

Nutrient Dynamics and Sustainability of Short Rotation *Eucalyptus camaldulensis* Plantations in Southern India

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Abstract

Though awareness of fertilizer application has increased over time, low nutrient use efficiency is still a major limiting factor for eucalyptus plantations in India. A study was carried out to understand the nutrient dynamics under different soil fertility conditions which was created by omission of macro nutrients (alone or in combination) and its comparison with balanced nutrient application (NPK). This study reveals two phases of nutrient accumulation. First, juvenile phase which was characterised by an increase in nutrient uptake till canopy closure followed by a phase when the nutrient demand declined. The nutrient partitioning in different tree components changed with age. The rate of accumulation of N and K decreased in order of Leaves > Bark > Branches > Wood > Underground parts. For P, Ca & Mg the rate of accumulation decreased in the order - Bark > Leaves > Branch > Underground parts > Wood. Balanced application of nutrients produced 44 per cent higher wood yield than trees grown on indigenous soil nutrient (-NPK) supply. This study conceptually and quantitatively compares the wide range of soil fertility regimes and explore the limitation of nutrients on plant and plant-soil-level. It explains the importance of efficient nutrient management for sustainability of plantations and ways to maximizing yield and improving soil nutrient balances at harvest.

Introduction

Indian paper industry ranks 15th globally in terms of size and accounts for 4% of the world's paper production. The per capita paper consumption in India is around 13 kg and is expected to grow at a CAGR of 6% (Annual report 2021), mainly due to growth in domestic demand, driven by the increase in literacy rate, growth in GDP and changes in lifestyle. The Indian National Forest Policy in 1988, proposed a complete ban on unregulated felling of trees in reserved forests (Mili and Bhaskar, 2016) which forced the pulp companies to look for alternatives to meet the ever increasing demand for pulp wood. This change in policy lead to rapid development of eucalyptus plantation forestry during the late 1990's. Introduction of clonal technology coupled with government and private investments helped in rapid expansion of eucalyptus based agro forestry systems (Ravindranath and Hall, 1994, Luna, 2009). Massive expansion of clonal eucalypt plantations on 4.8 m ha. (Davidson, 1993) which was about 71 per cent of total trees planted, gave rise to several issues of sustainability. The average productivity of these plantations was less than $10 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ and continued to declining with each rotations (Chaturvedi, 1973; Venkatesan et al., 1986; Lal 2003, Varghese et al., 2008 and Paiare Lal, 2010). Three consecutive harvests from coppice crops with minimal inputs reduced productivity and soil health, impacting the sustainability of these plantations (Kulkarni & Lal, 1995, Kulkarni, 2001 and Ginwal, 2014). Land use and soil productivity are important aspects for sustained production in fast growing plantations (Binkley and Stape, 2004; Nambiar 2006) but are generally ignored. The fact that fast growing short rotation eucalyptus plantations with high rates of nutrient export (Sankaran et al., 2006) could affect the ability of the site to support tree growth in successive rotations, was never considered. As productivity of a given species is the function of climate, soil fertility and management practices, a negative balance of 9.7 M t of soil nutrients (Tondon 2007) in Indian soil poses a major threat to sustainability. Long term studies have shown that effective management practices aimed at developing synergy between demand and supply of nutrients improves soil for sustainable productivity (Nambiar 1996, Nambiar and Sands 2013 and Nambiar and Harwood, 2014).

Fast growing short rotation eucalyptus plantations exert high pressure and depletes soil nutrient reserves. The magnitude of impact grows when the land available for these plantations are prone to further degradation by poor and exploitive site management practices like slash burning. These practices leave very low amounts of bioavailable nutrients for successive rotations, affecting the sustainability of the ecosystem. Knowledge of yield response to applied nutrients and effect on soil nutrient reserves after harvest will be critical in ensuring sustained gain in productivity. Studies providing information on the indigenous soil nutrient supply system and uptake by short rotation *Eucalyptus camaldulensis* clonal plantations in India are limited. This paper aims to study the (1) nutrient uptake and age wise accumulation in different plant parts, (2) soil nutrient budgeting and utilization efficiency of applied nutrients, (3) compare the balance between the input and output of nutrients and (4) economics of sustainable intensification of short rotation *Eucalyptus camaldulensis* plantations in southern India.

Materials And Methods

Study Site

The study was carried out at Mettupalayam (11°26' 23.35" N and 78°29' 20.79" E) in the foothills of Nilgiri hills in Southern India at an elevation of about 314 m above mean sea level. The site receives 700 mm annual rainfall with more than 50 per cent of the rainfall received during the north-east monsoon season (October to November). The maximum temperature is 38°C during summer and the

lowest temperature is 20°C during winter. The mean monthly weather parameters of the growing seasons (4 years) are presented in Fig. 1.

Study Material And Experimental Setup

A commercial *Eucalyptus camaldulensis* clone popular in the region was used for the study under-rainfed condition. Eight macro nutrient (NPK) treatments comprising (a) balanced fertilizer (NPK) application (b) nutrient omission treatments, omitting one or combinations of nutrients (-N, -P, -K, -NP, -NK, and -PK) and (c) control (-NPK) were applied to trees planted in five replications of randomized complete blocks of 25 trees planted at a spacing of 3 m between rows and 1.5 m within row. Nutrients N, P and K were applied at the rate of 200, 100 & 100 kg ha⁻¹, respectively in three equal splits, (1) one month after planting (establishment phase), (2) cessation of monsoon in November and (3) before canopy closure (1.5 years of age).

Soil Sampling

Soil samples were collected from each treatments tested from 10 cm interval up to a depth of 140 cm. using a core sampler (8 cm diameter) before start of the trial and after completion of each year until harvest (total 5 samples). Samples were collected and prepared as per standard procedure and a representative sample were used for analysis of soil physio chemical properties. Samples were analysed for soil reaction pH (Dhyan et al., 2005), Organic carbon (Walkely and Black 1934), available nitrogen (alkaline permanganate method, Subbiah and Asija 1956), and available phosphorus, Olsen- P, (Olsen et al., 1954), available potassium using flame photometer. Zinc, calcium and magnesium by atomic absorption spectroscopy (Dhyan et al., 2005). Physio chemical properties and initial soil nutrient status of the trial area is presented in Table 1.

Table 1
Soil profile of the experimental site

Soil Depth (cm)	Particle size distribution				OC (%)	pH	Ec (1:2.5) suspension
	Sand (2-0.05 mm)	Silt (0.05 – 0.002 mm)	Clay (< .002 mm)	Coarse fragments (> 2mm) % in whole soil			
0 – 10	79.3	6.4	14.3	17	0.35	8.8	0.1
10 – 20	66.7	5.5	27.8	17	0.32	8.9	0.1
20 – 30	41.6	6.8	51.6	36	0.53	8.9	0.1
30 – 70	45.0	4.4	50.6	54	0.40	8.8	0.1
70 – 120	54.1	7.4	38.1	50	0.10	8.5	0.1
120–140	70.6	4.1	25.3	63	0.18	8.2	0.2
Available Nutrients							
Nutrient	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (ppm)	Mg (ppm)	Zn (ppm)	Fe (ppm)
0 – 10	175.6	17.8	152.1	921.1	68.9	10.2	86.3
10 – 20	169.5	15.5	135.5	850	60.5	9.5	55.5
20 – 30	155	15	132	850	70.2	11.5	40.5
30 – 70	150	14	127	850	70.5	11	25.5
70 – 120	145	14	127	850	70.5	11.5	20
120–140	140	12	125	850	70.5	11.5	20

Measurements And Data Collection

Growth

Tree growth (height and diameter at breast height -DBH) and survival was evaluated at 12, 24, 36, and 48 months after planting. The productivity gain was calculated to study the response of the clones to nutrient treatments.

Total Biomass, Nutrient Uptake And Nutrient Use Efficiency

Ten trees from each treatment (two trees per replication) was harvested every year (1–4 years) for estimation of biomass produced. Trees were divided into the different components - leaves, wood, bark, branches, roots and fresh weight was recorded. Samples were dried till they attained constant weight to record dry biomass of each component. A representative sample of each component was ground, and passed through a 60 mm mesh sieve for estimation of total N, P, K, Ca and Mg accumulation in each component, and it was used for calculation of total uptake by tree. Total nitrogen was determined by volumetric estimation after mineralization and distillation as per Kjeldahl method (Bremner 1960), while P, K, Ca and Mg were determined after wet oxidation (Dhyan et al., 2005). Phosphorus was determined by Vanadomolybdophosphoric acid colorimetric method Ca & Mg were determined by atomic absorption spectroscopy and K by flame emission spectroscopy (Thandon, 1995).

