthesis measurements had shown no significant differences in photosynthetic rates between treatments. The differences shown in LAI therefore clearly demonstrate that the growth is driven by LAI than differences in photosynthetic rates in either of the species.

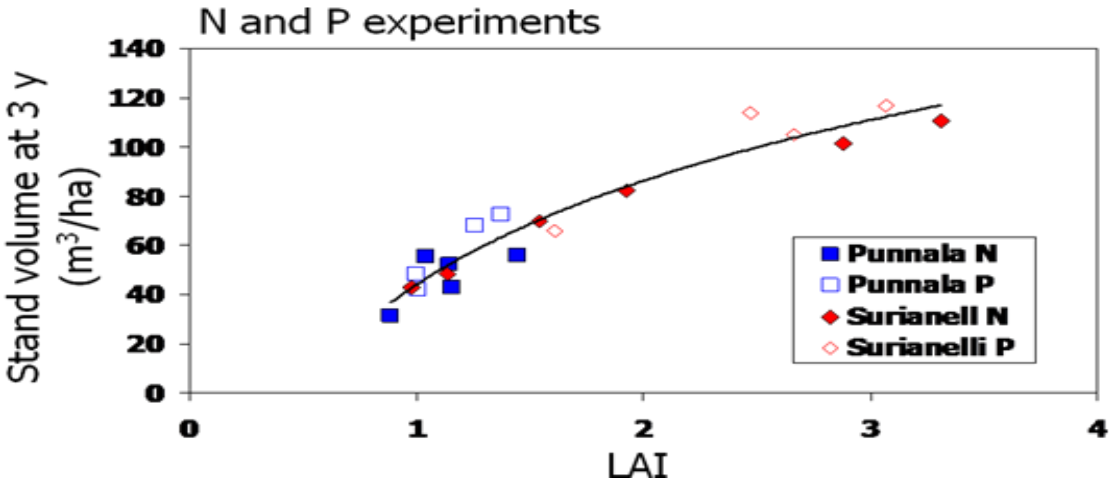


Fig. 48. Stand volume at the age of 3 years plotted against the LAI increase for N and P treatments in Punnala and Surianelli.

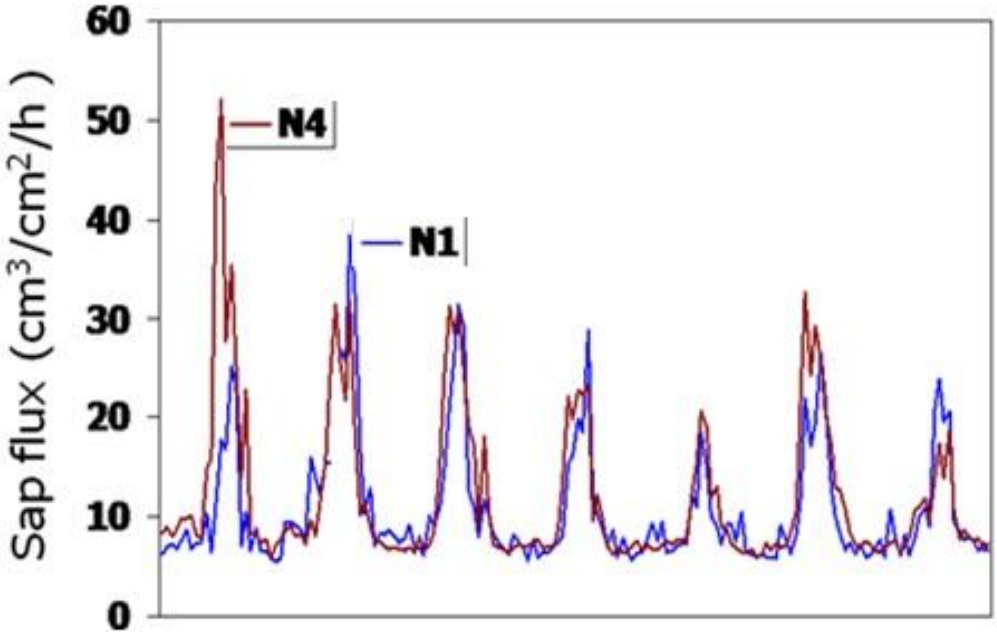


Fig. 49. Diurnal fluctuations in sap flux measured on trees belonging to N1 and N4 treatments at Punnala for a week.

6.14.3. Impact of inter-rotation site management practices on individual tree and whole stand water in the experimental plots: It may be noticed in Fig 49 that the instantaneous sap flux is very similar in both the treatments without any significant differences. The fluctuations are related to the local meteorological conditions. It may be noticed in Fig. 50 that N4 trees had higher transpiration rates than N1 trees. Differences in transpiration are driven by differences in basal area. Sap flow rates for unit sap wood cross sectional area were not significantly different.

The volume flow of water through the xylem was examined at two depths, namely, 10 mm and 20 mm in the wood of both eucalypt species. In both species the volume flow was faster in the outer xylem (Fig 51). At Punnala, although the difference was observed at the two depths, it was not significant. At Surianelli, the difference was significant at P=0.018. Inner xylem was associated with leaves/branches that are lower in the canopy, so have a lower light level, and/or have been lost during tree growth.

The aspect effect on xylem water flow was also examined at the two experimental sites. It may be noticed that the East/West aspect was quite significant (P=0.036) at Punnala for *E. tereticornis* trees. However, the North/South effect was not significant at Surianelli (Fig 52). Probably the slope of the site at Punnala has resulted in the aspect effect being significant at Punnala.

While testing the stand water use for species, site and seasons, the stand water use was measured during the pre-monsoon and post-monsoon periods. It was found that there was no significant difference between sites or species or seasons when soil water was not limiting (Fig. 53).

6.14.3.1. Stand water balance: Single tree measurements of sap water flow using the sap flow gauges were scaled up to stand water use with suitable equations having stand basal area as an important parameter. The water balance of the two experimental area was also calculated by suitable models already available (Tables 20 and 21).

Inputs: Iincident rainfall, mean 1985-2000 = 2265 mm/annum

Outputs: Transpiration, Interception, Soil Evaporation

Balance: Surface runoff, infiltration/soil store

Rainfall interception was estimated by Battaglia and Sands (1997):

Crown storage of rainfall = 0.5 LAI. Soil evaporation was calculated from the following equation:

E = α.equilibration evaporation + (1-α)*365*0.12 (α is the proportion of the year when surface soil is at field capacity, estimated to be 0.45 at Surianelli).

Equilibrium evaporation =fn (radiation at soil surface, relation between saturated vapour pressure and temperature, 0.12 is psychrometric constant).

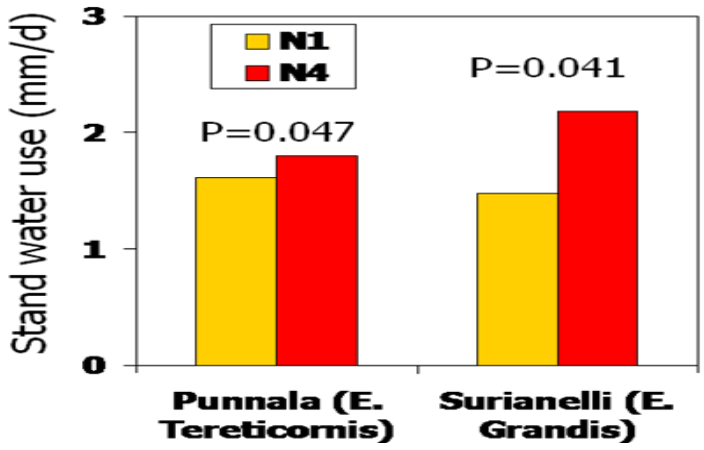


Fig.50. N1 and N4 treatment effects on stand water use at the two experimental sites in *E. tereticornis* and *E. grandis*.

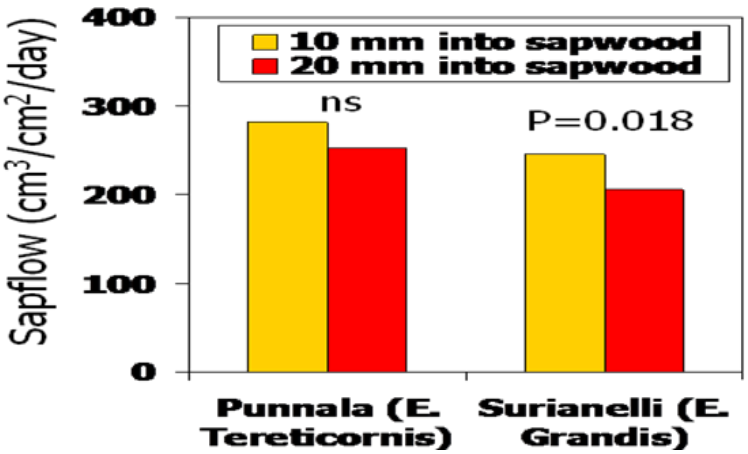


Fig. 51. Xylem flow with sapwood depth at the two experimental plots, Punnala and Surianelli (ns= not significant)

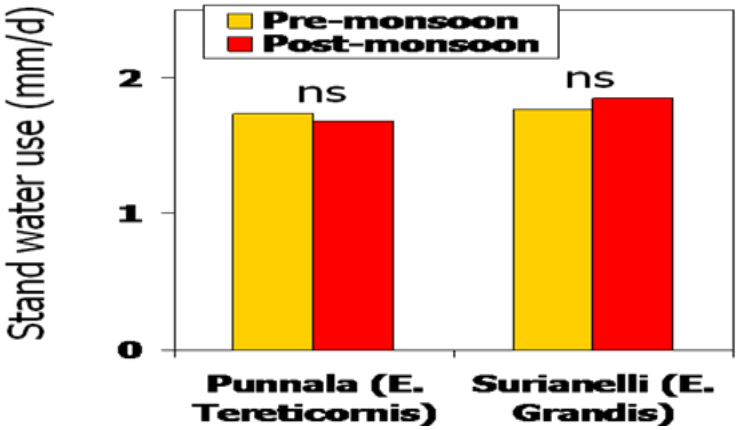


Fig. 52. Aspect effect on xylem water flow at the two experimental sites, Punnala and Surianelli (ns= not significant)

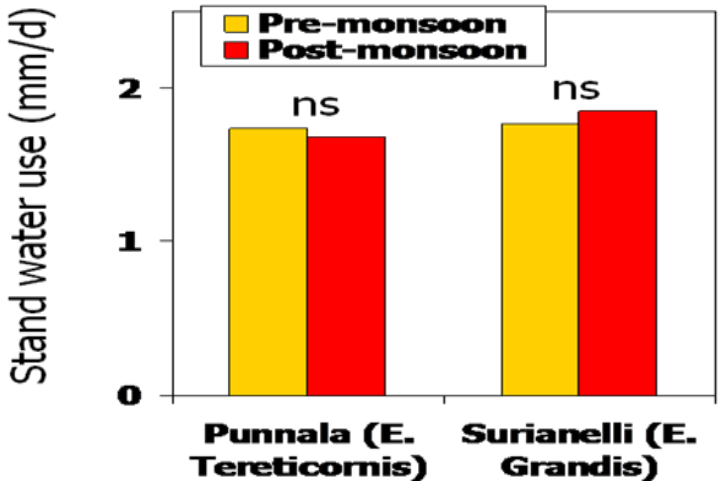


Fig. 53. Species, site and seasonal effect on stand water use measured at the two experimental sites, Punnala and Surianelli (ns= not significant).

Table 20. The water balance calculation for Surianelli.

Parameter	N1	N4
LAI	1.74	3.71
Interception (mm/annum)	-111	-211
Proportion of radiation reaching soil surface (Beer's law)	42%	16%
Soil evaporation (mm)	-327	-137
Rainfall (mm)	2265	2265
Transpiration (mm)	-540	-799
Balance (mm) (surface runoff, recharge)	1286	1118

Note: Transpiration calculated on an annual basis from daily transpiration, assuming that the relatively small measurement window (2 x ~2 weeks) was representative of the entire year and radial differences in sap flow with sapwood depth follow a similar pattern to *E. globulus* (Zang et al., 1996). In the above table higher transpiration losses in treatments with higher leaf area may be noticed, but these losses are significantly offset by lower soil evaporation losses.

It can be noticed that Punnala has lower rainfall than Surianelli, but also lower transpiration and interception in high N treatments. The transpiration values reported in this study are very similar to the values obtained in other eucalypt species measured in Northern Territory, Australia which has very similar climatic conditions as Kerala (Hutley et al. 2000). Kallarackal and Somen (2008) have reported transpiration between 2.71 and 4.17 mm/day in *E. tereticornis* and *E. grandis* in similar sites in Kerala.

Table 21.The water balance calculation for Punnala.

Parameter	N1	N4
Interception (mm/annum)	-66	-80
Soil evaporation (mm)	-417	-366
Rainfall (mm)	2000	2000
Transpiration (mm)	-588	-656
Balance (mm) (surface runoff, recharge)	929	897

6.14.3.2. Water Use Efficiency (WUE): It has been possible to work out the WUE of the trees in both the experimental sites using stand water use and growth data. The following equation was used. WUE = mm water used/ m^3 of wood produced (WUE based on total evapotranspiration).

