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LEAF LITTER BREAKDOWN AND NUTRIENT RELEASE IN THREE TREE PLANTATIONS COMPARED WITH A NATURAL DEGRADED FOREST ON THE COROMANDEL COAST (PUDUCHERRY, INDIA)

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Abstract. Leaf litter decomposition studied in three monoculture tree-plantations and a degraded forest at Puducherry on the Coromandel Coast (India) covering different seasons, showed significant positive correlation between the decomposition rate and rainfall across the land-uses and the forest. The decomposition constants and the half-life periods illustrated a higher decomposition rate in the forest (k=3.050 yr^{-1}) followed by that of *Acacia* plantation (k=2.368 yr^{-1}) while these were lower in *Eucalyptus* plantation (k=1.699 yr^{-1}). Cluster analysis (Bray-Curtis similarity index) of monthly decomposition rates depicted a dendrogram joining the first pair of teak and *Eucalyptus* plantations and the other pair of degraded forest and *Acacia* plantation; both pairs unified at a distance of 61%. The nitrogen (N) concentration in the decomposed leaf litter increased gradually while the C/N ratios showed a constant fall in the forest and *Acacia* plantation. Phosphorus, potassium and magnesium concentrations varied in the decomposed litter while calcium was meager across the plantations and the forest.

Key words: Acacia *sp.,* Eucalyptus *sp.,* Tectona grandis *plantation, C/N ratio, nutrients, land-use.*

INTRODUCTION

Plant litter decomposition is the process of biological disintegration of litter during which mineralization of complex organic compounds into simple inorganic forms occurs. It includes leaching, break up by soil fauna, transformation of organic matter by microorganisms and transfer of organic and mineral compounds to the soil (Loranger *et al.* 2002). Leaf litter constitutes the major part of the total litter fall, providing an important nutrient pool. The breakdown of leaf litter is thus a key component in nutrient cycling in tropical forests and tree-plantation ecosystems. The release of nutrients during litter decomposition is a key process governing the availability of nutrients in ecosystems (Moore *et al.* 2006) and an important ecosystem function, playing a crucial role in nutrient release in forest and tree-plantation ecosystems. It is a complex process regulated by a number of abiotic and biotic factors (Lavelle *et al.* 1993, Reddy 1995a). These factors include soil organisms – microorganisms, microfauna, mesofauna and macrofauna; litter quality denoted by the inorganic nutrients and organic compounds; and physico-chemical properties of the soil-litter system and climate (Reddy & Venkataiah 1989, Dyer *et al.* 1990, Berg *et al.* 1993, Meentemeyer 1995, Reddy 1995a, Seastedt 1995, Wood 1995, Aerts 1997, Singh *et al.* 1999, Sariyildiz & Anderson 2003, Pausas *et al.* 2004). Leaf litter of different plant species has diverse nutrient release patterns, which are related to quality, season, and environmental factors (Arunachalam *et al.* 2003, Abiven *et al.* 2005). Different litter parameters like initial litter N concentration and C/N ratio (Pérez-Harguindeguy *et al.* 2000) on the one hand and the lignin concentration or lignin : N ratio (Loranger *et al.* 2002) on the other, have been found to be correlated with, and useful as predictors of the decay rate. The soil organisms contribute to litter decomposition by playing the role of decomposers. The soil fauna through comminuting mechanisms fragment the substrates, thereby increasing the surface area leading to the acceleration of microbial activity (Wise & Matthias 1994, Reddy 1995b, Seastedt 1995, Coleman & Crossley 1996, Knoepp *et al.* 2000, Ekschmitt *et al.* 2005, Janzen 2006). It has been suggested that early decomposition is regulated by

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nutrient concentrations (especially N and P) while the late-stage decay is regulated by lignin concentration (Sangha *et al.* 2006).

Large tracts of forest have been converted into various other land uses, such as agriculture and exotic tree-plantations, leading to different litterfall and decomposition regimes. There are 187 million hectares of tree-plantations world-wide, representing approximately 5% of the global forest area. One percent (10 million ha) of all tropical forests was converted into tree-plantations from 1990 to 2000 (FAO 2001), a trend expected to continue in the ensuing decades. It is therefore important to understand the changes in decomposition processes and nutrient cycling encountered when converting natural forest or other land into plantation forests, or when rehabilitating natural forest for the sustainable management of tropical forests (Attignon *et al.* 2004).

The decomposition process has been described as having two phases, a leaching phase and a post-leaching phase, which are regulated by different litter quality parameters (Loranger *et al.* 2002). Moreover, the average annual decay rate coefficients (k) for temperate and tropical forest ecosystems have been estimated respectively at k = 0.9 and k = 1.8 (Torreta & Takeda 1999). However, there is some evidence of regionality in decomposition rates within the tropics, with k > 2 (high) for most African forests and k = 1–2 (medium to high) for forests in Southeast Asia and the Neotropics (Anderson & Swift 1983). African tropical forests showed very high (k ≈ 4) rates (Olson 1963), indicating rapid nutrient cycling. The decay rates can however be low (k < 1) even in tropical areas, depending on litter type, season and altitude (Verhoef & Gunadi 2001).