Nutrient Use Efficiency

Agronomic efficiency (AE), was estimated to find out the optimum nourishment needed for providing economically utilisable wood from different fertilizer treatments, based on the total uptake of nutrients and nutrient utilization for wood production. AE was estimated at the end of the rotation age (4years) as the yield increase per unit of nutrients applied, as given below.

$$AE = (Y - Y_0)/F$$

Where Y – Crop yield with applied nutrients (kg/ha),

Y_0 – Crop yield (kg/ha) of control treatment (no nutrients) and

F – Amount of nutrient applied (kg/ha).

Soil Nutrient Balance Sheet And Economics Of Applied Nutrients

The soil nutrient balance sheet was calculated at the end of the rotation age, as the difference between the nutrients applied (treatments added in the form of fertilizers) and the nutrients removed by the trees. The actual nutrient balance sheet was estimated as the difference between the initial and the final soil test values. Nutrient inflow through runoff were not considered for the computation. Benefit-Cost (B:C) ratio was estimated at the end of the rotation age (four years) to evaluate the overall value of plantation with the cost of raising the plantation under different nutrient management regimes. The prevailing sale price of produce and expenditure for cultural operations and fertilizers were used for calculation of monetary returns and benefit.

Data Analysis

The data were subjected to analysis of variance by using the software Statistical Package for Windows. One-way analysis of variance (ANOVA) was conducted to determine the effect of different nutrient treatments on stand growth, wood yield, dry biomass, and use efficiency of nutrients. Before performing ANOVA, data normality and the homogeneity of variances were tested. Statistically significant differences were designated at $p < 0.05$.

Results

Tree Growth

Survival was more than 95% in all nutrient combinations tested. Nutrient management had significant effect on tree growth during the initial phase of growth and development (1st year) and this trend continued till the rotation age (Table 3). Trees under balanced nutrient

application (NPK) produced maximum growth i.e. 27 & 67% more height and DBH, than the tress under control (-NPK) plot at four years of age. Productivity was significantly affected when major nutrients where omitted either alone or in combination. Comparison of mean annual increment (MAI) in stands when one nutrient was omitted (-N, - P or -K), showed that the highest growth reduction (13.8%) was observed due to omission of nitrogen followed by omission of potassium (-K, 22.9%) and Phosphorus (-P, 24.5) application. .Omission of combination of two nutrients (-NP, -NK, and -PK) also affected MAI. MAI was lowest (10.5) when nitrogen and potassium (-NK) were omitted, followed by omission of nitrogen and phosphorus (-NP, 13.0), and phosphorus and potassium (17.3).

Wood yield at the end of the rotation (4 years) also followed the same trend as that of growth parameters (Table 3 and Fig. 5). Maximum wood yield was obtained in stand which received balanced nutrient application (59 t ha^{-1}) which was 44% more than the stands which did not receive any fertilizer application (33 t ha^{-1}). Omission of nutrients alone or in combination from the balanced nutrient application significantly ($P < .001$) affected the wood production. Maximum decline in wood yield was noted when nitrogen and potassium in combination (-NK) were omitted (39%) followed by omission of nitrogen and phosphorus (-NP) 38% and phosphorus and potassium (-PK) 28%. Omission of any one nutrient from the balanced application also resulted into loss of productivity viz. omission of nitrogen (-N) resulted into loss of productivity by 28%, while omission of P and K reduced wood yield by 14 and 24% respectively in comparison of wood produced under balanced nutrient application.

Nutrient Up Take:

Total Nutrient Allocation and Uptake

Total Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg) accumulation in different parts of the tree and total nutrient uptake by *Eucalyptus camaldulensis* under different nutrient management practices are presented in Table 2. Comparison of average biomass produced and nutrient accumulation in different parts at 4 years of age revealed that wood biomass production was highest (58.6%) but the nutrient accumulated was only 31.2% of the total nutrients accumulated in tree. The biomass produced by the leaf decreased from 1 to 4 years (32, 23, 15, and 14%) while total nutrient accumulation in leaf accounted for 56, 59, 56 & 45%, respectively of the total nutrient uptake by the tree. The accumulation of nutrients in below ground parts was quite less (< 7%) in comparison to accumulation in above ground parts.

Nutrient application (treatments) significantly ($P < 0.05$) affected the nutrient accumulation in *Eucalyptus camaldulensis*. At two years (age of maximum nutrient uptake), accumulation of nutrients were in the order $N > K > Ca > Mg > P$ in all the nutrient treatment evaluated. Among the individual nutrients evaluated, uptake of nitrogen was highest (64.3%). Highest nutrient uptake was observed in stands which received balanced nutrient (NPK) application ($393, 33.7, 124.2, 47.7 \& 27.9 \text{ Kg N, P, K, Ca \& Mg ha}^{-1}$) while stands which did not receive any external nutrient application (control) trees could mine 144, 13, 30, 17 and 10 Kg N, P, K, Ca and Mg ha^{-1} respectively, from the soil reserves during the same period. Comparisons of nutrient uptake due to omission of any one of the major nutrient from the balanced nutrient application shows that the omission of N resulted into reduced uptake of nutrients in tune of 23, 35, 37, 37 and 37% of N, P, K, Ca and Mg respectively, which was followed by omission of K and P nutrients. While omission of combination of two nutrients Viz. -NP, -NK or -PK revealed that the omission of nitrogen and potassium (-NK) resulted into lowest uptake which was 64, 51, 69, 50, 47% N, P, K, Ca & Mg less in comparison to uptake under balanced nutrient application and this was closely followed by omission of nitrogen and phosphorus (-NP), while omission of phosphorus and potassium (-PK) had least effect on uptake of nutrients. Similar trend in uptake of nutrients were observed in all other stages of growth evaluated (Table 2).

Ca and Mg accounted for < 10% of the total nutrients accumulated in the tree at 2 years of age. Uptake of these two nutrients varied very little between different stages of growth, even though the areal dry biomass production increased from $16\text{--}54 \text{ t ha}^{-1}$. Uptake of the half of the total Mg (90 kg ha^{-1}) accumulated by the trees during the entire rotation age happened before canopy closure, while uptake of calcium continued till late stages of development and it did not show significant change in all the stages evaluated. The rate of accumulation of calcium in different components of the trees followed Bark > Branch > leaf > wood (Fig. 4).

Distribution Of Nutrients In Tree Components

The nutrient content and partitioning into different tree components, and changes with age are presented in Table 5. Among the different components, concentration of nutrients were highest in leaves followed by branches and bark, and lowest in wood and below ground portion. There is a close relationship between the biomass production and nutrient content ($r = 0.97$) in above ground biomass

components. At the age of two years nutrient accumulation was at the peak with leaves accounting for > 60%, followed by wood (16%), branches & bark (9%) and underground portion (6%). The accumulation pattern of nutrients in different components of the tree can be summarized as below.

For N and K was in order of Leaves > Bark > Branches > Wood > Underground parts, for P, Ca & Mg the order was Bark > Leaves > Branch > Underground parts > Wood. The pattern of partitioning of nutrients in different nutrient treatments was more or less the same. Therefore, we restrict our discussion to observations for the balanced nutrient treatment.

Age And Accumulation Of Nutrients

The age had significant effect ($P < 0.01$) on the accumulation of all the nutrients in the aerial components of the trees (Table 2). The nutrient uptake increased sharply during the initial growth phase and reached the maximum at two years of age, which coincided with canopy closure, thereafter uptake of all nutrients reduced gradually with the lowest at the age of four years.

The leaf showed decrease in concentration of all the nutrients after canopy closure, still the percentage of total leaf nutrient concentration were always higher than all other components. The nutrient concentration in leaves was always close to 50% of the total nutrients accumulated by trees during the entire rotation. In the second year (age of maximum nutrient uptake) out of the total nutrients accumulated in the tree, N occupied the major share i.e. 63% followed by K (20%), Ca (8%), P (5%) and Mg (4%).

Total nutrient content in the wood was always in range of 16–30% of the total nutrient accumulated in the tree, even though the wood biomass increased from 48, 54, 67, & 70% from 1–4 years of age. Wood accounted for only 22–35% N, 9–28% P, 14–19% K, 1.7–6% Ca and 1.5–4.6% of total nutrients at one to four years of age, which is approximately 38–72% lower than the nutrients accumulated in leaves. The age related decline in nutrient concentration in per kg of wood was clearly observed during 1–4 years of age. After completion of first year, 7.3 gm. of total nutrients was observed in one kg of wood produced while this reduced to 6.7, 3.2 and 3.1 gm. kg^{-1} of wood during 2nd to 4th year. Age induced changes in nutrient concentration in bark also changed age. The total nutrient content in the bark increased from 9–12% of the total nutrient uptake of the tree from 1–4 years of age. The nitrogen content in bark saw more than 100% increase when compared between uptake in first year and 4th year (13.4–30.5 kg ha^{-1}). Potassium and magnesium content in bark did not show much effect of age as it was almost stable throughout the age studied. Magnesium content in the bark was always close to 5 kg ha^{-1} indicating continuous uptake of this element during the growth phase studies. Calcium concentration in bark ranged between 0.15–31.8% of the total nutrient uptake. There was 21 per cent reduction in Ca concentration between second to fourth year and its concentration was more in stem wood.