Table 22. Water Use Efficiency of *E. tereticornis* and *E. grandis* at Punnala and Surianelli respectively for the N1 and N4 treatments

Experimental site	N1	N4
Punnala	29	21
Surianelli	58	39

In Table 22, greater WUE can be seen under the N4 treatments. Species difference is partly offset by difference in wood density.

7. Discussion

7.1. Site biomass and nutrient pools: The four sites in this study represent the range of eucalypt plantations in Kerala with contrasting fertility at both highland and lowland areas. Kayampoovam and Vattavada had relatively high fertility while Punnala and Surianelli had relatively poor fertility. This was also reflected in the productivity of the previous stands (Table 1). These results are in agreement with eucalypts grown in plantations across the world. Main differences between species in utilization patterns appeared to be lower N concentrations in the stem (wood and bark) in *E. grandis* compared to *E. tereticornis* and higher bark Calcium in *E. grandis* compared to *E. tereticornis.* Nutrient concentrations of N, P, K and Mg for the leaves, bark, branches and wood were within the ranges found in several studies by Judd (1966) for *E. grandis*. However, bark Ca at Surianelli (4.06%) was higher than the range of 0.77- 3.3% reported in other studies (Judd, 1996) even though concentrations of Ca in the soil were relatively low.

Productivity of eucalypt wood was highest at the most fertile site (Vattavada) and lowest at the least fertile sites (Punnala and Surianelli). Stem biomass at 7 years was similar to that found elsewhere in India for *Eucalyptus* hybrids (Tandon et al., 1993) and *E. globulus* (Jeeva and Ramakrishnan, 1997; George and Varghese, 1991). Production of stem material was equivalent to 6.6, 3.5, 4.4 and 16.6 t ha^{-1} yr^{-1} dry weight for Kayampoovam, Punnala, Surianelli and Vattavada, respectively. With the exception of Vattavada, productivity was generally lower than reported for eucalypt plantations elsewhere in the world, for example 10-21 t dry weight ha^{-1} $yr^{-1}$for *E. globulus* in Western Australia (O'Connell et al., 2000), 13-21 t dry weight ha^{-1} yr^{-1}across nine *E. urograndis* sites in Brazil not affected by waterlogging or high gravel content (Spangenberg et al., 1996). Low productivity at Kayampoovam, Punnala and Surianelli sites can be attributed to poor genetic stock, poor regeneration from coppice, inadequate nutrition, incidence of diseases and competition from weeds (Jayaraman and Krishnankutty, 1990; Sharma et al., 1985). Additionally, the relative short rotation time may induce lower productivity levels, as other studies have shown steady improvements in plantation productivity from 2-10 years of age (Tandon et al., 1993; Jeeva and Ramakrishnan, 1997).

7.2. Export of nutrients in plant biomass: Post-harvest export of nutrients can significantly deplete site nutrient stores, especially at lowland sites where local villagers remove most of the remaining harvest residues and above-ground biomass for fuel or green manure. These practices result in much greater losses of nutrients than

would occur if only stem wood was harvested. For example, at Kayampoovam and Punnala, total loss of N would be 397 and 449% of exports in stem wood only. Leaf material was a major store of N and removal of this fraction almost doubled the export of N from the sites. Collection pressure on leaf material is low compared to other residues, but current management practice is to burn the residues which can lead to significant volatilization loss of N from the sites.

Loss of P through intensive harvest of biomass for pulpwood, fuel and green manure every 7 years (20-56 kg P ha^{-1} $rotation^{-1}$ for the 4 sites) was similar to the 25 kg P ha^{-1} loss reported by George and Varghese (1991) for *E. globulus*. Losses of this magnitude are likely to significantly affect P supply to subsequent crops. This will have the greatest impact on plantation productivity where soil P availability is already limiting the growth as is the case at Punnala and Surianelli (Sankaran et al., 2000). Removal of biomass from the 4 sites is estimated to have major impact on the stores of above ground and exchangeable soil cations, if all of the above-ground biomass except leaf material was removed from those sites. For example, the above-ground pools represented up to 70, 216 and 68% of the exchangeable pools of K, Ca and Mg, respectively in the top 1 m of soil across the 4 sites in this study. Significant reserves of nutrients are likely to exist below this, but the top soil is likely to be the main source of nutrients taken up by the trees.

Export of cations has been identified as a major problem in planation forestry. For e.g., Spangenberg et al. (1996) found that the quantity of Ca and K exported from some *E. urograndis* plantation site in Brazil was greater than was present on the cation exchange complex in the top 1 m of soil. Likewise, Huntington et al (2000) found that export of Ca from old field soils in south-eastern USA was 5-fold the natural replenishment rates for a range of re-growth species. In this study it was calculated that Ca depletion would decrease forest productivity below economic thresholds within 80 years. Effects of nutrient loss are cumulative in the system investigated in this study with significant removals at the end of each rotation period of 7 years. It is likely that removing these quantities of Ca and Mg every 7 years may result in productivity decline unless remedial management strategies are adopted.

Stem bark contains major stores of Ca and Mg, and is also a significant pool of K at all sites. Hence removal of bark causes a significant drain on soil cations. Removal of stem wood, stem bark and branches is estimated to cause a 73-125% increase in the export of Ca and Mg from the 4 sites compared with removal of stem wood and branches only. Both *E. grandis* and *E. tereticornis* are smooth-barked species, for which the bark is

known to be a significant store of Ca. Wise and Pitman (1981) reported that, in Australia, four smooth barked species (*E. grandis, E. maculata, E. saligna* and *E. viminalis*) had 2.8-14.8 fold more Ca stored in the bark than was in the stem wood at 10 yrs of age, whereas, rough-barked species (*E. sieberi* and *E. laevopinea*) had 0.19 fold and 1.7 fold more Ca stored in the bark, compared with the stem wood. Thus, debarking and redistribution of the bark of smooth-bark species at the site is desirable to reduce export of Ca from the sites.

Soils in Kerala are inherently low in Ca due to the existing high leaching conditions. The heavy export of Ca from eucalypt plantations will add to this loss. This will lead to increased soil acidification and nutrient imbalance and the plantation productivity will be affected unless remedial strategies are adopted.

The understorey plants are likely to be important in nutrient cycling at the present study sites. They represent a significant proportion of the forest floor biomass and nutrients, especially at the low land sites (Fig. 3). Cutting of the understory can occur several times during the course of a rotation where weed control is practiced, or when these plants are used as green manure in agricultural crops. Removal of understorey may have significant impact on nutrient cycling within the plantations, as it represents a large pool of nutrient and additionally the turnover rate can be higher than in the overstorey (O'Connell and Grove, 1996).

7.3. Effect of burning: Residues remaining on the harvested sites are routinely burnt under normal plantation management practice in India. However, this can result in significant losses of nutrients and organic matter, which is an important component in cycling and storage of nutrients in soil. Nitrogen pools were between 247-358 kg ha^{-1} across the sites (Fig 3) and most of the N remaining in components left on site will be lost through volatilization if residues are burnt (Raison et al., 1985). Burning of harvest residue has been shown to result in N loss of approximately 300 kg ha^{-1} from sites in Australia (O'Connell et al., 2000) and 199-325 kg ha^{-1} in Amazonia (Mackensen et al. 1996). Retention of the residues to decompose *in situ* would promote return of N and other nutrients to the soil.

Burning of harvest residues also releases a proportion of the P held in the biomass. Some volatilization of P may occur at temperatures that are reached in a harvest residue burn (Raison et al., 1985), but most of the P is released as inorganic forms back into the soil (Folster & Khanna, 1997), the availability of which decreases over time as it is absorbed to the clay and Al/Fe-oxide particles in soil (Barrow & Shaw, 1975).

Organic P can constitute more than 50% of the total P in the surface horizons of forest soils and it plays an important role in soil P cycling (Attiwill & Adams, 1993). So, loss of organic P may reduce the rate of P cycling in soil and availability of P to the plantation crop at a later stage in the rotation. Nutrients other than P and N are also likely to be lost during burning through volatilization (Folster & Khanna, 1997) but the effects have not been quantified to the same degree as they have been done for N and P. In addition to direct nutrients losses through volatilization, burning can also increase the susceptibility of steep sites to soil erosion (Thomas et al. 1999), which may result in significant nutrient export during the monsoon. Loss of the top soil would result in very high quantities of nutrients exported from the site. For example, total N pools in the top 10 cm of soil of the sites ranged between 2.33 t ha^{-1} and 4.61 t ha^{-1}, which was an order of magnitude higher than was stored in all of the above-ground biomass.

7.4. Implication for plantation management: The natural replenishment rate of nutrients in the study sites is likely to be much lower than is exported currently through burning or other practices. Hence, the net export may be depleting the site nutrient capital and exacerbating the nutrient deficiency. N and P limitations to plantation growth have already been documented at these sites (Sankaran et al., 2000). Responsiveness of eucalypt plantations to application of Ca and other cations has not been assessed in this study but the magnitude of cation export (as a proportion of available site pools) appeared to be high for all 3 cations studied. Productivity at some plantations may already be limited because of the lack of these nutrients and changes in management strategy may be required to overcome this situation.

Natural sources of nutrient inputs include deposition in rainfall and dust, release of P from soil weathering and biological fixation of N. Miller (1984) reported rainfall and dust inputs of 1-22 kg ha^{-1} y^{-1} N and 0.02 -2.3 kg ha^{-1} y^{-1} P from a range of studies in Europe and North America. Similarly inputs of P from soil weathering are also relatively low with measured values of less than 1 kg ha^{-1} y^{-1} across a range of studies (Newman, 1995). Hence, P exported from the site is not likely to be replaced from natural resources. Inputs of N through biological fixation can be significant in natural forests where legume species are present in the understorey (e.g., up to 14 kg $ha^{-1}y^{-1}$ in *E. diversicolor* forest in Australia, Grove & Malajczuk, 1992) but legumes were not a major component of the understorey at any of the study locations. Incorporation of legumes as an understory or intercrop is a management option that may partially offset export of N from the site (Nichols et al., 2001; Agmathu and Broughton, 1985).

However, legume crops may also compete with the plantation crop for site resources (as is shown as part of this study) and this issue need be managed in the overall context of plantation productivity.

Natural replenishment rates of cations are also likely to be relatively low compared to export. For example, Zabowski (1990) reviewed Ca, Mg and K inputs from precipitation and weathering in 24 studies from the literature and found average Ca inputs from precipitation to be 5.5 kg ha-^{1} y^{-1} (range: 0.6-14 kg ha^{-1} y^{-1}) and from mineral weathering to be 24.3 kg ha^{-1} y^{-1} (range 0-120 kg ha^{-1} y^{-1}). Input of Ca from weathering in the soils derived from granite/gneiss (7 studies) ranged from 0.2-21 kg ha^{-1}y^{-1}. Weathering inputs of Mg across the range of studies was 0.82 -52 kg ha^{-1} y^{-1} (mean 9.2 kg has^{-1} y^{-1}) and weathering inputs of K across the range of studies was 0-26 kg ha^{-1} y^{-1} (mean 5.3 kg ha^{-1} y^{-1}). These figures show that inputs from weathering and precipitation are low, compared to potential export rates found in this study. Net nutrient export from these sites is likely to have led to depletion of available pools which may contribute to the observed declining plantation productivity in successive short-rotation plantations. Productivity on the poor fertility sites, such as Surianelli and Punnala are likely to be affected sooner than on the higher fertility sites such as Vattavada, which has the higher intrinsic nutrient supply capacity and thus a greater buffering against loss.

Estimates of nutrient export calculated in this study were for plantations with relatively low productivity. Potential exists to markedly increase productivity through use of improved genetic stock, addition of N and P fertilizers and more effective weed control. Such measures may reduce export of nutrients from understorey component, but would significantly increase rates of export in other components. Removal of nutrients at higher rates than reported here may result in an even faster degradation of site quality unless practices to retain nutrients on site and /or replace nutrients are implemented. Hunter (2001) also found that increasing the growth of *E. camaldulensis* and *E. grandis* through irrigation and macronutrient addition led to a dilution of other nutrients, some of which were at marginal levels in the higher productivity treatments.

Chemical fertilizer addition is routinely practiced in many countries where pulpwood is grown in short rotation to restore site nutrients and /or improve productivity, but such fertilizers may be an expensive option. A high proportion of the cations could potentially be returned to the sites via return of ash residues. This is practiced in Sabah, Malaysia where ash is returned from a paper and pulp mill back to the site to reduce export of calcium (Nykvist, 1997). This is a good option to reduce nutrient drain.

Another option to reduce nutrient export would be to minimize collection and prevent burning of nutrient rich components. Eucalypt twigs, bark and leaves and understory material contain most of the above-ground biomass nutrients, soretention of these components on site would significantly reduce export of nutrients.