While there have been many studies on various aspects of litter decomposition (Lavelle *et al.* 1993, Coleman & Crossley 1996, Heal *et al.* 1997), only a few studies have compared the various aspects of litter decomposition across different habitats, particularly the tree-plantations with their adjacent forest ecosystems (Musvoto *et al.* 2000, Reddy 2002, Attignon *et al.* 2004) or tropical coastal sandy ecosystems (N'goran *et al.* 2006). The present study attempted to focus on leaf litter breakdown and nutrient release in three different tree-plantation ecosystems, *Tectona grandis*, *Acacia nilotica* and *Eucalyptus* sp., compared with an adjacent natural degraded forest. We particularly looked at spatio-temporal variations in the rates of leaf litter decomposition in terms of breakdown, release of nutrients, Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg), as well as the C/N ratio during the process of leaf litter decomposition in relation to the seasonal variation in rainfall during the study period.

MATERIALS AND METHODS

Study Site. The present study was conducted on the Coromandel Coast at Pondicherry (now known as Puducherry) (11°56'N, 79°53'E), the erstwhile French colony in India (Fig. 1). Puducherry experiences four seasons annually with two distinct wet periods – SW monsoon extending from mid-June to September and NE monsoon from mid-October to mid-December, and two dry periods – a mild winter from December to February and summer from March to mid-June. The Puducherry region receives about 60% of its rainfall during the NE monsoon, which was nil during January and February and minimum during March to mid-June with intermittent rains (Fig. 2), and it experiences a hot and humid climate during most of the year, with a temperature ranging from 32°C to 40°C.

Three monocultural tree-plantations (teak *Tectona grandis*, *Acacia nilotica*, and *Eucalyptus* sp.) were compared with a natural degraded forest ecosystem in the present investigation to assess the spatio-temporal variations in decomposition rates of leaf litter and nutrient release across the land-uses and the forest. The tree-plantations possessed trees with an average age of 20 years. In all the plantations and the

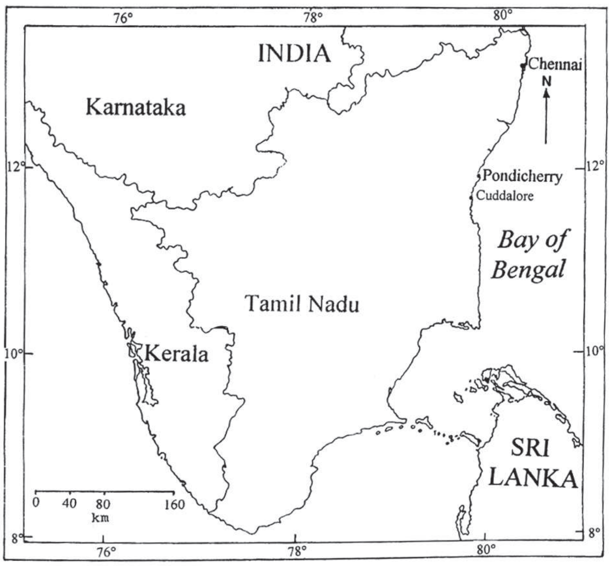


FIG. 1. Location of Puducherry on the Coromandel Coast of India.