Agronomic Efficiency

Agronomic efficiency (AE), assesses the impact of applied nutrients on biomass production and this too was significantly affected due to omission of one or more nutrients from the balanced nutrient application ($p < .001$). Highest efficiency of the applied nutrients (63%) was recorded for balanced nutrient application followed by omission of one nutrient and minimum use efficiency was observed when two nutrients in combination were omitted from the balanced dose of nutrient application (Fig. 3). Efficiency of applied nutrients was not uniform when two nutrients in combination were omitted, for example when nitrogen and potassium (-NK) were omitted use efficiency reduced to 31% while omission of phosphorus and potassium (-PK) the nutrient use efficiency was 47%. Omission of N alone resulted in reduced use efficiency (47%), while phosphorus and potassium omission resulted in use efficiency of 59 and 40%, respectively.

Soil Nutrient Balance Sheet

The estimated input-output ratio of nutrients and soil nutrient balance at harvest is presented in Figs. 7 & 8. The soil nitrogen balance sheet, revealed a positive soil balance under application of balanced dose of fertilizers (7.7 kg ha^{-1}) while all other combinations, resulted in negative soil nitrogen reserves. Lowest nitrogen reserve was observed under no fertilizer application (control – 45.8 kg ha^{-1}). Omission of nitrogen along with phosphorus (-NP) and potassium (-NK) resulted in negative soil nitrogen balance to the tune of -25.1 and -31.1 kg ha^{-1} , respectively. A negative Phosphorus balance sheet was recorded in all the fertilizer combinations. Maximum depletion of soil phosphorus reserves was observed in the control treatment (-7.9 Kg ha^{-1}) while its level remained as the initial soil test values (0.5 Kg ha^{-1}) in balanced nutrient application.. This trend was similar in soil potassium levels also, lowest soil K reserves was

recorded in control (-69.2 Kg ha^{-1}), while a positive balance sheet (2 kg ha^{-1}) was observed with balanced nutrition. Omission of nutrients resulted in negative balance sheet of potassium reserves ranging from -3.2 to -21.6 Kg ha^{-1} .

Benefit - Cost Ratio

Figure 6 presents the merit of different nutrient management practices by comparing the benefit with the cost involved. Balanced nutrient application had a significantly higher B: C ratio (2) compared to the control (1.1). The profitability reduced when nutrients N (1.2), P (1.7) and K (1.4), and in combinations, were omitted.

Table 2
Effect of nutrient management practises on total biomass, allocation into different tree parts and uptake of major nutrients by
Eucalyptus camaldulensis at different growth stages.

Treatments	Biomass (Kg/ha)		Biomass allocation (kg/ha)					Total Up take (kg/ha)				
	Above Ground	Under Ground	Total	Wood	Leaves	Bark	Slash	N	P	K	Ca	Mg
Year 1												
0	5981.7	1295.3	7277.0	2877.0	2413.9	304.3	386.5	65.4	5.9	13.1	6.3	5.3
SD	742.6	357.4	998.4	48.1	40.4	5.1	6.5	8.1	0.7	1.6	1.1	1.3
-N	8493.2	1839.1	10332.3	4152.4	3390.4	439.2	511.1	67.7	7.6	20.3	19.7	11.2
SD	739.2	357.0	990.3	48.9	39.9	5.2	6.0	5.9	0.7	1.8	1.9	2.2
-P	13653.0	2956.5	16609.5	6675.2	5372.5	706.0	899.2	160.1	13.2	41.7	29.7	18.0
SD	747.1	338.3	986.9	48.9	39.4	5.2	6.6	8.8	0.7	2.3	5.5	5.8
-K	12214.6	2645.0	14859.6	5972.0	4805.9	631.6	805.1	145.9	9.7	42.2	19.3	14.9
SD	753.1	367.1	1008.9	48.9	39.3	5.2	6.6	9	0.6	2.6	2.3	3
-NP	7602.8	1755.1	9357.8	3717.1	3038.3	393.2	454.1	62.6	7.4	16.9	13.5	9.1
SD	745.7	352.4	994.9	47.6	41.0	5.0	6.4	6.2	0.7	1.7	1.3	1.2
-NK	11849.3	1646.3	13495.6	5793.4	4662.5	612.8	780.7	137.4	9.1	34.2	17.1	13
SD	749.9	363.3	1012.9	48.9	40.0	5.2	6.0	8.5	0.6	2.1	2.6	2.1
-PK	8105.0	2565.9	10670.9	3858.5	3320.6	408.1	517.9	66.6	7.6	17.5	18.1	10.6
SD	732.2	356.5	1010.2	48.9	39.3	5.2	6.6	6.1	0.7	1.6	1.4	1.9
NPK	14726.0	3188.8	17914.8	7199.8	5793.7	761.5	971.0	178.6	15.1	54.5	32.4	18.8
SD	740.1	419.6	1045.6	48.9	39.3	5.2	6.6	9.0	0.8	2.7	5.5	6.6
Year 2												
0	12313.9	2440.7	14754.5	6388.5	3429.4	1678.0	817.9	144.4	12.9	29.8	16.6	9.8
SD	835.2	319.5	1148.0	53.4	28.7	14.0	6.8	12.6	1.9	9.5	4.3	1.2
-N	24065.2	5056.8	29122.0	12655.1	6650.1	3130.3	1629.7	303.5	21.9	77.9	30.1	17.5
SD	585.0	462.8	1019.4	53.4	28.1	13.2	6.9	13.3	5.6	9.6	6.2	2.3
-P	27637.8	5838.0	33475.8	14690.6	7539.8	3557.5	1849.9	353.1	29.2	95.1	50.2	26.7
SD	452.5	479.9	870.5	53.8	27.6	13.0	6.8	13.2	2.0	10.5	10.2	5.1
-K	24617.6	4890.1	29507.6	13118.5	6699.2	3147.0	1652.9	322.4	21.1	96.1	30.3	21.1
SD	575.9	444.1	955.6	53.7	27.4	12.9	6.8	13.4	2	11.5	5.1	1.9
-NP	17315.2	3278.3	20593.5	9138.6	4812.1	2216.8	1147.8	149.2	17.2	46.3	31.1	16.5
SD	693.4	337.1	971.6	53.8	28.3	13.1	6.8	13.1	1.4	8.3	6.1	3.3
-NK	15565.3	2992.7	18558.0	8165.3	4341.3	2026.4	1032.4	137.8	16.4	38.5	23.8	14.7
SD	613.8	331.8	929.4	53.7	28.6	13.3	6.8	14.0	1.2	7.9	4.2	1.7
-PK	16538.9	3210.2	19749.1	8704.8	4563.8	2171.1	1099.1	146.8	17.3	39.8	32.7	17.2
SD	595.0	328.8	880.8	53.7	28.2	13.4	6.8	14.3	1.2	8.7	6.1	2.2
NPK	29828.3	6227.7	36056.0	16051.4	8151.9	3680.7	1944.3	393.3	33.7	124.2	47.7	27.9