In summary, it is predicted that removal of harvest residues or burning them at the site would result in extensive export of nutrients from the site which cannot be replenished through natural inputs. Quantities of nutrients exported are generally seven fold higher than that would occur if only the stem would was removed from the site since the other residues contain higher amount of nutrients. Nutrients availability (N and P) is already a limiting factor to growth at Punnala (*E. tereticornis*) and Surianelli (*E. grandis*) and N is marginally limiting growth at Kayampoovam (*E. tereticornis*). Calcium is one of the major nutrients exported and it has been identified in many studies as one of the elements most susceptible to loss in short-rotation forestry (Spangenberg et al., 1996; Nykvist, 1997; Huntington et al., 2000). Ameliorating this situation will require return of nutrients to the site or minimizing removal of nutrient rich resides (barks, twigs leaves and understory). The local villagers could potentially be allocated a proportion of the stem material for fuel as compensation for not being able to collect the bark and twigs. Discontinuation of burning would help preserve N and P on the site and prevent top soil erosion. Chemical fertilizers could be used to replace nutrients exported from the site but the costs may be an impediment. The outcomes of this project has proved that productivity of short-rotation eucalypt plantations can be enhanced through improved management practices including use of chemical fertilizers to correct deficiencies (Sankaran et al., 2007). And, where gains of productivity can be made, the cost of fertilizers per tonne of biomass returned is generally minimal and increased productivity can cover all the costs many times over (Wise and Pitman, 1981).

7.5. Slash retention and tree growth: Slash retention in plantations helps to conserve the site nutrient capitals, retain moisture, and reduce erosion all of which contribute to favorable growing conditions for plants (Haywood et al., 2003). Though the amount of nutrients in harvest residues (Fig. 4) correspond to a relatively small proportion of the total site nutrients to 1 m depth of soil in the study sites (Table 4), it does represent a significant part of the biologically active component of site nutrients. This study has shown that the current inter- rotation site management practices in Kerala such as slash removal or burning can result in a significant export of site nutrients which cannot be replenished through natural inputs. This is supposed to be one of the main reasons for

low productivity of eucalypt plantations in the state. Against this scenario, retention of the slash at the site will definitely improve site nutrient capitals and improve productivity of the plantations. Although slash retention at these sites did not significantly improve growth in the current rotation, increase in tree productivity due to slash retention has been reported especially on low fertility sites of eucalypts in Australia (Mendham et al., 2003), Brazil (Gonsalves et al., 2004) Congo (Nzila et al., 2004), China (Xu et al., 2004) and South Africa (du Toit et al., 2004).

The non-significant effect of slash management on the Kerala sites is partly due to the small amount of slash remaining at the sites (6. 4 -19.4 t ha^{-1} across sites) (Fig. 4) due to the low productivity of the previous crop. In comparison, the slash recorded from the two sites of *E. globulus* in Western Australia was to the tune of 31-51 t ha^{-1} (Mendham et al., 2003). Though Vattavada had a relatively high amount of slash (19. 4 t ha^{-1}), the inherent soil fertility was also high (Table 4). Other probable reasons for the lack of response could be: 1) application of starter fertilizer which masked the effect of slash and 2) the spatial distribution of slash was in such a way that tree roots were not able to access nutrients released from the slash until they ramified and colonized more area. Nevertheless, given the large quantities of nutrients in slash and the potential to markedly increase productivity on these sites, retention of slash is advised over future rotations. Also, slash acts as an important buffer against nutrient loss through leaching during the wet season. In short, the cumulative effect of slash retention will probably be evident in the longer term and this is essential for improving and sustaining productivity of eucalypt plantations. This is especially vital wherever fertilizer applications cannot be practiced due to budgetary or other constraints.

Productivity in the organic matter (OM) plots with minimal inputs was not as high as in the high input treatments at most of the sites. Nevertheless, mean annual increment in the OM plots at 6.5 years was significantly higher (47-224%) than those of the previous crop at the respective sites (Table 8). Use of genetically better planting stock and periodic weeding at the sites were the main reasons for the higher productivity in the experimental plantations compared to the plantations raised by the Kerala Forest Department and Kerala Forest Development Corporation. It is thus apparent that adoption of these practices alone would result in a significant benefit in terms of eucalypt plantation productivity. The added benefits from nutrient addition were highly significant at some, but not all, sites. So, application of fertilizer (beyond a starter amount) needs to be targeted on a site specific basis for maximum effectiveness.

The mean annual increment (MAI) across the organic matter manipulation experiments in *E. grandis* (29.2 - 55.4 m^3 $ha^{-1}yr^{-1}$) was significantly higher than in *E. tereticornis* plantations (13.4 - 17.1m^3)) In both cases, the productivity was markedly higher than the previous rotation (Table 8). Productivity was mostly higher or in a few cases similar to productivity of several *E. tereticornis* plantations (8-18 m^3 ha^{-1} yr^{-1}) in moist tropical/subtropical zones (Chaturvedi, 1983; Rawat and Negi, 2004; Dogra and Sharma, 2005). Productivity achieved in *E. grandis* plantations was significantly higher than for other *E. grandis* plantations in Kerala (Singh et al., 1988; Tandon et al., 1988). The reasons for improvement include use of better genetic material and management interventions. However, the productivity of *E. tereticornis* plantations is still significantly lower than the biological potential of the genus. Potential reasons for this include: 1) *E. tereticornis* is a naturally low yielding species susceptible to several fungal diseases (Sharma et al., 1985) and the sites available for planting *E. tereticornis* in Kerala are generally very degraded with low fertility and/or shallow soils which can become water stressed (Kallarackal and Somen, 1997a).

7.6. Eucalypt response to legume intercropping: The legume species used in this study have contrasting growth habits as well as residue qualities. Growth of *Stylosanthes* was most vigorous, with maximum biomass of 6 Mg ha^{-1} at both sites similar to that reported for several legume species grown as a cover crop under a range of young tree species in the central United States (Alley et al., 1999). All the legumes also had a marked seasonality in biomass production so that significant quantities of residues were deposited on the soil prior to monsoon. Although *Stylosanthes* had the highest biomass, it also has a relatively low tissue N concentration (Table 11), mainly due to the high stem: leaf ratio of the above-ground biomass. Hence, the above-ground N content of this species was correspondingly low (a maximum of 42 kg N ha^{-1} in the biomass at 15 months after establishment at Kayampoovam), in contrast with the N content of *Mucuna* (75 kg ha^{-1}) and *Pueraria* (118 kg ha^{-1}).

Legume inter-cropping potentially has multiple benefits for eucalypt cultivation, including N fixation, diversification of products include fodder, as well as weed control and minimization of leaching losses (Malik et al., 2001). Tian et al. (2001) found *Pueraria phaseoloides* accumulated 150-250 kg N ha^{-1} within 4-18 months growth, 68% of which was derived from atmosphere when grown on soils low in P and K, and 87% when soil P and K was sufficient. They also found that *Pueraria* roots capture nutrients deep in the soil and *Pueraria* fallow can reduce decline of soil organic matter and increase in concentration in particulate soil organic matter. Some or all of these benefits may be conferred through legume intercropping in eucalypt plantations.

Choice of legume species for inter-cropping is critical since climbers like *Mucuna* and *Pueraria* can smother trees if they are not pruned periodically. While it is easy to prune and manage *Pueraria,* the coarse stems and large leaves of *Mucuna* make management labour-intensive. The fast growing and smothering habit of *Mucuna* resulted in 20% mortality of trees at Punnala experimental site. *Mucuna* also competed with young trees for light more than the other legumes though its biomass was considerably lower than that of *Stylosanthes*. Both *Pueraria* and *Stylosanthes* significantly improved standing volume at Punnala, the site which had strong response to N fertilizer. However, at Kayampoovam, where soils are shallow, lack of response to legume intercropping may have been due to water limitation and relatively small response to N fertilizer.

The initial growth depression of eucalypts in the legume plots was probably due to competition for surface soil water and nutrients between the trees and legumes. But this effect disappeared after 18 months and there was a consistent trend from then until the end of the rotation of improving growth compared to controls. It is thus apparent that the tree roots may have explored more of the soil profile by 2 years, resulting in reduced competition between the tree crop and legumes. Beneficial effects of intercropping eucalypts with leguminous trees such as *Acacia mearnsii*, *A. holosericea* and *Paraserianthes falcataria* have been reported by DeBell et al., (1997), Forrester et al. (2004) and Xu et al. (2004) and are a potential option for improving N fertility of sites. However, maintenance of perennial legumes can be labour-intensive during the early stages of growth when the trees are of a similar height to the legume crop.

7.7. Effect of thinning on plantation productivity: The thinning experiments at the Eg sites have shown that below 2300 stems per hectare has a negative impact on overall productivity up to the end of the rotation. Standing volume in the thinned experiments was generally catching up by 5 years, but based on current productivity levels, the trees in the thinned experiments will need several more years before they reach the same standing volume as the un-thinned experiments. Thus the only consideration for thinning may be to increase log size, if the mill requires larger logs, or if converting to a saw-log regime. Studies elsewhere have shown that thinning can reduce tree stress due to more even use of site resources (mainly water) during the growing season, but the situation in the Eg growing locations in Kerala is not extreme, and most sites have sufficient water to support high stocking rates without suffering from excessive mortality. Moreover, this experiment has shown in short-rotation cycles, it would be ideal to have maximum number of smaller logs per hectare to realize higher productivity rather than lower number of larger logs.

7.8. Weed management: Weeds compete with trees for site resources (water, nutrients and light) and adversely affect wood yield (Nambiar and Sands, 1993; Little, 2002). Weed control is widely practiced in plantation forestry across the world, but it has not been possible to tap its full potential in eucalypt plantations in Kerala due to inefficient implementation practices. Social and political issues prohibit herbicidal application in several parts of India, including Kerala. So, weed control has to depend upon mechanical/manual means and these methods are seldom practiced in a thorough manner for several reasons.

The current study has demonstrated that weeding alone can improve plantation productivity substantially in *E. tereticronis* plantations (Fig. 13). The mechanism for improved productivity is probably different at the two sites, with Kayampoovam a more water stressed site (due to shallow soil depth) and Punnala a more nutrient–stressed site, indicated by a strong response to N fertilizer. During the dry period, the pre-dawn water potential at Punnala reached a minimum value of -1.0Mpa (indicating a low water stress) and at Kayampoovam, the value was -2.5 Mpa, suggesting that the trees were quite water stressed. So, the weeds competed with trees for waterat Kayampoovam and for nutrients at Punnala. Systematic management of weeds at both the sites resulted in high productivity of eucalypts at these sites.

The *Eg* sites showed a smaller response to weed management (Fig 14). The cause of this may also be different at the two sites. At Vattavada, a highly fertile site, weeding improved plantation productivity over the initial 1.5 years and thereafter there was no response. This could be ascribed to the early canopy closure of the plantations due to high inherent fertility and available water. Weeds were not a serious issue at this site. However, at Surianelli, a weed infested ex-grassland with low soil fertility; the lack of response to weeding may be an unreliable result, because most of the weeded plots were subject to wild elephant damage causing mortality of about 25% of the trees in the fully weeded treatment. Presence of weeds in the non-weeded plots restricted access by elephants, so fewer trees were lost to elephant damage in that treatment. The length of the time that weeds need be controlled will depend on how long they compete for site resources. In *Eg* plantations, canopy closure occurs at approximately 2 years, so weed control need not be intensive beyond this time. However, the canopy in *Et* remains open throughout the rotation, so weeds may need to be controlled for longer periods to achieve maximum tree growth.

7.9. Impact of trenching on plantation productivity: There was no significant effect of soil trenching on tree growth at any of the sites. It is probable that trenching may have an impact at a later stage in the rotation when water becomes a limiting factor. The overall trend at certain sites is indicative of this impact. Also, the conservation of top soil 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 be evaluated thoroughly.

7.10. Fertilizer applications and tree growth: Many studies have shown significant responses to N and P fertilizer application in plantations including *Pinus taeda* in Central Lousiana, USA (Haywood et al., 2003), *Eucalyptus grandis* in Brazil and South Africa (Goncalves et al., 2004, du Toit et al., 2004), *E. urophylla* in China (Xu et al., 2004, 2005) and *Eucalyptus* sp. in Australia (Cromer et al., 2002). Results from these studies are, in general, in agreement with the results of the current study. Nitrogen was the most limiting nutrient, with large responses in both Et and Eg plantations. However, the responses to fertilizer were quite variable across sites, suggesting that there were inherent differences in the nutrient supply characteristics of soils. So, nutrient applications need be targeted to sites that are responsive. Nutrient applications are more important in nutrient poor soils such as Surianelli and Punnala. Vattavada, which is rich in N and P will not respond to any nutrient application. The lack of response to P application at Kayampoovam is related to the high amount of available P found in the soils and the water limitation at the site. Studies conducted as part of this project (discussed below) has proved that N mineralization may be useful for predicting response to N fertilizer across sites, but this relationship needs further testing and validation across a broader number of sites before it could be operationally employed.

7.11. CAI/MAI curves: The current annual increment (CAI) and mean annual increment (MAI) curves for fully weeded plots at Kayampoovam, Punnala, Surianelli and Vattavada are shown in Fig. 54. These indicate that 5-6 years may be an appropriate time to harvest plantations at Kayampoovam, Punnala and Vattavada since no further improvement in growth can be expected beyond this period as the CAI values drop below MAI values by that time. Results from other treatment plots also agree to this observation. However, it would be worthwhile to retain the Surianelli plantation for a few more years for maximum productivity since the CAI values stand higher than the MAI values in most treatment plots at 6.5 years (Fig. 54).