Treatments	Biomass (Kg/ha)			Biomass allocation (kg/ha)				Total Up take (kg/ha)				
	Above Ground	Under Ground	Total	Wood	Leaves	Bark	Slash	N	P	K	Ca	Mg
SD	446.5	511.5	894.9	54.5	27.7	12.5	6.6	13.2	2.4	16.9	7.5	2.2
Year 3												
0	25091.1	6471.8	31562.8	17896.5	4492.3	1887.6	814.6	130.0	10.5	24.8	16.5	8.2
SD	598.5	581.4	874.3	71.3	17.9	7.5	3.2	8.7	1.8	4.4	5.2	3.1
-N	41656.9	12812.0	54468.9	28477.4	7962.5	3603.3	1613.6	269.8	16.8	72.9	29.0	14.6
SD	712.3	627.8	935.8	69.1	19.3	8.1	3.5	30.6	1.9	11.5	6.5	3.4
-P	44943.8	14759.1	59702.9	30107.1	8866.4	4111.1	1859.3	288.3	24.9	90.1	43.5	23.2
SD	996.8	912.5	1093.6	67.0	19.7	9.1	4.1	16.0	1.5	14.1	11.2	8.3
-K	42253.5	13206.2	55459.7	28724.9	8158.7	3706.5	1663.4	286.6	17.9	91.1	31.9	18
SD	1048.1	673.5	872.4	68.0	19.3	8.8	3.9	26.6	1.6	14.3	5.1	6.1
-NP	31888.2	8766.9	40655.1	22249.1	6018.5	2516.8	1103.7	131.4	13.9	34.8	29.4	13.5
SD	592.9	518.9	360.0	69.8	18.9	7.9	3.5	12.0	1.0	4.4	7.1	3.4
-NK	30210.9	8223.9	38434.8	21131.0	5675.1	2369.4	1035.3	123.3	13.5	33.5	22.0	12.1
SD	1328.2	472.7	1713.7	69.9	18.8	7.8	3.4	11.3	1.0	4.5	3.5	2.1
-PK	32621.1	9185.9	41807.0	22534.9	6300.2	2629.4	1156.6	133.8	14	41.3	32.2	14.1
SD	1721.2	463.4	1791.4	68.4	19.1	8.7	3.9	10.3	1.9	4.2	8.2	3.2
NPK	48031.9	15918.6	63950.5	32235.6	9792.6	4389.1	1614.6	348.1	28.7	119.2	45.6	24.4
SD	1354.1	371.8	1440.7	67.1	20.4	9.1	3.4	23.8	1.1	15.3	6.5	4.1
Year 4												
0	30976.1	6421.9	37398.1	22296.5	5354.9	2243.3	1081.4	126.1	11.5	20.5	15.2	7.0
SD	514.3	159.0	371.8	74.5	17.9	34.9	3.6	14.5	1.3	2.9	3.9	0.9
-N	47416.4	9165.4	56581.7	35066.5	7628.5	3185.4	1535.8	131.3	15.0	31.8	29.5	13.7
SD	692.8	260.8	509.0	74.6	18.0	34.8	3.6	17.1	1.5	2.4	4.9	2.8
-P	70705.8	13172.6	83878.4	50795.3	12417.3	5072.5	2420.7	283.5	25.9	65.3	41.8	19.6
SD	1209.1	372.3	1053.4	74.4	18.2	34.4	3.5	17.6	3.1	6.9	4.3	3.2
-K	63256.5	14767.0	78023.5	45438.8	11119.1	4535.5	2163.1	281.9	18.9	66.4	30.5	15.9
SD	716.6	497.2	418.6	74.4	18.2	34.4	3.5	27.7	4.2	9.6	6.8	2.5
-NP	39356.1	8798.5	48154.7	28409.2	6650.7	2886.4	1409.8	121.4	14.5	26.4	20.7	11.2
SD	918.6	246.9	700.4	74.7	17.4	34.9	3.7	16.4	1.8	5.2	5.8	2.0
-NK	40887.7	8183.6	49071.4	29273.1	7047.5	3070.6	1496.4	130.2	14.9	27.5	26.7	13.0
SD	688.9	229.2	500.7	74.7	17.5	35.3	3.7	14.7	2.2	3.5	2.6	1.5
-PK	51956.5	12805.7	64762.2	34658.5	10813.0	4393.2	2091.8	265.3	17.8	53.7	27.6	13.3
SD	705.5	418.1	966.2	74.4	18.3	34.3	3.5	32.4	4.7	12.9	6.7	2.8
NPK	72341.2	15906.4	88247.6	50931.8	13573.7	5543.3	2292.4	345.0	29.7	85.2	43.9	20.3
SD	782.7	438.4	730.8	74.6	18.4	34.8	3.1	27.5	3.7	9.3	6.9	2.0

Table 3
Effect of nutrient treatments on growth and wood yield in *Eucalyptus camaldulensis*

Age (year)	Parameters	0	-N	-P	-K	-NP	-NK	-PK	NPK	SD
1	Height (m)	4.1	4.3	5.5	5.3	4.2	4.2	5.1	5.7	0.85
	DBH (cm)	4.8	5.7	6.3	6.1	5.3	5.5	6.0	6.5	0.98
	Wood Yield (t ha ⁻¹)	3.6	5.2	8.3	7.5	4.6	4.8	7.2	9.0	
	MAI	5.4	8.2	12.8	11.6	6.7	10.8	7.4	14.3	
2	Height (m)	6.9	7.4	8.8	8.6	7.1	7.3	8.4	9.5	0.92
	DBH (cm)	6.3	7.7	9.5	9.2	6.9	7.6	7.2	10.0	1.83
	Wood Yield (t ha ⁻¹)	8.0	15.8	18.4	16.4	11.4	10.9	10.2	20.1	
	MAI	8.4	12.8	23.0	21.4	9.8	15.8	12.1	27.5	
3	Height (m)	9.9	10.1	11.0	10.7	10.1	10.1	10.7	11.7	0.63
	DBH (cm)	7.4	9.3	11.4	11.1	8.3	9.1	8.7	12.1	2.24
	Wood Yield (t ha ⁻¹)	22.4	35.6	37.6	35.9	27.8	28.2	26.4	40.3	
	MAI	10.5	17.0	27.9	25.9	13.6	19.6	16.4	33.0	
4	Height (m)	10.1	10.6	12.2	11.9	10.1	10.5	10.4	12.9	1.09
	DBH (cm)	7.4	9.5	11.7	11.5	8.4	9.3	9.0	12.4	2.31
	Wood Yield (tha ⁻¹)	33.3	42.8	51.1	45.4	36.5	42.8	37.0	59.9	
	MAI	8.1	13.8	24.5	22.9	13.0	10.5	17.3	28.8	

Discussion

Sustainable practices particularly efficient nutrient management in short rotation eucalyptus plantations not only helps to increase productivity of standing crop but also maintain soil health to support successive rotations. We compared the loss in productivity due to absence of major nutrients alone or in combination (-N, -P, -K, -NP, -NK, -PK & -NPK) in comparison to a balanced nutrient application (NPK) schedule. *Eucalyptus camaldulensis* responded very significantly to lack of available nutrients.

Growth

The poor growth in nutrient deficient stands indicates that soil fertility is a major factor in productivity of eucalyptus Tran and Tremblay (2000); de Aguiar Ferreira and Stape (2009) and Crous et al., (2011). Application of nutrients plays important role in survival and growth of the plantation by creating favourable soil chemical properties for root establishment (Viera et al. 2016). Productivity of plantations can be increased by early nutrient application in soils with low or high natural fertility (Brown et al. 1997 and Gonçalves & Barros, 1999). In the present study mean annual increment peaked at the age of 3 years and declined later in all nutrient treatments, reflecting the decline in foliar efficiency. The decline in net production is associated with increase in ratio of annual respiration to annual photosynthesis with increasing stand biomass (Rayan *et al.* 1994). Among the nutrients, nitrogen plays a vital role in nutritional and physiological status and promotes changes in mineral composition of the plants. Most plants only utilize less than one-half of nitrogen fertilizer applied (Zhu 2000; Zhu and Chen 2002) because of its high mobility in soils (Palm et al., 1997). In this study nitrogen omission either alone or in combination mostly limited eucalyptus growth. The effect of omission of nitrogen with other nutrients was evident as DBH of trees decreased by 23, 25 and 27 percent due to omission of N, NP and NK compared to balanced nutrient application (NPK). High temperature and low fertility status of the study site may have resulted in rapid organic carbon decomposition and nitrogen loss, Swift et al. 1979, Cornejo et al. 1994 and Sangoi et al. 2007. Nitrogen uptake by crops also vary significantly with season, site and soil type (Gastal and Lemaire 2002). Synergistic interaction of nutrients is observed in the present study with increased nutrient use

efficiency under balanced nutrient application as well as other nutrient combinations tested (Fig. 6). The interaction of NK and NP are well known, they are not only important for biomass production but also influence root growth and hence application is important during the growing season (Aulakh and Malhi 2005).

Phosphorus is essential in large quantity for growth of plants as it is involved in cellular functions, metabolism and growth.. Plants take up phosphorus dissolved in the soil solution and it is always short in supply in comparison to demand for growth (Lambers et al. 2010, McGroddy et al. 2004, Sardans et al. 2012). The current study did not show any significant difference in stand growth (height & diameter) due to omission of phosphorus alone, while significant reduction in tree height (21 & 19 per cent) and diameter (32 & 25 per cent), was noted due to omission of phosphorus, in combination of other nutrients NP and PK, respectively (Table 3). The marked response in growth of trees which received NP and PK appears to be a synergistic effect of nutrient combination as combined effect on growth were higher than the effect of P alone. Nutrient interaction is probably one of the most important factors affecting yields (Fageria *et al.* 2014). Minick et al. 2011, found that phosphorus enhanced gross nitrification rates in mature northern hardwoods and suggested that high microbial nitrate immobilization prevented a net nitrification response.

Potassium is considered second only to nitrogen in importance for plant physiology. Potassium is an extremely dynamic ion, which is moderately mobile (Weil & Brady. 2017) in the soil system. The challenge in biomass production is to increase the concentration of available potassium to the required level to achieving optimum crop yield. Though the experimental site had sufficient reserves of potassium (Table 1), the quantity available in easily exchangeable condition may be very small which caused significant reduction in tree height and DBH with K omission. Similar effects of growth stimulation with potassium and nitrogen application in Ponderosa pine was reported by Garrison *et al.* 2005, highlighting the role of potassium in reducing mortality in stands. Another important factor of balanced potassium application is luxury consumption in plants (Hommels et al. 1989, Kang et al. 2014), in absence of other nutrients and abundance of potassium in soil, plants will take up large quantities of potassium without any corresponding effect on growth (Karam et al., 2009 and Guo 2007).