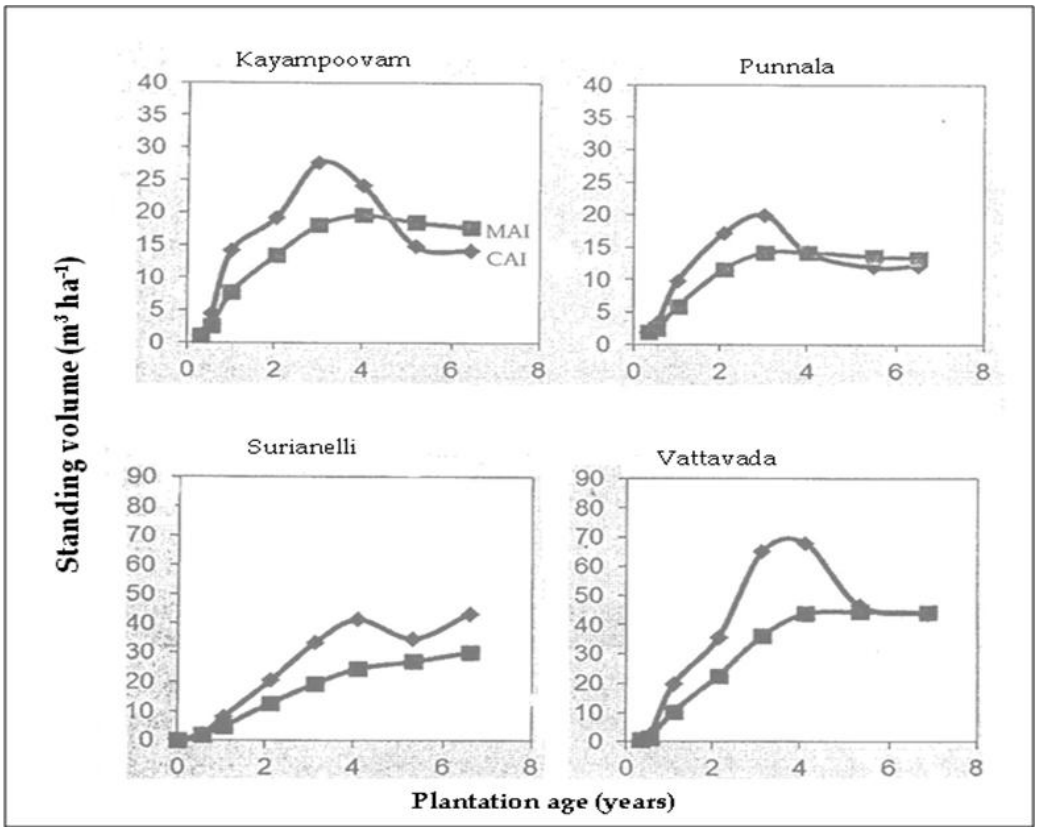


Fig. 54. CAI and MAI curves at different age of plantations in the fully weeded plots

7.12. Soil nutrient dynamics in OM plots

Total soil nutrient pools: There were no significant effects of residue retention on soil carbon and only a few changes on total soil N and P. This is partly because there were only small amounts of nutrients in harvest residues compared to total soil pools and the variability in the measurement of soil pools. It was estimated that there was 9-16 t ha^{-1} of total N at these sites (to 1 m depth) and 50-150 kg N ha^{-1} in the harvest residues representing only 1% or less of the soil pools. It was also shown that the biomass pool represented less than 0.5% of the total soil pools to 1 m. Some studies conducted elsewhere have shown little response to slash management in total soil pools (in loblolly pine in the USA, Zerpa et al., 2010 and *Eucalyptus globulus* in Australia, Mendham et al., 2003a). This is in contrast to some other studies where significant increase in soil nutrients were found with residue retention in humid tropics in Africa (Chijioke, 1980), savannas in Congo (Trouve et al., 1994) and sodic and lateritic soils in India (Mishra et al., 2003, Swamy et al, 2004). Retention of double amounts of native

forest floor organic residues significantly increased the nutrient availability in *Eucalyptus* plantations in Australia, Congo and Brazil (Corbeels et al., 2005, Laclau et al., 2010) and loblolly pine plantations in the USA (Zerpa et al., 2010). Though it was not possible to find significant effects of residues on soil nutrient pools during this study, they may have been more significant if the productivity of the previous rotation was higher and if the soils had lower starting nutrient capital.

7.12.1. N mineralization: Though *in situ* N mineralization measurement gave good differentiation between sites and soil depths, it was not possible to detect any significant differences between slash treatments. This observation is supported by a study by O'Connell et al. (2004) who found that effects of slash management were apparent but not significant for the first 2 years after treatment in *E. globulus* in Western Australia and became significant for years 3-5. The lack of apparent effect during the present study may have also been associated with lower levels of slash (9-27 t ha^{-1}) compared to 31-51 t ha^{-1} in the study by O'Connell et al (2004). Though no significant change was recorded in N mineralization rates in this study, it was clear that harvest residues contain significant pools of N (Fig. 6) and their retention on site improves N status through release of mineral N directly from decomposition of the harvest residues (Goncalves et al., 1999; Blumfield and Xu, 2003). The insignificant effect of the slash may also be due to the high C: N ratio of the residues. Microbial cells require 1 unit of N for every 10-15 units of carbon utilized. The low N content of the added slash residues will thus lead to an immobilization thereby restricting the effects of N for the first few years. This study has shown that in the controlled environment of a leaching experiment residue retention did result in significant increases in soil N release across sites but the experimental design did not allow to ascertain whether the additional N was directly from release of the N from the residues or cycling through the soil N mineralization processes.

In contrast to the aerobic mineralization measures, it was clear that retention of harvest residues did result in a significant increase in the anaerobically mineralizable N from the soil, suggesting that it is a more sensitive measure of soil N supply capacity. O'Connell et al. (2004) also found slash retention had a significant impact on anaerobically mineralizable N at 2 *E. globulus* sites in Western Australia which was correlated with greater aerobic N mineralization

measures. These results suggest that retention of harvest residues is likely to convey incremental benefits for sustaining the nutrient availability in the soil for tree uptake.

7.12.2. Microbial biomass: The impact of slash retention on increasing the microbial biomass suggests that the residue–retained treatments had a higher level of labile carbon than those without, despite the observation that total carbon was not significantly influenced by residue treatment. Increase of microbial biomass through slash retention has also been reported by other workers (Carter et al., 2002; O'Connell et al., 2004). In this study, the upland Vattavada and Surianelli sites tended to exhibit very high microbial biomass-C compared to the lowland sites (Fig. 23). This is possibly associated with faster decomposition of residues (Fig. 33) at the lowland sites and thus there was only less material left on site at 2 years when the microbial biomass was assessed. Mendham et al. (2003b) also found that soil microbial biomass increased markedly in slash retained treatments under *E. globulus* in Western Australia at age 1 year, and the trends were still evident at age 5 years but were mostly non-significant. The higher temperatures and rainfall in Kerala are likely to promote faster decomposition of slash compared to Western Australia so the effects on microbial biomass are likely to be more transient in Kerala thus helping to explain the lack of a significant response at the lowland sites at age 2 years.

The impact of slash burn treatment on the ratio of microbial biomass C to anaerobically mineralizable N at the Kayampoovam site suggested that the burn treatment substantially influenced the capacity of the microbial biomass to mineralize nitrogen at that site. Similar results were reported by Hossain et al. (1995) in a native eucalypt forest in Australia with different burning frequencies with the most frequently burnt site having both lower N minerlization and lower microbial biomass. It may also be noted that burning generates an in-situ temperature influx which leads to N volatilization (N loss). Also, increased decomposition and polymerization during burning render the carbon sources to a recalcitrant pool making them inaccessible to microbes. Microbial cells deprived of its energy source (carbon) and cell building units (nitrogen) gets substantially reduced under such conditions. Microbial biomass carbon as an indicator of soil health suggests that burning treatments will lead to site quality deterioration in eucalypt plantations.

7.12.3. Implication of organic matter manipulation for site management: In general, the influence of harvest residue manipulation on soil N, P and C was relatively minor in the short term period of this study with only a few detectable changes to the soil characteristics explored. Retention of harvest residues at the sites did increase the N mineralization and microbial biomass and it is evident that the residues contain large quantities of these critical nutrients. So, as explained already, residue retention will improve nutrient supply for subsequent rotations of *Eucalyptus*. The minimal response of the soil to harvest residue manipulation was reflected in the minimal response of the tree productivity to the above treatment until the end of the rotation though the sites did respond to N fertilizer application. This suggests that the relatively low quantities of the harvest residues, their distributed nature and fast decomposition may not benefit the trees as much as the fertilizer application in the short term. Eucalypt plantations in Kerala are subject to repeated harvesting and complete removal of organic matter or burning them. The nutrients thus exported are not generally replaced through nutrient supplementation because of costs and other considerations. So, retention of slash is a potentially cost-effective solution that need be implemented to improve and sustain productivity.

7.13. N mineralized in long-term incubation of legume and eucalypt residues: Net N release characteristics of the legume residues differed significantly under controlled conditions in the laboratory. Studies conducted elsewhere often showed a period of N immobilization caused by crop residues followed by N release but the net effect of N immobilization may be reduced when residues were applied on the surface of soil (Sakala et al., 2000; Corbeels et al., 2003). However, though the residues were surface applied, residues of *Stylosanthes* and eucalypt still showed net immobilization of N at the start of the experiment.

Differences in cumulative N release between residue types were broadly consistent with several measures of litter quality. *Mucuna* leaves which had the highest N concentration and lowest soluble polyphenol + lignin : N ratio, released high amounts of N while *Stylosanthes* residues which had lowest N concentration and highest soluble polyphenol + lignin : N ratio, caused net immobilization of N throughout the incubation period in both the soils. Total N was the simple and one of the best measures of residue quality with the lignin+ soluble polyphenol: N ratio also strongly correlated to cumulative net N

mineralization (Fig 27). Frankenberger and Abdelmagid (1985) reported a similar effect of residue N concentration on net N mineralization. However, the present results do not agree with the findings of Palm and Sanchez (1991) and Handayanto (1997) who found that polyphenol: N ratio had a strong influence on N release. In the present study, soluble polyphenol: N ratio was a poor predictor of net N release. But, for the range of residues used in this study, it would be sufficient to use the total N concentration to predict net N release rates, but lignin may also play a significant role in the governing N mineralization where it is present in high concentration (Fox et al., 1990).

The effect of mixing eucalypt and legume residues influenced the initial net releases for some legume/soil type combinations with most predicted N mineralization higher than observed mineralization (Fig 28). However, any effects of mixing residues on quantity of N released were generally transient, with similar net N release between mixed and non-mixed samples at later leaching times. The transient effect was probably due to the capacity of leaves to initially immobilize more mineral N than was released from native soil N pools, thus resulting in immobilization of legume derived N as well (Sakala et al., 2000). The absence of persistent strong interaction between legumes and eucalypt residues despite the high concentrations of soluble polyphenols in eucalypt residues is in contrast with the results of Handayanto et al. (1997) who observed a cumulative reduction in N availability over 14 weeks where residues high in polyphenols were present. The variable relationships between residue soluble polyphenol concentration and pattern of N mineralization-immobilization may have been caused by different protein binding capacities of soluble polyphenols from different residue types (Mafogoya et al., 1988). Accordingly, the protein binding capacity of the soluble polyphenols in eucalypt foliar residues may have been lower that of *Peltophorum dasyrachis* examined by Handayanto et al (1997).

7.13.1. Issues to be addressed in legume management: Though legumes are a cost-effective source of N, the quality of the plant residues play an important role in regulating the release of N. Also, the timing of N uptake and release are also critical considerations for legume management in the field. During the initial stages of tree growth when N uptake is low and the root system is not fully exploiting the soil volume, legumes may capture some of the N that is mineralized from the native soil as well as adding to the soil N pool through N_2

fixation. *Stylosanthes* may not be effective in capturing soil N during the first growing season since it had lower N uptake compared to other legumes. However, once residues start accumulating on the soil surface, the lower N concentrations of litter may result in greater N immobilization.

The potential for N fixation may also be considered as an important criterion while selecting the legume species for intercropping. This is especially important in short-rotation plantations where relatively high rates of N are exported during inter-rotation period through removal logs and harvest residues. Though *Stylosanthes* residues had a lower capacity to supply the N requirement of the tree crop in the short rotation, the high C: N ratio of the residues of this legume is consistent with the qualities required for accumulation of soil organic matter (Cadisch and Giller, 2001). Maintenance of/or improvement of soil organic matter is another critical factor for long-term sustainable productivity (Tiessen et al., 1994) and hence the legume for intercropping should balance the N supply criteria and the long-term benefit of soil organic matter improvement.

In summary, though *Stylosanthes* had the highest biomass, its residues were of low N concentration and resulted in N immobilization for over a year in lab incubation experiments. The incubation experiment proved that the degree of N mineralization and immobilization was directly related to the N concentration of the residues. Net N release from plant residues decreased in the order *Mucuna*>*Pueraria*>*Eucalyptus*> *Stylosanthes*.

7.14. Nitrogen addition and related N mineralization across sites

7.14.1. Response to N fertilizer and indices of soil N supply: Total soil N, soil C:N ratio and N released during aerobic and anaerobic incubation were examined in relation to N fertilizer application to find the best indicator to predict response to N addition. Of these, anaerobic N showed no correlation with response to N fertilizer. The results agree with findings of Scott et al. (2005), that anaerobic N was not related to N fertilizer response in in short-rotation *Liquidambar styraciflua* plantations across a range of soils in Southern USA. Curtin and McCallum (2004) also found anaerobically mineralizable nitrogen to be of little value for predicting N supply in agricultural soils, although some studies have found anaerobic N to be more useful in other situations (Stockdale and Rees 1994). In this study, total N, soil C:N ratio and aerobic N mineralization showed

more promise as indicators of response to N fertilizer with the best indicator being the aerobic N mineralization index which is in agreement with the findings of Scott et al (2005) and Curtin and McCallum (2004).