Nutrient Dynamics

Growth and total nutrient uptake (N, P, K, Ca and Mg) in eucalyptus was not constant throughout the stages studied. In present study the growth and nutrient uptake can be divided into two phases, first being the early growth stage, where net primary production is used to build up of photosynthetic capacity (Bouillet et. al. 2002) and this lasted beyond 2 years of age and coincided with canopy closure. At this stage there was a marked increase in total nutrients accumulation (52%) over the nutrients accumulated in first year. High nutrient demand during the initial phase of development is mainly due to rapid increase in canopy size, lack of internal translocation of nutrients and low nutrient release from decomposing litter (Corbeels et al. 2003). At this phase, development of fine root system is more which helps trees to take up large quantity of nutrients from the soil (Miller 1984, Bouillet et al. 2002, Laclau *et al.* 2003). The second phase saw a 19% decline in total nutrient uptake in comparison to the period of highest uptake (Table 2). After canopy closure the demand for nutrients remains high up to the end of the rotation, however the nutrient uptake during the second phase saw some decline which was result of development of nutrient conservation mechanism and internal translocation of nutrients from the older components to young developing parts (Miller 1995). These mechanisms lead to significant reduction in the dependence of trees on soil nutrient. Studies suggest that amount of nutrient taken by eucalyptus during the different stages of growth changed only slightly but the availability of nutrients from the soil changed as the age of plantation increased. Laclau *et al.*, 2003 reported that on an average 38, 30, 51, -13 and 6 per cent of N, P, K, Ca and Mg requirements of the trees were met by the internal translocation from the old tree components to young developing tissues during the phase after canopy closure. Sites where annual burning is not practiced, litter accumulates on the forest floor and mineralization of nutrients from litter plays a crucial role in supply of nutrients. Laclau et al., 2001 reported that dense feeding root system develop below the decomposing litter on the forest floor and nutrients are taken up quickly by the vegetation than from the deep soil towards the end of rotation. In short rotation eucalyptus crops lack of efficient nutrient management and decomposing litter (due to burning of slash) affects the biomass production after canopy closure due to mining of soil nutrient reserves in the early growth phase which is not replenished.

Table 5

Nutrient management practices and its effect on nutrient partitioning, percentage of total nutrient accumulation in different tree components of *Eucalyptus camaldulensis* at various growth stages.

Components of <i>Eucalyptus camaldulensis</i> at various growth stages.												
	Uptake Year 1			Uptake Year 2			Uptake Year 3			Uptake Year 4		
Leaf												
	N	P	K	N	P	K	N	P	K	N	P	K
- NPK	44 (75.2)	3.4 (5.8)	5.9 (10.1)	101.9 (76.8)	5.3 (4)	14.4 (10.9)	87.2 (77.7)	4.3 (3.9)	11.4 (10.2)	65.3 (76.4)	3.1 (3.6)	8.6 (10)
-N	43.2 (61.6)	4.3 (6.2)	10.6 (15.1)	115 (69.6)	7.6 (4.6)	22.4 (13.6)	200.7 (75.9)	8.3 (3.2)	40.2 (15.2)	65 (65.2)	5.2 (5.2)	15.9 (16)
-P	100.9 (66.9)	7.8 (5.1)	21.7 (14.4)	253.3(72.4)	13.6 (3.9)	50.2 (14.3)	194.7 (71.8)	11.8 (4.4)	42.4 (15.6)	124.9 (65.8)	8.4 (4.4)	35.4 (18.7)
-K	97.4(69)	5.5 (3.9)	21.9 (15.5)	236.5 (74.1)	9.6 (3)	49.7 (15.6)	203.3 (73.4)	8.2 (2.9)	47.2 (17.1)	114.4 (65.6)	6.3 (3.6)	37.1(1.2)
-NP	39.6 (64.2)	4.9 (8)	8.8 (14.3)	111.9 (73.1)	8.6 (5.6)	18.7 (12.2)	89.5 (71.7)	7.2 (5.7)	16.2 (13)	65.1 (68.3)	5.8 (6.1)	13.3 (14)
-NK	91.4 (70.8)	5.6 (4.4)	17.8 (13.8)	86 (70.6)	7.6 (6.2)	14.2 (11.7)	74.9 (69.2)	6.6 (6.1)	14.8 (13.7)	70.1(69.1)	5.3 (5.3)	13 (12.9)
-PK	42.2 (62.9)	4.5 (6.7)	9.1 (13.6)	102.4(69)	7.8 (5.3)	18.7 (12.6)	87.4 (67.9)	6.4 (4.9)	20.3 (15.8)	111.6 (68.6)	6.7 (4.1)	30.3 (18.6)
NPK	105.2 (62.8)	8.7 (5.2)	28.4 (16.9)	249.7 (67.5)	16.2 (4.4)	66.4 (17.9)	219.9(69)	12.1 (3.8)	61.2 (19.2)	156.4 (65.5)	10 (4.2)	48.7 20.4)
Wood												
- NPK	10.1 (72.1)	0.5 (3.3)	2.6 (18.5)	23.4 (64.8)	2 (5.5)	6.5 (17.9)	24.5 (65.8)	2.4 (6.6)	8.1 (21.8)	42.1 (73.8)	4 (7)	7.7 (13.6)
-N	11.6 (63.9)	0.7 (3.6)	3.3 (18.3)	36.4 (63.8)	2.5 (4.3)	11.5 (20.3)	34.1 (67)	2.6 (5)	9.5 (18.6)	44 (69.1)	3.9 (6.1)	9.1 (14.2)
-P	28.9 (73)	1.1 (2.8)	6.3 (15.9)	50.2 (65.4)	3.5 (4.6)	12.9 (16.8)	54.1 (70)	4.2 (5.5)	12.3 (15.9)	111.8 (80.2)	6.6 (4.7)	12.9(9.3)
-K	20.5 (66.9)	0.9 (2.8)	6.8 (22.2)	38.1 (60.2)	2.8 (4.4)	14.6 (23.1)	42.5 (64.7)	3.3 (5)	15.5 (23.6)	113.7 (81.1)	5.3 (3.8)	14.8 (10.6)
-NP	11.8 (67.7)	0.5 (2.7)	3.2 (18.5)	38.2 (74.1)	1.8 (3.6)	6.2 (12.1)	27.3 (67.6)	2.2 (5.5)	7.3 (18.1)	37.8 (69.9)	4.4 (8.2)	7 (12.9)
-NK	19.2 (69.3)	0.9 (3.1)	5.4 (19.7)	18.2 (58.4)	2 (6.6)	4.5 (14.4)	20.3 (53.9)	2.9 (7.7)	10.4 (27.6)	40.4 (67.7)	3.9 (6.6)	9.2(15.4)
-PK	12.6 (66.5)	0.6 (3.2)	3.4 (17.9)	24.3 (58.5)	2.1 (5.2)	8.3 (20.1)	28.8 (63.5)	2.4 (5.4)	9.6 (21.2)	105 (82.1)	5.2 (4.1)	11.8(9.3)
NPK	40.1 (76.3)	1.5 (2.9)	7.8 (14.9)	69.7 (64.7)	5.4(5)	19.1 (17.7)	75.5 (72.4)	5.1 (4.9)	17.8 (17.1)	124 (78.4)	8.3 (5.2)	17 (10.7)
Bark												
- NPK	2.6 (39.6)	1.1 (17.1)	0.9 (14)	6.1 (36.5)	2 (12.2)	1.7 (10.1)	5.6 (37)	2.5 (16.5)	2.1 (14)	6.9 (38.3)	3.2 (17.4)	1.6 (8.9)
-N	3.9 (29.2)	1.5 (11.4)	1.5 (11)	15.8 (43.8)	2.6 (7.3)	4.8 (13.4)	7.4 (27.8)	3.3 (12.4)	3.3 (12.5)	9.2 (30.2)	4.2 (13.8)	2.5 (8.3)
-P	11.8 (46.3)	2.5 (9.9)	2.8 (10.9)	18 (39.2)	4.5 (9.8)	5.7 (12.4)	19 (38.6)	5.5 (11.2)	6.3 (12.8)	25.6 (46.7)	6.6 (12)	4.5 (8.2)
-K	10.7 (49.5)	1.9 (8.7)	3 (13.8)	15.5 (39.1)	3.5 (8.8)	6.4 (16.3)	17.4 (43.6)	4.1 (10.3)	6.8 (17)	24.1 (49.2)	5.2 (10.6)	5.2 (10.6)

Uptake Year 1				Uptake Year 2			Uptake Year 3			Uptake Year 4		
-NP	2.7 (27.5)	1 (9.8)	1.4 (14.6)	6.1 (28.8)	1.7 (8.2)	2.8 (13.1)	5.7 (28.4)	2.1 (10.5)	3.3 1(6.3)	7 (30.8)	2.7 (11.6)	2.5 (10.9)
-NK	10.2 (53)	1.4 (7.4)	2.3 (11.9)	5.7 (23.6)	2.6 (10.7)	1.8 (7.6)	11.7 (33)	3.1 (8.8)	3.3 (9.3)	7.9 (29.4)	3.9 (14.6)	1.6 (6.1)
-PK	3.2 (27.9)	1.4 (12.4)	0.9 (8.3)	6.6 (24.3)	2.8 (10.1)	2.9 (10.6)	6.4 (27.3)	3.1 (13.2)	2.2 (9.2)	21.2 (50.4)	3.9 (9.3)	4 (9.4)
NPK	13.4 (46.5)	2.9 (10)	4.2 (14.5)	20.2 (37.3)	5.5 (10.1)	9.1 (16.8)	21.3 (40)	6.3 (11.8)	8.5 (16)	30.5 (46.5)	8 (12.1)	7.2 (11)
Slash												
- NPK	5.3 (49.7)	0.5 (4.2)	3 (28)	8.3 (49)	1.9 (11.4)	5.1 (29.8)	7.5 (48.1)	1.6 (10.2)	4 (26)	6.4 (66.5)	0.5 (5.7)	1.5 (15.1)
-N	5.3 (36.1)	0.8 (5.4)	3.9 (26.5)	9.4 (41.2)	2.5 (11.1)	8.7 (38.1)	16.5 (44.3)	2.7 (7.3)	14.7 (39.5)	7.2 (53.8)	0.7 (5.3)	2.3(17)
-P	10 (36.4)	1.2 (4.3)	8.9 (32.4)	21.1 (43.7)	4.5 (9.2)	19.5 (40.4)	17.8 (39.1)	3.7 (8.1)	17.6 (38.7)	14.4 (59.5)	1.2(5)	4.4 (18.2)
-K	9.6 (40.6)	1 (4.1)	8.4 (35.4)	17.2 (40.4)	3.2 (7.6)	19.3 (45.4)	15.3 (36.2)	2.7 (6.5)	18.3 (43.2)	14.3 (63.4)	0.9 (4)	4.7 (20.9)
-NP	5.2 (43.2)	0.5 (3.9)	2.6 (21.8)	8.9 (42.3)	2.7 (12.9)	7.3 (34.6)	8 (40.7)	2.3 (11.5)	6.2 (31.6)	6.4 (58.2)	0.7 (6.3)	1.9 (17.1)
-NK	9.3 (43.7)	0.7 (3.5)	7 (32.9)	8.3 (22)	3.2 (8.4)	15.8 (41.8)	6.5 (31.1)	2.2 (10.3)	6.2 (29.8)	6.6 (54.5)	0.7 (5.9)	1.9 (16.1)
-PK	5.3(39)	0.7 (5.5)	3.2(23.3)	9.5 (44.3)	2.6 (12)	7.3 (33.9)	8.5 (36.2)	2.1 (9.1)	7.7 (32.8)	13.4 (65.7)	0.8 (4.1)	3.8 (18.6)
NPK	10.5 (34.5)	1.4 (4.5)	11.5(37.5)	26.5 (43.8)	5.1 (8.4)	25.4 (42.1)	23.4 (39.7)	4.4 (7.4)	24.3 (41.3)	16.9 (58.1)	1.4 (4.8)	6.1 (20.9)
Under Ground												
- NPK	3.3 (55.1)	0.4 (7.3)	0.7 (10.9)	7.1 (64.4)	0.7 (6.1)	1.5 (13.5)	6.4 (65)	0.6 (5.6)	1.2 (12.1)	5.4 (54.1)	0.7 (6.9)	1.1 (11.3)
-N	3.7 (35.6)	0.4 (3.8)	1 (9.6)	8 (48.9)	0.7 (4.4)	2.3 (14.2)	13.9 (63.9)	0.7 (3.2)	3.6 (16.6)	5.9 (41.5)	1 (7.3)	2 (14.4)
-P	8.5(44)	0.6 (3.3)	2.1 (10.8)	18.2(54.7)	1.1 (3.5)	4.8 (14.3)	15.3 (57.1)	0.9 (3.4)	4.3 (16)	15.3 (54.6)	1.7 (6.1)	4.4 (15.7)
-K	7.8 (51.9)	0.5 (3.1)	2.1 (14.1)	16.6 (62.6)	0.9 (3.5)	4.8 (18.1)	14.8 (61.5)	0.8 (3.3)	4.5 (18.9)	15.3 (55.9)	1.3 (4.7)	4.7 (17.1)
-NP	3.3 (38.5)	0.6 (7.1)	0.8 (9.8)	7.1 (53.1)	0.6 (4.6)	1.9 (14.4)	6.4 (55.1)	0.5 (4.4)	1.6 (14.2)	5 (45.2)	0.9 (8.5)	1.8 (16)
-NK	7.3(54)	0.4 (3.2)	1.7 (12.6)	15.7 (64.9)	0.8 (3.4)	3.9 (16.1)	4.5 (34.3)	0.6 (4.3)	1.7 (13)	5.4 (44)	1 (8.5)	1.6 (13.4)
-PK	3.4 (36.1)	0.4 (3.8)	0.9 (9.3)	7.3 (49)	0.7 (4.5)	2 (13.3)	7.1 (49.2)	0.6 (4.1)	2 (14)	14 (57.2)	1.2 (4.8)	3.8 (15.5)
NPK	9.4 (46.6)	0.7 (3.6)	2.7 (13.5)	20.2 (58.7)	1.5 (4.4)	6.2(18.1)	17.8 (56)	1.3 (4.1)	5.9 (18.7)	17.2(53.1)	2 (6.2)	6.2 (19.2)

Uptake of nutrient Kg ha⁻¹, Figures in parenthesis show the percentage of total nutrient accumulated in dry matter

Nutrient Allocation

Total nutrient uptake by *Eucalyptus camaldulensis* under balanced nutrient application in short rotation was 524 kg ha^{-1} which resulted into production of 72 t ha^{-1} above ground dry biomass. The concentration of major nutrients for production of unit volume of aboveground dry biomass followed the sequence: leaf > branches > bark > wood. Leaves represented 18 per cent of the total biomass and 45 per cent of total nutrient accumulated (Table 5). Maximum nutrient accumulation in leaves was at 2 years (365 kg ha^{-1}) of which 67% was total N 4% P, 17% K, 6% Ca and 4% Mg. At harvest age (4 years) total leaf nutrients decreased by 34%. Canopy development during the initial stages of growth is associated with high nutrient accumulation and low nutrient use efficiency. After canopy closure the nutrient requirements decline due to recycling, re-translocation of accumulated nutrients. Laclau *et al.*, (2003) and Helmisaari (1992) reported seasonal variation in the concentration of N, P, and K in Pine due to re-translocation. Fife *et al.*, (2008) found a similar pattern of re-translocation of N, P and K from the leaf, in response to new shoot production in five tree species of diverse leaf form, growth rate and genetic structure.

Stem wood represented the highest proportion of biomass (74%) and relatively lower nutrient concentration (30%) at harvest (Table 5). Inagaki and Tange, (2014) observed that the ratio of nitrogen (woody part to leaves) increased as growth progressed, and nitrogen concentration in woody cells may decrease mainly due to translocation of a large proportion of nitrogen during wood senescence. Stanley and Montagnini (1999) and Bouvet *et al.*, (2013) reported 10-fold higher nitrogen concentration in leaves than wood.

The accumulation of Ca continued while Mg reduced as the trees approached rotation age which shows that the trees depend on soil for Ca supply, while most of the Mg demand is fulfilled by internal translocation. Laclau *et al.*, 2003 also reported internal translocation of nutrients from old tree components to young developing ones from second year till harvest.. While N, P, K and Mg showed positive values, Ca, Mn, Fe and Al showed negative values due to the poor mobility in plant system. These mineral elements are transported from roots to leaves through xylem but mobility is poor in phloem (Schulze *et al.*, 2005, Marschner 2012, Shi *et al.*, 2016).

Soil Nutrient Budgeting

Ignoring nutrient management in low fertility sites results into depletion of soil nutrient reserves very fast, endangering the sustainability of plantations (Goncalves *et al.*, 1997, Dorana and Zeiss 2000 and Goncalves *et al.*, 2008).