7.14.2. Modeled N mineralization as a predictor of fertilizer response: Results of the present study have shown that a modeled index based on predicted annual N mineralization (using a function of soil moisture and temperature) is not a reliable index of response to N fertilizer. However, Goncalves and Carlyle (1994) and O'Connell and Rance (1999) showed that it was feasible to model N mineralization through an understanding of the microbial responses to temperature and moisture, as well as knowledge of the basal rate of N mineralization, which is specific to a given soil. The methodology of these authors was extended in this study to examine the utility of this technique for predicting a more general response to N fertilizer. The moisture and temperature response curves were of a similar shape in this study to those of O'Connell and Rance (1999). There was some variability around the moisture response, but the variability within sites was as much as the variability between sites, thus a common regression could be fitted to the data across 4 sites. Curiously, the Eg sites in the uplands were more responsive to temperature, having higher relative N mineralization. In general, pools of anaerobic N in upland sites was high, however these sites experience low annual temperature variations. Thus, higher response to temperature may be useful in explaining the lesser usefulness of high anaerobic index for the inclusion in diagnostic tool and explaining the response to added N fertilizer in these sites.

The predicted annual N mineralization rates of 26 to 118 kg ha^{-1} a^{-1} (0-10 cm depth) for all sites in this study were generally similar to those recorded by O'Connell and Rance (1999) in south-western Australian soils (69-113 kg ha^{-1} a^{-1} at 0-20 cm depth) but slightly lower than those found in other studies in tropical ecosystems. Two studies can be quoted here: Maithani et al. (1998) found annual rates of N mineralization for 138-162 kg ha^{-1} a^{-1}(0-10 cm) under sub-tropical rain forest in north-eastern India and Smith et al. (1998) found (0-20 cm) 195 kg ha^{-1} a^{-1}(*Pinus caribaea* plantation) to 328 kg ha^{-1} a^{-1}under native forest in Amazonia state in Brazil. The low N mineralization predicted at Surianelli (26 kg ha^{-1}) is attributable to the low basal rate, the site being a grassland previously.

The present study has shown that the best indicator of response to fertilizer across the 4 sites was the net N released during aerobic incubation. The Vattavada site had the highest productivity and thus the greatest demand for N. Predicted net annual above-ground N uptake by the stand was around 90 kg ha^{-1} a^{-1} slightly less than the predicted 112 kg ha^{-1} a^{-1}mineralized from the soil. The predicted annual N mineralization at Surianelli was much lower than the observed uptake thus explaining the response to applied N fertilizer. The two lowland *E.t* sites had high levels of predicted net N mineralization and relatively low N requirement, but much of this N is predicted to be mineralized during the dry season when soil moisture is likely to be limiting tree growth. The seasonality of growth was not measured in this study which may be required to further resolve the supply and demand dynamics at these sites and assist development of more suitable generic index for sites with similar soil characteristics.

7.15. Decomposition of harvest residue and nutrient release: As is evident from the Fig. 6, the amounts of nutrients in harvest residues correspond to a relatively small proportion of the total store of site nutrients to 1 m depth of soil (Table 4). Nevertheless, the pool of nutrients in harvest residues does represent a significant part of the biologically active component of site nutrients. Hence, as discussed earlier, any practice of export of harvest residues or burning them can adversely affect the site nutrient pools and impact the productivity in the longer term. Studies on slash decay have shown that the residues decayed rapidly especially at the Et site. Almost all of the leaf and bark residues decayed by the end of the first year and over 50% of the twigs also had disappeared. The order of decay of the residues is similar for Eg sites but it took longer time to decompose. In general, the decay rate of each residue fraction depends on its chemical composition. Leaves contain more of proteins and soluble carbohydrates which are labile and twigs contain more of cellulose and lignin which are not easily decomposed. The order of the decay rate of eucalypt slash residues was - leaves faster than bark and bark faster than twigs. This was in agreement with the findings from a number of studies on decay of harvest residue of eucalypts (e.g., Jones et al., 199; O' Connell, 1997).

The decomposition rates of harvest residues recorded here are higher than that has been reported generally for eucalypt litter in the tropics (mean *k* yr^{-1} is 0.90 - O'Connell and Sankaran, 1997)) and in the same geographic area (0.74 for *E.*

tereticornis, Sankaran, 1993). In this study, the *k* values recorded for leaves at the *Et* sites were, 3.55 and 2.93 for Kayampoovam and Punnala, respectively and those for *Eg* sites were 1.062 (Vattavada) and 1.548 (Surianelli). Higher *k* values were also recorded for bark and twigs. This rapid rate of decomposition is probably due to the higher concentrations of nutrients, especially N and P, in green harvest tissues compared to litter which is composed of senescent tissues. Similar differences have been reported in temperate eucalypt plantations (Shammas et al., 2003; Jorge et al., 2009, O'Connell et al., 2004). However, the decay rates of all residue fractions of *E tereticornis* and *E. grandis* are faster compared to those reported in *E. diversicolor* forests in Western Australia (O'Connell, 1997) *E. globulus* plantations in South-Western Australia (Shammas et al., 2003) and Spain and Portugal (Jones et al, 1999) and *Eucalyptus dunnii* plantations in Uruguay (Jorge et al., 2009). The high temperature and moisture regimes in the humid tropics would explain the rapid decomposition of residue fractions in Kerala. The comparatively slow decay rates in Vattavada are due to the low temperature, comparatively low rainfall (1800 mm yr^{-1}) and other climatic factors prevailing at this high elevation site (altitude, 1800 m asl).

The pattern of nutrient release indicated that eucalypt bark is a rich source of nutrients (especially Ca) compared to leaves and twigs (Wingate-Hill and MacArthur 1990) though the decay rate of bark is lower than that of leaves after an initial rapid phase. So, debarking at the site may conserve a substantial amount of Ca, K, P and Mg for the benefit of future plantations (Laclau et al., 2000; Santana et al., 1999). However, Jorge et al. (2009) have reported that the bark of *Eucalyptus dunnii* was the most resistant to decomposition compared to leaves and wood in plantations in Uruguay.

The fast turnover of harvest residues was coupled with fast release of nutrients from harvest residues in Kerala (Table 15; Fig. 34). The order of nutrient release from the harvest residue fractions was, in general, similar to those reported by other workers (O'Connell, 1997, Shammas et al., 2003). Release of K was the fastest from all residues probably through leaching resulted from rainfall soon after placing the litterbags in the field (July-August). Accumulation of calcium in eucalypt residues observed at three sites in this study has also been reported for *E.globulus* plantations by Shammas et al. (2003) in SW Australia and *E. dunii* plantations in Uruguay (Jorge et al., 2009). Ca is an important component in cell walls and membranes of plants and only a small proportion of this nutrient is present as Ca^{2+} (Marschner (2003). This would explain why release of Ca from

harvest residues takes a longer time compared to other nutrients. Immobilization of N during the first 7 months of decomposition relative to P, at all sites, probably suggests that N may be the main nutrient which limit microbial activity at those sites which affect decay of residues.

Overall, 38-77 kg ha^{-1} of N, 3.5 -18 kg ha^{-1} of P, 40-127 kg ha^{-1} of K, 40-271 kg ha^{-1} of Ca and 12-26 kg ha^{-1} of Mg was released from residues at Et sites during the first year. The lower value in the range of nutrients reported above were recorded from the site at Punnala which was the least productive of all the four sites and thus nutrient pools in the harvest residues were significantly low compared to Kayampoovam site. Similarly, Surianelli was less fertile compared to Vattavada which is reflected in the nutrient pools released/accumulated. The slow decomposition of residues at Vattavada will also explain the comparatively slow release and accumulation of nutrients.

Slow decomposition and retention of harvest residues at Vattavada probably acts as an important buffer against nutrient loss through leaching during the wet season. This may be particularly important for site N stores which appear to be readily immobilized in the decomposing harvest residues.

7.16. Measuring wood volume and growth in *E.tereticornis* and *E. grandis* plantations

As indicated, the objective of the study was to assess accuracy of methods to estimate standing volume of trees in tropical eucalypt plantations. For this purpose, one experimental plantation (ca. 4.5 ha) each of *E. grandis* and *E. tereticornis* (6.5 yr- old) was harvested and conical, stacked and billet volume determined. It was found that recovered billet volume (under bark) was closely related to a conical approximation of stem volume of standing trees. There was a strong correlation between measured conical volume, billet volume and stack volume (debarked logs) of *E. tereticornis* and *E. grandis*.

The rate of moisture loss in logs after stacking in the field was also measured, so that buyers and sellers can make an informed decision about the likely moisture content, rather than assuming it is 50% as is currently the case in Kerala. The studies indicated that both position in the stack and time elapsed after stacking significantly affected moisture content of logs. The upper most logs in the stack of *E. tereticornis* had the highest moisture loss by the end of two weeks (71 %)

while this was true for logs on the side of the stacks for *E. grandis* (60.8%). In both cases, moisture loss after 2 weeks was the least in logs placed at the bottom of the stack. Though moisture content of smaller logs was slightly higher at the time of harvest, moisture loss was also higher from smaller logs over time for both *E. tereticornis* and *E. grandis* (Fig 38).Visser et al. (2014) also observed that log diameter (of radiata pine) had a significant influence on drying since smaller diameter logs exhibit a larger surface area to mass ratio and smaller distance water must move from the inner log to the surface in order to evaporate. According to Rezende et al. (2010), moisture loss from eucalypt logs (*E. urophylla)* occurred at different intensities as a function of log diameter with greater moisture losses noted in logs without bark and those with smaller diameters.

The rate of drying varied significantly within each log, depending on the end diameter, and the distance from the end, with the thinnest end drying faster than the thickest end, and slower drying away from the log ends. However, the rate of drying was not significantly different between logs of *Et* and *Eg*. While logs of *Et* continued to lose moisture up to 4 weeks, logs of Eg maintained almost the same moisture content up to 6 weeks. The slightly high moisture content of *Et* logs at 6 weeks was probably due to intermittent rains between 4 and 6 weeks at that site. Rezende et al. (2010) reported that, in Brazil, greater moisture loss from logs of *Eucalyptus urophylla* occurred only in the first three weeks decreasing significantly afterwards.

Bown and Lasserre (2015), who studied air-drying of piled logs of *Eucalyptus globulus* and *E. nitens* in Chile, reported that the season, especially the temperature and relative humidity are the main drivers of moisture loss from logs compared to the effect of species, debarking and log length. Simpson and Wang (2004) also arrived at the same conclusion based on their studies on logs of ponderosa pine and Douglas-fir in the United States.

In summary, the conical approximation was found to be a robust measure of the volume of standing trees in tropical eucalypt plantations, and judicious stacking and choice of the stacking season could optimize moisture loss from logs of different sizes. Additionally, the impacts of stacking and field storage time on moisture content should be accounted for interactions between buyers and sellers, recognizing that logs of lower moisture content cost less to transport, and sellers should be paid on a dry weight basis.

7.17. Plant Physiological studies

Water and nutrients are two important requirements for the functioning of a plant. Since plants take up most of the nutritents along with water, both the factors work together in nature. Eucalypts have been alleged to consume excessive water; thereby they are a big threat depleting the water table. However, these reports are controversial because many eucalypt species have been shown to have good stomatal control when the soil dries up (Kallarackal and Somen, 1997a, b). At the same time, it has been also shown that eucalypts roots penetrate almost 10 m deep in Kerala, reaching the water table (Kallarackal and Somen, 2008). This would certainly mean that they extract much more water than many of the native species where the rooting depth is much less. According to White et al. (2016) water use alone is a very blunt instrument for making land-use decisions. Exploring the relationships among growth and water use highlights the importance of a multi-factor analysis and approach to land-use planning. Wood production per unit of evapo-transpiration (plantation water productivity) is determined by: the transpiration efficiency of dry-matter production; the proportional allocation of dry matter to wood; and the ratio of evaporative losses to transpiration. The variation in productivity and water use with climatic and site characteristics is complex and the subject of a vast amount of literature in the past. This apparent complexity can be reduced to this simple statement: "managing plantations to maximise their growth will also maximise plantation water productivity at the stand scale" (White et al., 2016).

Notwithstanding the above environmental issues, the productivity of the existing plantations in Kerala has been reported to be very poor according to international standards. The current study is an attempt to identify the real problems of low productivity, assuming that it could be due to shortage of nutrients or water. Continuous water potential measurements round the year, made in this study shows that at least at the two sites examined in detail, water potential of the leaf rarely goes below -0.5 MPa. This occurs in premonsoon period hardly for one or two months. It has been shown in studies on *E. globulus* in Australia that growth of the trees becomes water limited when the water potential reaches -0.5 MPa, as shown in Fig. 42.

Kerala gets two rainy seasons, which really keep the soil wet. In many locations the water table is also rather shallow, allowing the roots to extract water from the water table. Moreover, previous studies in Kerala have shown that the

rooting depth of *E. tereticornis* can go up to 10 m, which is the depth of the phreatic aquifer in many locations (Kallarackal and Somen, 2008).