Soil nutrient balance sheet (N, P and K) at the time of harvest showed significant differences among the nutrient doses evaluated. In the present study reduction in soil nutrient reserves from the initial level was observed at harvest while, the exchangeable nutrients showed a negative balance of N (45.8), P (7.9) and K (62.9) kg ha^{-1} in the control. Low soil organic matter content (0.35%), high C:N ratio of litter, slow rate of nitrogen mineralization, and lack of synchronisation in demand and supply affected the nitrogen uptake in the eucalypt plantation, leading to mining of soil nutrient reserves from stands when nitrogen was omitted, resulting in a negative soil nitrogen balance. Balanced application of nutrients in splits, catering to the periods of high nutrient demand helped to narrow the gap between demand and supply of nutrients and maintain the soil nutrient reserves (William *et al.*, 2003). The bioavailability of phosphorus is strongly tied to soil pH with maximum solubility and availability at pH 6.5. Despite the availability of sufficient exchangeable phosphorus in soil (17.8 kg ha^{-1}) the alkaline nature of soil affected its availability in the present study. Balanced nutrient application resulted in a positive phosphorus balance (0.5 Kg ha^{-1}). The build-up of soil phosphorus can be attributed to the improved uptake with split application of nutrients, coinciding with the periods of high nutrient demand (Sims and Smith, 2001).

The potassium balance was positive (2 Kg ha^{-1}) in stands which received balanced nutrient application.. Split application of nutrients increased the exchangeable potassium levels and maintained the potassium in soil, which is a sign of sustainable production system. Omission of potassium drained the soil reserves to levels that can't be compensated naturally. Potassium is supplied from the K^+ ions in the interlayers of micaceous clay minerals in soil which is dominated by 2:1 phyllosilicate, where entrapment of potassium ions happens due to collapse of layers and becomes non available to plants (Mortland and Lawton, 1961 and Amonette, *et al.*, 1994). The extent of soil nutrient loss is determined by various factors like nutrient content/removal through biomass produced, nutrient reserves and input into soil. From ecological point of view, preventing biomass removal while harvesting can have a positive impact on soil nutrient reserves. At four years of age total nutrient accumulation in leaves was 45% of total nutrient accumulated by the tree, while 19% nitrogen, 49% phosphorus, 29% potassium, 68% calcium and 70% magnesium of the total nutrients accumulated in stem was in bark. Leaving leaves and bark after harvesting on the soil surface helps in microbial mineralization of nutrients and their abundance in soil solution (Santana *et al.* 2002) and helps in sustainability of short rotation eucalyptus plantations.

Profitability of fertilizer is the key factor determining the fertilizer use and sustainability of plantations. The study demonstrated that nutrient application in eucalyptus plantation is a potentially successful investment strategy but the financial performance of fertilizer treatments will affect the profitability considerably (Knott, et al. 1996). Wood production per unit area increased in the range of 10 to 79% in different nutrient combination treatments, compared to the control (Table 2). Balanced nutrient dose in eucalyptus resulted into highest B: C ratio (1.9) and was sustainable in terms of economic returns. Stands which balance nutrient application the net returns was 55% higher returns from the returns from control (no fertilizer application). This variation highlighted the need of careful selection of fertilizer combinations to increase profitability and sustainability of short rotation eucalyptus plantations these findings are in agreement with Kun-nan *et al.*, (2002) in eucalyptus, Pampolino *et al.*, (2007) in rice, Anand *et al.*, (2017) in hybrid Maize,

Conclusion

This study evaluated the dynamics of major nutrients (N, P and K) in biomass production and impact of excluding one or more nutrients on the productivity and profitability of short rotation *Eucalyptus camaldulensis* plantations in southern India. Generally, three crops of 4 year rotation (including two coppices), are taken in intensively grown eucalyptus plantations in India. The same piece of land is expected to supply all the required nutrients for 12 years after planting. The study provides information on nutrient allocation (N, P, K Ca and Mg) in different components of the tree, and also describes the variation in nutrient accumulation with age. Nutrient uptake (N, P, K and Mg) was generally high in the initial growth phase (till canopy closure), after which it declined due to internal retranslocation. Soils differ in their capability to fulfil the nutrient demand of intensively cultivated eucalyptus plantations for one or more rotations. For high productivity, short rotation eucalypt plantations need intensive silviculture, with external application of mineral nutrients. Sustained wood supply can be ensured by efficient nutrient management practices. Wood production from the eucalyptus plantations will be adversely affected in absence of adequate nutrients and post-harvest management. The study also reflects the effect of omission of one or more macro nutrient on soil nutrient reserves, export of nutrients from the soil with biomass harvest and its effects on profitability and sustainability of eucalyptus plantations. To ensure sustained wood production, it is necessary to consider the benefits of efficient nutrient and other silvicultural operations to compensate the present and future needs. Further research is needed to elucidate soil test based plantation management model that would sustain the nutrient balance of the ecosystem and achieve the targeted wood yield.

Declarations

1. The study was carried out with financial support from ITC Limited, the trials were laid out on ITC Life Sciences and Technology research farms. Apart from this no grant/financial support were received to carry out the work from any other agency
2. I am employee of ITC Limited and I received financial support viz. salary, supplies and travel reimbursement from the company to carry out the work.
3. Data supporting the findings of the study are available within the article in form of tables and figures.