LAI is a parameter which is very much dependent on nutrition, water availability, light and temperature (Battaglia et al., 1998). Productivity is linearly related to light interception and non-linearly related to LAI. With increases in leaf area index there will be self-shading effect in a plantation. The relationship between leaf area index and light interception has a steep initial slope that decreases continually towards an asymptote of complete interception (White et al., 2010). This characteristic relationship has a number of important consequences, but the most important here is a non-linear relationship between leaf area index and water use. Up to a leaf area index of three, the relationship is close to linear but further increases in leaf area index have progressively less impact on total water use (White et al., 2016). In the present study, nutrition might explain much of the LAI variation as the other factors were found to be not limiting.

The water balance calculation reveals that water available for recharging the soil is not so much deficient in the watershed where the eucalypts are planted. The transpiration has been measured using the sap flow method, which is certainly very sensitive at plant level, although not so much at the catchment level. In this study we have certainly made some assumptions, especially extrapolating the transpiration at the catchment level from seasonal measurements at the plant level. However, it should be pointed out that the results of water use presented in this report should not be taken as absolute values, they are only relative in terms of N and P treatments. Evaporative losses due to soil evaporation, weed transpiration and canopy interception can make up more than half of the total stand water use (White et al., 2016). Reducing weed transpiration and soil evaporation increased productivity by 30% in a farm in the tropics as reported by White et al. (2016). However, all these kinds of management practices need not reduce the overall evapotranspiration. When the evapotranspiration of the ground vegetation is reduced, the transpiration of the upper canopy can increase (Kelliher et al., 1995). The water use during the dry season, namely the pre-monsoon period indicates that the root has access to water as there is no reduction in water use. Reducing planted area, but selecting areas where water use is greatest, may be one option for managing the trade-off between wood production and water use at the catchment scale (White et al. 2016).

It can be concluded from the results of the plant physiological experiments that:

- Silvicultural treatments influenced plantation growth through increases in leaf area rather than increases in photosynthesis per unit leaf area.

- Trees at both Punnala and Surianelli are not significantly water stressed, but much lower leaf water potentials reported at Kayampoovam indicate the potential for greater water stress in Kerala.

- Where soil depth is greater than 5-6 m, severe water stress is unlikely in this environment, because the water tables are generally shallow.

- Water use is slightly greater under treatments with higher leaf area, but a significant proportion of rainfall is not transpired/evaporated, and thus is available for groundwater recharge/surface runoff.

- Increased productivity through intensive management only marginally increases water use but improves WUE of wood production.

8. Summary of results and recommendations

1. Harvest residue management while preparing the sites for planting

This study has shown that burning/removal of harvest residues during the inter-rotation period will result in large loss of nutrients from the site. Though the trials by retaining/adding slash at the sites indicated no significant improvement in tree growth, the nutrient status of soils at some sites was benefitted. It is concluded that harvest residue retention may not have large effect on productivity immediately but will contribute to conserving site resources and is likely to have an effect on the long-term productivity and sustainability.

Recommendation: Do not burn or remove harvest residue from the plantations. Instead, these may be spread evenly in the respective harvested plots in an operationally acceptable way and allow to decompose. Slash decomposition is proved to be faster than litter decomposition and substantial amount of nutrients are proved to be added to the soil during this process.

2. Ensuring the quality of planting stock

Use of genetically superior planting stock for improving productivity of euclaypt plantations has been demonstrated through the present research program. If the planting stock is of superior quality even fertilizer application can be avoided.

Recommendation: Do not use locally available seeds of inferior quality for raising nurseries. Use clones raised from genetically superior plus trees or seedlings raised from seed lots of genetically superior provenances identified by KFRI as highly productive and disease resistant. Good quality seed lots are available from CSIRO Tree Seed Centre, Canberra or agents appointed by them.

3. Weed control

Weeds are known to compete with trees for water and nutrients and affect their growth significantly. Weeding trials carried out under this study have shown that regular weeding will improve productivity of up to 2-3 folds in eucalypt plantations.

Recommendation: Regular and intensive weeding is recommended in eucalypt plantations. This has to be done during March-April, July-August and November –December. At some sites, where weed growth is not intense, the weeding during March-April can be avoided. In *E. grandis* sites, the cost of weeding will be a bare minimum after the initial 2 years of tree growth since the closure of tree canopy after that would reduce weed growth in the plantations significantly.

4. Fertilizer application

Soil nitrogen (N) and phosphorus (P) are identified to be the most important limiting nutrients for growth of eucalypts in Kerala. This project has shown that application of N and P fertilizer can significantly improve tree growth but the responses were highly variable and site-specific. In short, the results indicated that maximum growth response was obtained with up to 60 kg N $ha^{-1}yr^{-1}$ at the least responsive sites (Kayampoovam-*Et* and Vattavada-*Eg*) but more fertilizer than this was required at poor fertility sites like Punnala –*Et* and Surianelli –*Eg*. As regards P, sites like Kayampoovam, Surianelli and Vattavada do not require P fertilizer to improve productivity but higher growth can be obtained at sites like Punnala by adding approximately 60 kg h^{-1} yr^{-1}.

Recommendation: Since the response to fertilizer has been very site-specific, only a broad recommendation is provided. Use 20 kg P (220 kg super phosphate) per ha and 50-150 kg N (110-330 kg urea) per ha (depending on site quality) in the first year of planting as a split dose (i.e., 1/3 at the time of planting and 2/3 after 6 months –preferably during north-east monsoon). Repeat the same dosage in the second year. Equal halves of the total quantity could be applied twice this time, during June–July and October –November. Higher rates of N should be applied to ex-grassland and lower rates to ex-forest sites to derive maximum benefits.

5. Legume intercropping

Legume intercropping offers potential benefits including suppression of weedy vegetation, conservation of soil stores of nutrients during the establishment phase and supply nitrogen through fixation of atmospheric nitrogen. In Kerala,

Mucuna and *Peuraria* are generally grown as an intercrop in rubber plantations. *Stylosanthes* is grown as an intercrop in forest plantations in Karnataka. In the current trial, *Peuraria* and *Stylosanthes* intercropping gave a small improvement in tree productivity at 5 and 6.5 years in the N deficient *E. tereticornis* site. There was no effect at the other site since water was a limiting factor. *Mucuna* intercropping required a greater level of management since it can smother trees.

Recommendation: Growing legumes such as *Peuraria* and *Stylosanthes* as intercrops in low fertility eucalypt plantations (in the first year of planting itself) has potential to improve tree growth. Moreover, it offers benefit to local people through livestock grazing opportunities. However, choice of the legume need be done with caution. Use of creepers may be avoided since these can smother trees if not managed periodically.

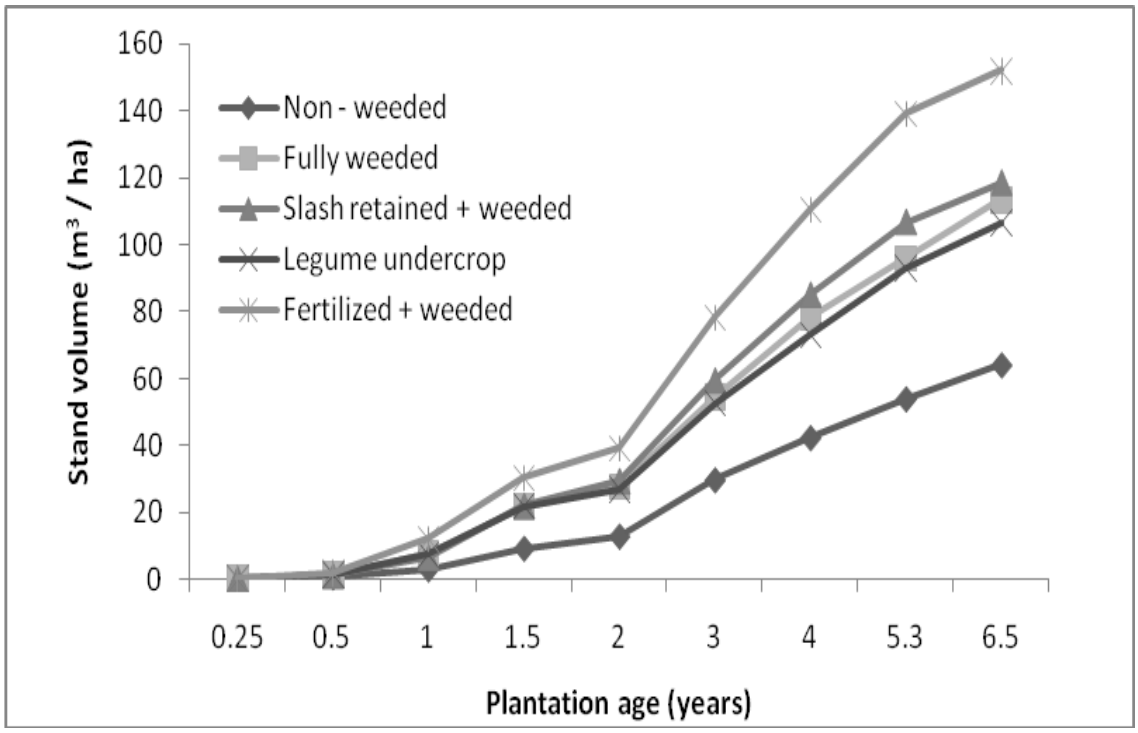
6. Trenching

Trenching in plantations has been shown to improve growth of rubber trees in Kerala through decreased soil erosion during the monsoon and increased water retention. However, trenching in eucalypt plantations during this study did not show significant effect on tree growth during the rotation although a trend for higher productivity was apparent at Surianelli (in plots with staggered trenching) and Vattavada (contour and staggered trenching) compared to non-trenching treatment. It can be concluded that trenching may become more important as the trees become water stressed later in the rotation or it may prove to be effective in water stressed sites on steep slopes.

Recommendation: Trenching in sloppy areas will control soil erosion and retain soil moisture at the site. Construct shallow contour trenches (1 m long, 0.3m wide and 0.3 m deep) in plantations raised on steep slopes.

Recommendations are also summarized in a booklet entitled 'Improving eucalypt plantation productivity in India' published by KFRI in June 2005.

55 a.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140
120
100
80
60
40
20
0
Stand volume (m³ / ha)
Non - weeded
Fully weeded
Slash retained + weeded
Legume undercrop
Fertilized + weeded
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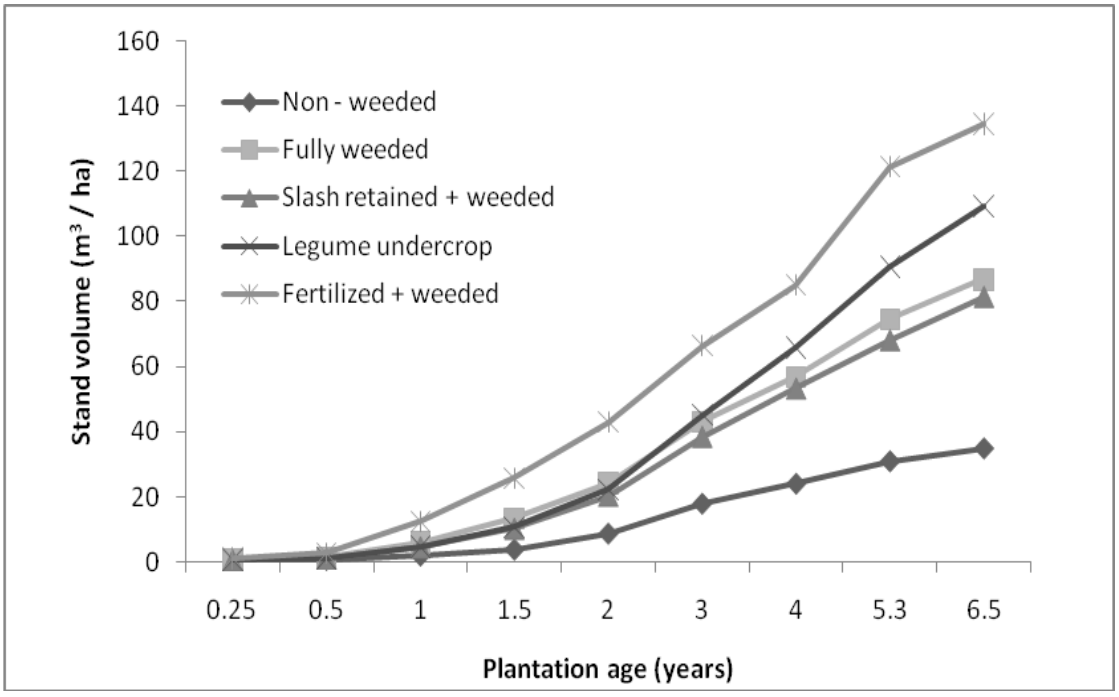
0.5
1
1.5
2
3
4
5.3
6.5
Plantation age (years)

55 b.


160
140
120
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80
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40
20
0
Stand volume (m³ / ha)
Non - weeded
Fully weeded
Slash retained + weeded
Legume undercrop
Fertilized + weeded
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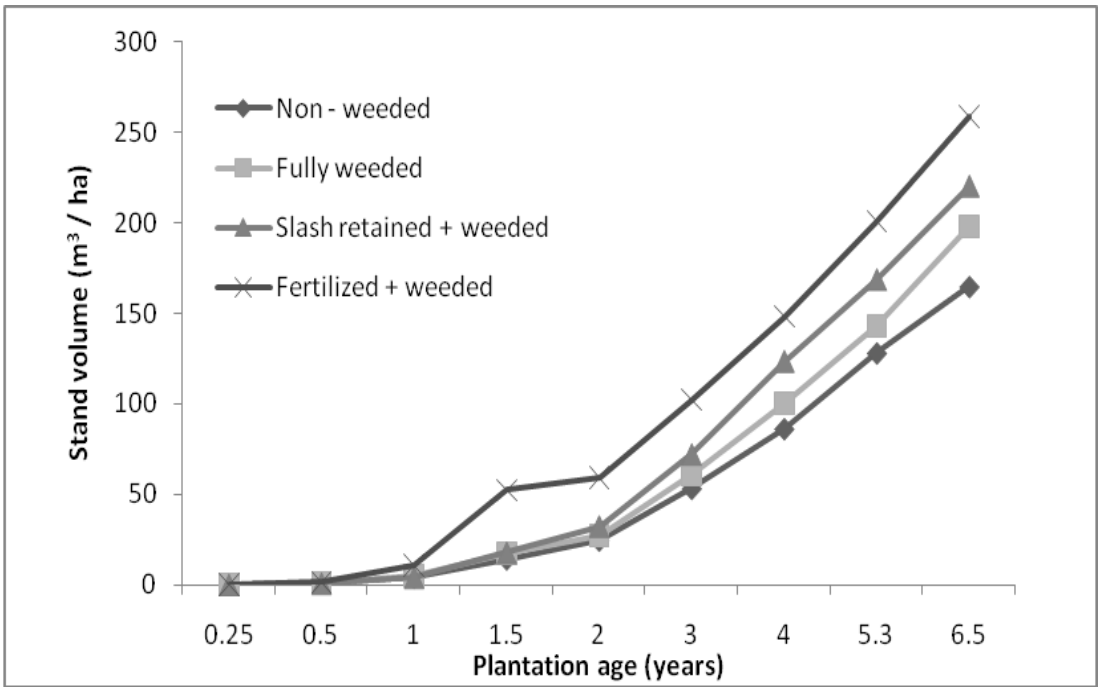
0.5
1
1.5
2
3
4
5.3
6.5
Plantation age (years)

55 c.



55 d.

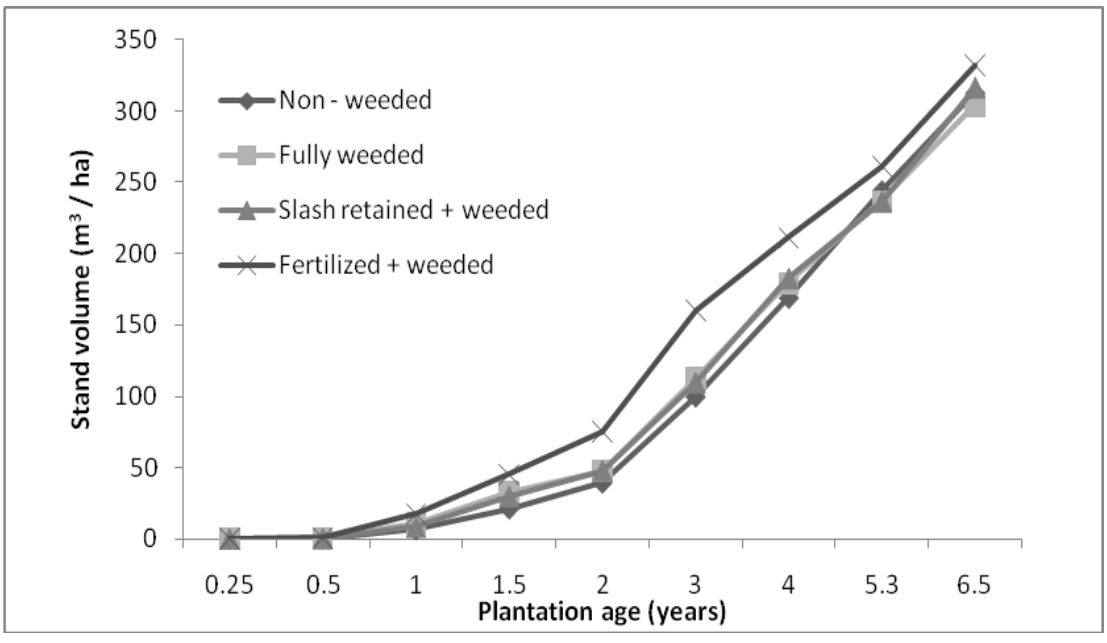


Fig. 55 a-d. Eucalypt plantation response to management across a range of silvicultural treatments, (a) Kayampoovam, (b) Punnala, (c) Suriannelli and (d) Vattavada. Statistical comparison within each site was not possible since treatments have been drawn from several experiments.

General recommendations: Seedlings may be planted in 30 x 30 x 30 cm pits and inward (hill ward) sloping platforms (50 x 50 cm) may be constructed. Where growth is optimum for *E. grandis*, 3 x 2 m spacing can be used. For *E. tereticornis*, spacing of 2.5 x 2.5 m may be tried instead of the current 2 x 2m.

Intensively managed eucalypt plantations can be harvested at the age of 5-6 years beyond which there may not be any significant improvement in tree volume.

9. Conclusions

Large increase in eucalypt productivity in Kerala could be achieved by use of good quality planting stock, timely and efficient weeding and judicious application of fertilizers wherever necessary (Fig. 55). Intercropping of legumes will help to enhance productivity at nitrogen deficient sites. Retention of harvest residues (slash) at sites will be useful to enrich soil nutrient stores in the longer term.

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Appendix 1. Summary of statistical analysis of tree growth in response to various treatments (P values) ANOVA (Genstat)

Measurement time/treatments	0.25 year	0.5year	1year	1.5years	2years	3years	4 years	5.3 years	6.5 years
OM manipulation									
K	<0.01	<0.01	ns*	ns	ns	ns	ns	ns	ns
P	<0.01	<0.01	<0.05	<0.05	ns	ns	ns	ns	ns
S	-	<0.01	<0.001	<0.05	<0.01	<0.05	ns	ns	ns
V	<0.01	ns	ns	ns	ns	ns	ns	ns	ns
N addition									
K	<0.05	<0.01	ns	ns	ns	ns	ns	ns	ns
P	ns	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01
S	-	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05	ns
V	<0.01	<0.01	<0.001	<0.001	<0.01	<0.001	ns	ns	ns
P addition									
K	ns	ns	ns	ns	ns	ns	ns	<0.05	<0.05
P	<0.01	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	<0.01	<0.05
S	-	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	<0.05	<0.01
V	<0.01	<0.01	<0.001	<0.001	<0.001	<0.001	<0.05	ns	ns
Weed control									
K	ns	<0.001	<0.001	<0.001	<0.001	<0.01	<0.01	<0.01	<0.01
P	ns	<0.05	<0.05	<0.05	<0.01	<0.01	<0.01	<0.05	<0.01
S	-	ns	ns	ns	ns	ns	ns	ns	ns
V	ns	<0.05	<0.05	<0.05	ns	ns	ns	ns	ns
Legume intercropping									
K	ns	ns	ns	<0.5	ns	ns	ns	ns	ns
P	ns	ns	ns	<0.05	ns	ns	ns	<0.05	<0.01
Thinning									
S	-	-	-	-	ns	<0.01	<0.01	<0.01	<0.05
V	-	-	-	-	<0.001	<0.01	<0.01	<0.01	<0.05
K- Kayampoovam; P – Punnala; S- Surianelli; V-Vattavada; ns* – Not significant									

Appendix 2. Tree volume (m^3ha^{-1}) in the OM plots at the four sites

Sites/ Year	0.5 year		1year		1.5 years		2 years		3 years		4 years		5.3 years		6.5 years	
Expts.	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Kayampoovam																
O	**0.67**	0.23	**4.06**	1.17	**14.92**	3.43	**20.23**	4.98	**45.81**	10.87	**71.88**	18.28	**92.12**	21.63	**113.63**	26.19
B	**0.39**	0.06	**3.18**	0.43	**12.07**	2.08	**16.62**	3.68	**37.63**	7.42	**55.64**	9.60	**72.59**	13.99	**87.36**	19.09
BS	**0.79**	0.15	**5.15**	0.83	**16.55**	1.93	**22.86**	4.29	**47.17**	7.78	**70.40**	11.80	**87.88**	15.39	**109.40**	17.87
DS	**0.62**	0.26	**4.40**	1.23	**16.70**	3.90	**24.24**	6.65	**51.48**	8.15	**76.32**	14.02	**94.76**	15.56	**116.54**	21.97
L	**0.79**	0.23	**5.03**	1.02	**18.07**	3.57	**24.67**	4.07	**51.20**	6.62	**74.62**	9.79	**90.62**	15.03	**111.45**	22.27
SS	**0.67**	0.09	**4.62**	0.69	**16.47**	1.20	**23.49**	0.94	**50.57**	0.90	**75.14**	2.74	**91.34**	3.99	**108.84**	3.00
Punnala																
O	**0.69**	0.10	**4.37**	0.59	**9.70**	1.31	**22.14**	1.76	**40.17**	3.88	**55.46**	9.83	**73.94**	14.31	**80.88**	14.58
B	**0.29**	0.11	**2.73**	0.81	**6.97**	2.55	**17.84**	5.82	**37.09**	12.17	**54.13**	17.24	**76.44**	27.88	**86.37**	31.39
BS	**0.86**	0.37	**5.44**	1.84	**12.19**	3.82	**25.55**	5.22	**46.68**	8.20	**61.87**	10.74	**86.20**	14.73	**96.38**	15.85
DS	**0.64**	0.12	**4.02**	0.72	**9.24**	1.45	**21.41**	3.32	**41.52**	7.73	**57.79**	12.49	**78.53**	21.20	**90.16**	25.16
L	**0.73**	0.18	**4.46**	1.18	**10.54**	3.60	**23.82**	5.25	**44.15**	9.04	**59.60**	9.90	**80.96**	15.37	**91.23**	14.87
SS	**0.58**	0.04	**3.90**	0.44	**8.95**	0.87	**21.14**	2.23	**39.03**	1.84	**53.84**	3.48	**69.60**	3.85	**78.16**	3.81
Surianelli																
O	**0.21**	0.03	**1.62**	0.48	**7.39**	2.09	**15.21**	4.12	**50.80**	14.70	**89.82**	22.87	**141.90**	30.60	**182.69**	39.75
B	**0.05**	0.02	**0.57**	0.17	**3.39**	1.42	**9.51**	3.92	**37.41**	10.83	**73.75**	18.72	**121.80**	25.59	**166.69**	31.44
BS	**0.34**	0.04	**2.55**	0.45	**10.08**	2.56	**18.40**	3.51	**51.73**	7.38	**84.47**	9.66	**127.34**	7.49	**170.71**	11.47
DS	**0.24**	0.06	**2.05**	0.48	**10.17**	1.98	**21.83**	1.31	**61.59**	2.57	**104.05**	7.25	**159.16**	11.68	**208.07**	16.14
L	**0.22**	0.09	**2.10**	0.86	**10.23**	4.74	**20.51**	8.30	**60.32**	21.06	**99.77**	30.36	**148.13**	40.70	**192.56**	48.20
SS	**0.27**	0.09	**2.39**	0.71	**12.82**	1.30	**24.94**	0.71	**69.71**	5.07	**108.11**	5.89	**152.37**	10.00	**199.47**	9.91
Vattavada																
O	**0.48**	0.13	**11.48**	4.64	**33.98**	13.17	**56.78**	17.88	**134.68**	37.30	**209.10**	53.47	**292.76**	60.84	**374.02**	75.33
B	**0.44**	0.06	**10.80**	3.41	**34.03**	9.61	**52.91**	10.67	**132.26**	29.57	**205.22**	45.43	**293.81**	47.46	**382.96**	60.13
BS	**0.94**	0.56	**15.14**	6.36	**39.50**	12.44	**56.36**	13.21	**137.11**	36.25	**207.93**	48.86	**291.40**	49.66	**354.58**	58.22
DS	**0.47**	0.10	**11.68**	2.78	**35.91**	6.12	**56.08**	8.37	**132.70**	15.61	**211.22**	14.27	**290.99**	16.37	**368.49**	20.89
L	**0.57**	0.16	**14.13**	2.15	**41.90**	4.02	**61.77**	3.50	**149.00**	14.22	**224.07**	22.53	**290.20**	47.29	**372.55**	39.00
SS	**0.51**	0.14	**12.92**	4.21	**38.68**	11.41	**56.35**	12.79	**127.63**	31.10	**189.70**	39.32	**259.07**	46.09	**328.42**	49.59

Appendix 3. Mean tree volume ($m^3\ ha^{-1}$) in different treatments at the time of harvest (6.5 years) at various sites (standard deviation in brackets)