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Figures

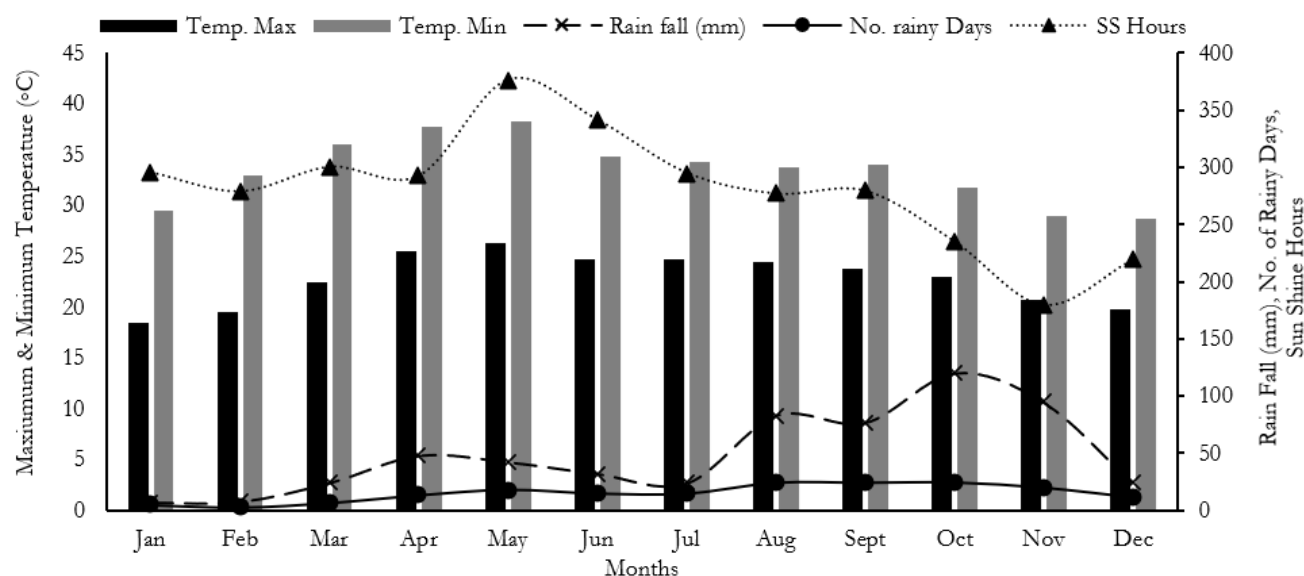


Figure 1

Average monthly weather parameters of the area during the study period

Study Material and Experimental Setup

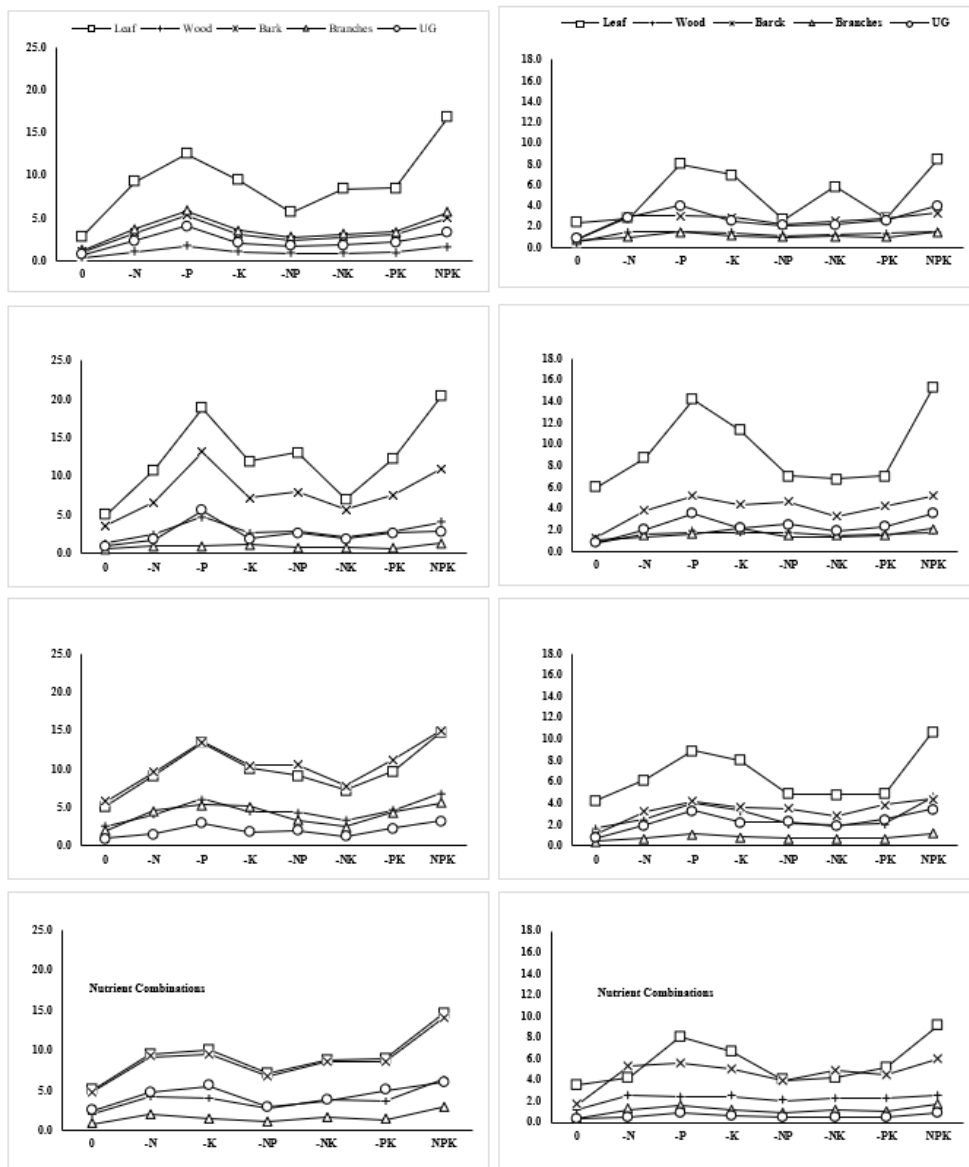


Figure 2

4 .Calcium and Magnesium uptake and accumulation in different components of *Eucalyptus camaldulensis* at different growth stages.

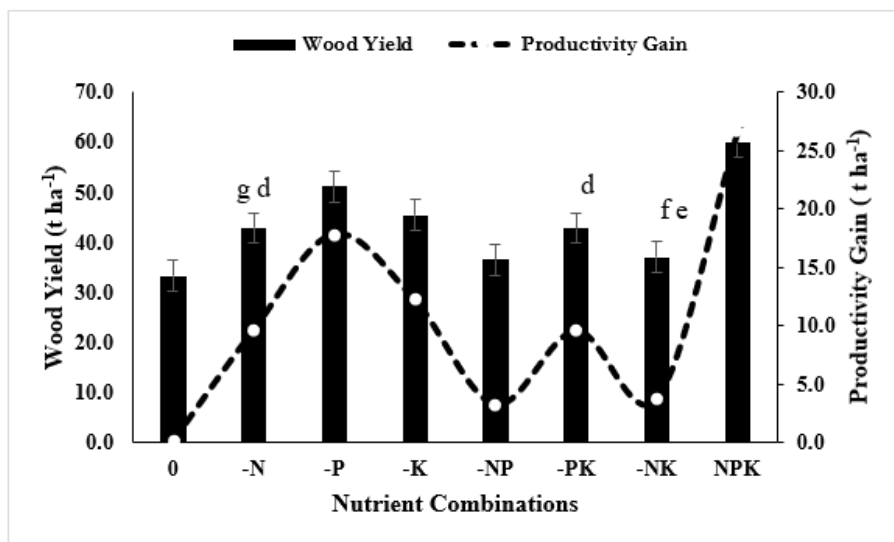


Figure 3

5 Wood yield and productivity grains under different nutrient applications over no nutrient application in *Eucalyptus camaldulensis* at the end of rotation age.

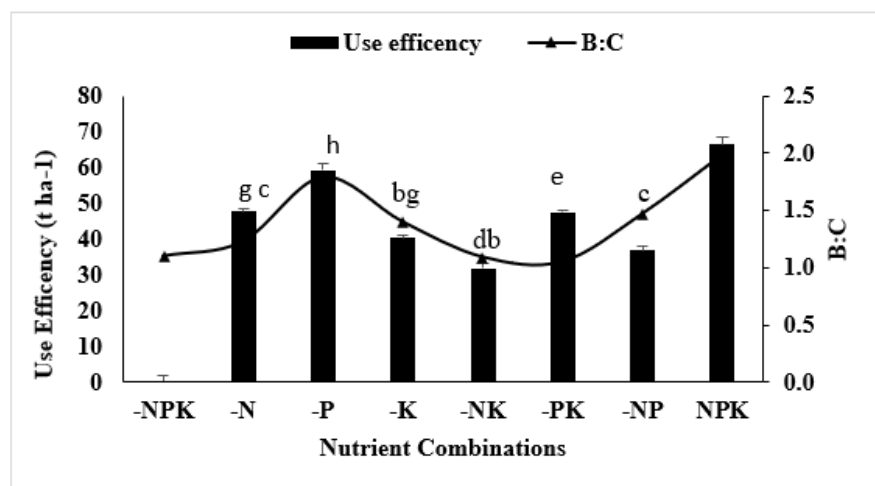


Figure 4

6 Agronomic use efficiency and profitability of nutrient application under short rotation *Eucalyptus camaldulensis* in short rotation.

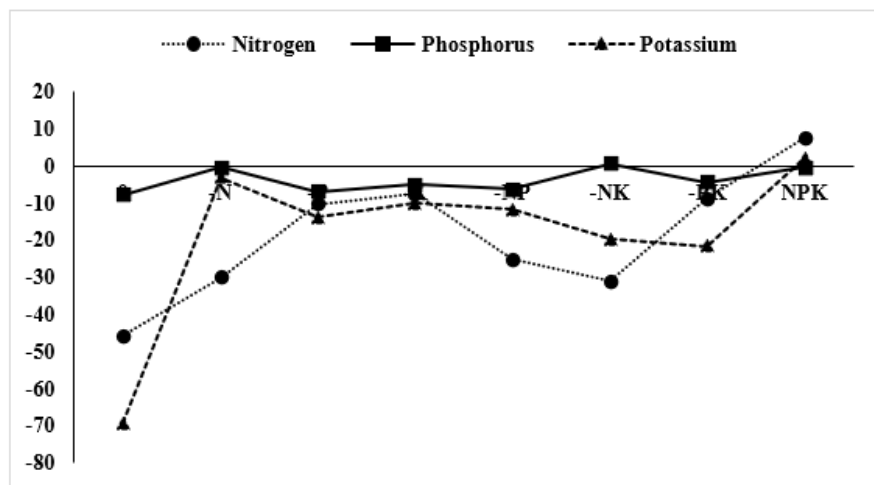


Figure 5

7. Soil nutrient balance sheet of major nutrients under different nutrient management practices in *Eucalyptus camaldulensis*

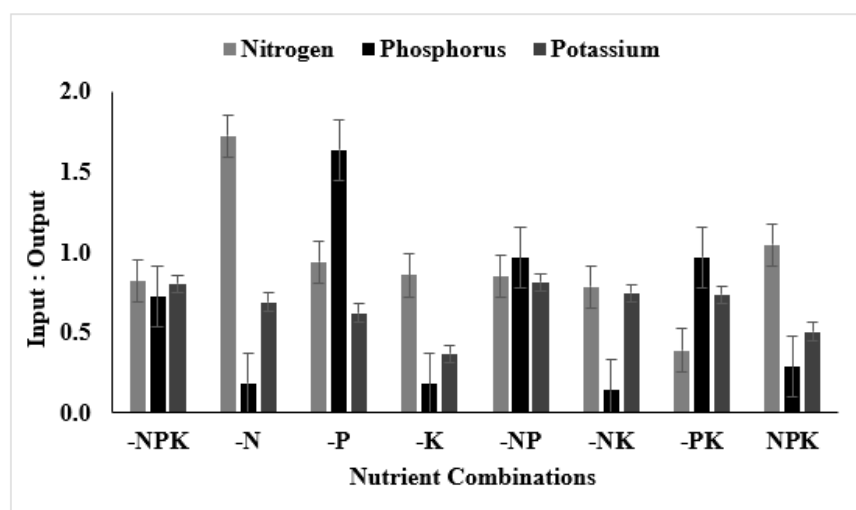


Figure 6

8. Input: output ratio of major nutrients in different management regimes in *Eucalyptus camaldulensis*