Site/treatment	Kayampoovam	Punnala	Surianelli	Vattavada
OM treatment				
O slash	113.63(26.19)	80.88 (14.58)	182.69 (39.75)	374.02 (75.33)
SS	108.84 (3.00)	78.16 (3.81)	199.47 (9.97)	328.42 (49.59)
DL	116.54 (21.97)	90.16 (25.16)	208.07 (16.14)	368.49 (20.89)
L	111.45 (22.27)	91.23 (14.87)	192.56 (48.20)	372.55 (39.00)
BS	109.40 (17.87)	96.38 (15.85)	170.71 (11.47)	354.58 (98.22)
B	87.36 (19.09)	86.37 (31.39)	166.69 (31.44)	382.96 (60.13)
Legume intercropping				
Control	96.99 (13.50)	75.30 (9.51)	ne	ne
Mucuna	105.10 (23.32)	77.55 (17.45)	ne	ne
Pueraria	97.21 (20.71)	97.71 (12.96)	ne	ne
Stylosanthes	93.41 (45.81)	95.62 (6.80)	ne	ne
Thinning				
S 08	ne	ne	134.96 (38.85)	278.54 (77.82)
S 12	ne	ne	190.55 (27.10)	337.11 (62.27)
S 16	ne	ne	201.66 (38.24)	371.32 (50.11)
S 23	ne	ne	255.08 (50.88)	409.06 (22.94)
Weeding				
NW	64.20 (6.01)	34.78 (21.67)	164.75 (56.32)	312.79 (31.51)
SW	66.29 (22.44)	45.33 (16.91)	180.27 (56.83)	314.18 (48.80)
CW	113.57 (22.77)	86.95 (14.43)	197.87 (41.85)	304.01 (23.74)
P addition				
S	101.46 (25.54)	82.05 (19.62)	205.10 (32.68)	293.05 (17.45)
P1	155.35 (20.10)	97.78 (13.59)	281.15 (13.09)	344.11 (30.37)
P2	104.17 (29.85)	121.83 (23.56)	250.85 (25.38)	317.79 (52.43)
P3	122.36 (43.10)	132.41 (33.99)	278.90 (23.20)	336.05 (29.05)
P4	135.94 (33.02)	126.80 (35.12)	267.83 (26.93)	319.96 (62.51)
P5	118.70 (38.55)	131.93 (27.52)	270.68 (29.02)	350.48 (28.62)
N addition				
NoNp	97.94 (32.84)	63.06 (7.51)	188.92 (44.35)	336.58 (27.44)
N1	85.76 (37.21)	84.00 (30.14)	205.67 (43.22)	358.67 (19.72)
N2	99.51 (26.54)	102.54 (21.80)	233.00 (54.34)	369.63 (61.98)
N3	118.73 (25.11)	91.50 (17.38)	247.08 (40.76)	354.46 (34.74)
N4	127.12 (54.78)	130.38 (19.09)	244.48 (31.89)	371.17 (39.44)
N5	105.67 (10.60)	110.59 (16.24)	269.51(19.98)	370.08 (46.93)
Soil trenching				
NT	ne	126.39 (20.81)	146.98 (7.09)	285.86 (13.80)
CT	ne	136.41 (25.79)	148.21 (20.54)	303.17 (31.41)
ST	ne	126.65 (28.71)	180.85 (40.74)	294.00 (32.23)
ne –no experiment				

Surianelli – Plot Layout

85 DI	88 PV	89 DU	92 C
86 DU	87 C	90 PV	91 D I
100 PV	97 D I	96 C	93 DU
99 C	98 DU	95 D I	94 PV

Legume Experiment

49 P3	52 P1	53 P5	56 S	57 P5	60 P2
50 S	51 P2	54 P4	55 P3	58 P4	59 P1
72 P4	69 P5	68 P2	65 P1	64 S	61 P3
71 P1	70 S	67 P3	66 P5	63 P2	62 P4

P Experiment

25 N4	28 N1	29 N3	32 N2	33 No NP	36 N1
26 N2	27 N5	30 No NP	31 N5	34 N3	35 N4
48 N3	45 N4	44 N1	41 N4	40 N2	37 No NP
47 No NP	46 N5	43 N2	42 N3	39 N1	38 N5

N Experiment

1 BS	4 L	5 BL_3	8 BS	9 BL_2	11 B
2 B	3 BL_0	6 BL_2	7 BL_0	10 BL_3	12 L
24 BL_2	21 BL_3	20 BL_0	17 L	16 BL_2	13 B
23 L	22 B	19 BS	18 BL_3	15 BS	14 BL_0

OM Experiment

Weed Experiment

73 NW	82 SW	81 CW	101 NT	103 ST	106 CT
74 SW	83 CW	80 NW	102 CT	104 NT	105 ST
75 CW	84 NW	79 SW	111 ST	110 NT	107 CT
76 NW	77 SW	78 CW	112 CT	109 ST	108 NT

Trenching Experiment

Site History

This site was a grassland before planting with eucalyptus in 1978. The trees were clearfelled in 1991 after 3 rotations (1 seedling and 2 coppice). The site was replanted in 1991, and harvested in May 1998

Site Information

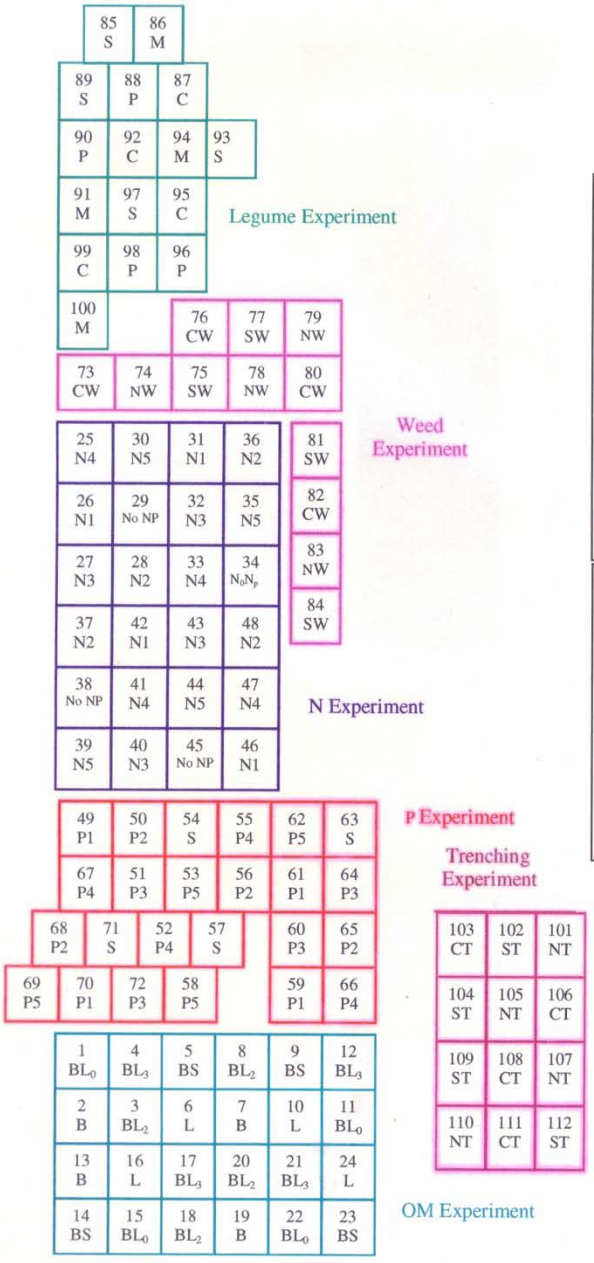
Altitude (masl):	1280
Slope (°):	4
Rainfall (mm/yr):	3000
Surface soil pH:	5.4
Surface soil OC:	4.78

Species: *E. grandis*

Soil texture:

Fine sandy light medium clay to sandy loam

Punnala Plot Layout



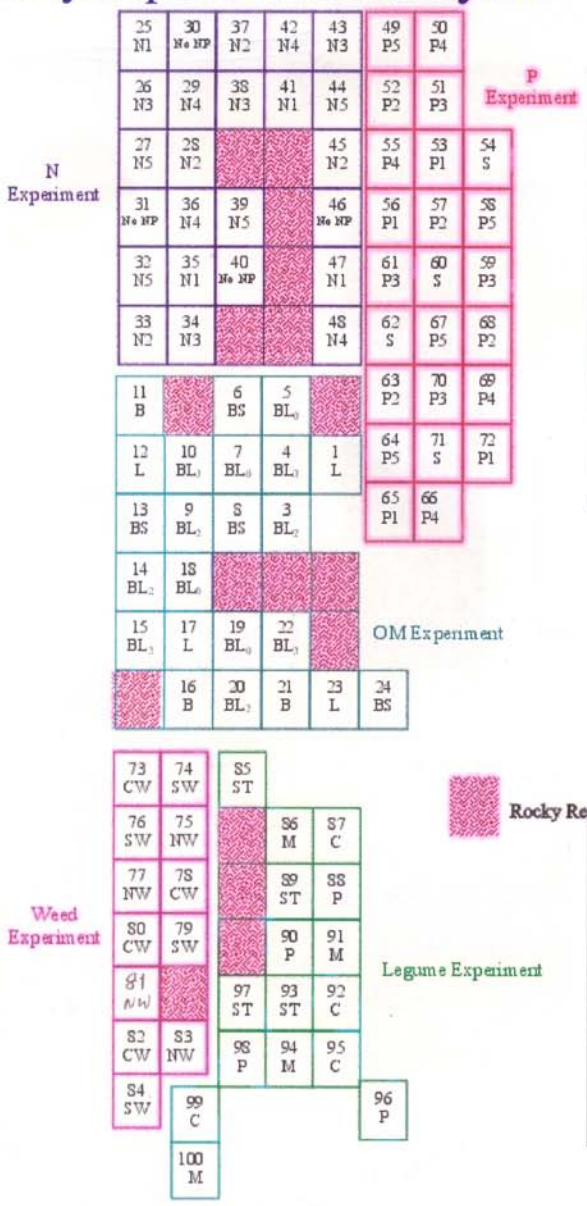
Site History

Originally a degraded moist deciduous forest before planting with eucalypts in 1977. The trees were first harvested in 1991. The first coppice growth (2R) was harvested in April 1998. The site has high humidity, high evaporation and low wind velocity.

Site Information

Altitude (masl):	150
Slope (°):	5
Rainfall (mm/yr):	2000
Surface soil pH:	5.3
Surface soil OC:	3.77
Species: *E. tereticornis*	
Soil texture:	
	Sandy loam to clay loam

Kayampoovam Plot Layout



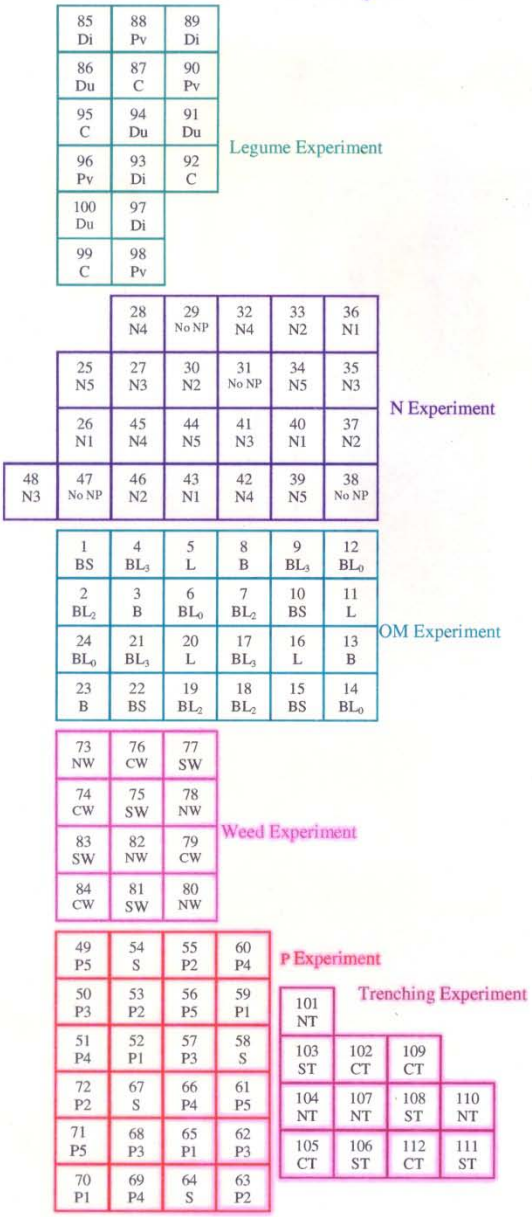
Site History

Originally a degraded moist deciduous forest where *E. tereticornis* was planted in 1977. The trees were first harvested in 1991. The first coppice growth (2R) was harvested in March 1998. The site is characterised by moderate rainfall (less summer rain), low humidity, high evaporation and high wind velocity

Site Information

Altitude (masl):	120
Slope (°):	10
Rainfall (mm/yr):	2700
Surface soil pH:	5.6
Surface soil OC:	2.81
Species: *E. tereticornis*	
Soil texture:	
Coarse sandy light clay to medium clay	

Vattavada Plot Layout



Site History

This site was planted with eucalypts in 1958 after clearing natural semi-evergreen (shola) forest. The trees were clearfelled in 1991 after 3 rotations of the crop and replanted in the same year. The first crop (seedling) was harvested in mid 1998.

Site Information

Altitude (masl):	1800
Slope (°):	15
Rainfall (mm/yr):	1800
Surface soil pH:	5.4
Surface soil OC:	3.97
Species: *E. grandis*	
Soil texture:	
Silty clay loam to medium clay	