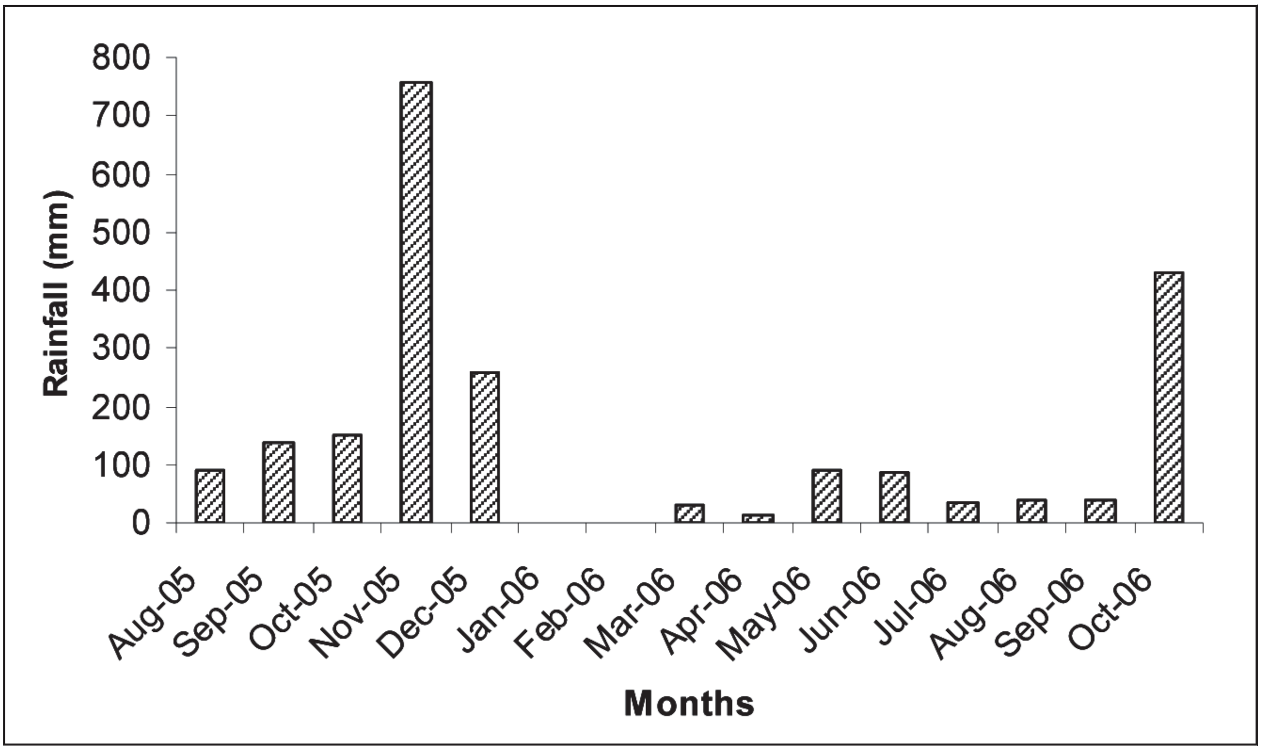


FIG. 2. Monthly rainfall at Puducherry during the study period.

degraded forest the soil was sandy and acidic in nature. The physico-chemical characteristics of the soil are tabulated in Table 1.

Degraded forest. Any land with canopy cover of < 30% as mapped by satellite is considered degraded forest as per Forest Survey of India classification. As there are hardly any primary forests around Puducherry, the present patch of degraded forest was selected for this comparative study. The site was about 1330 m^2 with the natural tree, herb, shrub, and grass

TABLE 1. Initial soil characteristics of degraded forest and the three plantations.

Sl. No.	Parameter	Unit	Degraded Forest	Teak	Acacia	Eucalyptus
1	pH		5.46	6.26	5.29	5.81
2	Temperature	°C	37.5	35.2	38.8	41.3
3	Electrical Conductivity	mmhos/cm	0.11	0.05	0.07	0.02
4	Moisture Content	%	4.90	0.16	0.19	0.13
5	Water Holding Capacity	%	36.30	35.92	33.89	34.25
6	Cation Exchange Capacity	meq/100 gm	4.30	3.18	3.22	2.59
7	Bulk Density	gm/cc	1.26	1.35	1.42	1.43
8	Organic Carbon C	%	1.28	0.61	0.72	0.29
9	Available Nitrogen N	%	0.08	0.05	0.07	0.06
10	Phosphorus as P_2O_5	µg/gm	77.70	48.50	32.20	38.70
11	Potassium K	µg/gm	94.38	42.60	29.48	17.28
12	Calcium Ca	µg/gm	446	199	199	99
13	Magnesium Mg	µg/gm	210	244	244	244
14	Sodium Na	µg/gm	27.35	16.00	32.20	11.38

vegetation represented mainly by *Chloroxylon swietenia*, *Cassia fistula*, *Phoenix*, *Zizyphus*, *Acacia auriculiformis*, *Acacia planifomis*, *Calotropis* sp., *Jatropha* sp. and *Ocimum* sp. and with a litter layer of mixed leaves of about 4.0 cm. The average tree height was 2.38 m with canopy cover of < 30%.

Teak (Tectona grandis) *plantation*. This covered an area of about 1110 m^2 with about 125 trees and a distance between the trees of 3 m, and a litter layer of about 3.5 cm. The average tree height was 16.46 m.

Acacia (*Acacia* sp.) *plantation*. This covered an area of about 1560 m^2 with 485 trees and a distance between the trees of 1.8 m, and a litter layer of about 4 cm. The average tree height was 14.33 m.

Eucalyptus (*Eucalyptus* sp.) *plantation*. This covered an area of about 1340 m^2 with 305 trees and a distance between the trees of 2 m, and a litter layer of about 3 cm. The average tree height was 20.73 m.

Sampling. The litter decomposition rate was studied using the standard litter bag method (Crossley & Hoglund 1962). In each of the plantations, the leaf litter corresponding to the plantation was sampled; whereas in degraded forest sampling was done using mixed leaf litter with at least three different species in each sample. Freshly fallen leaves were collected from the surface of the ground by hand (wearing gloves), placed in bags and transferred to the lab, where they were air-dried at room temperature for 5 days. A weight of 10.000 g of dry leaf litter measured using a balance with a precision of 0.0005 g (accuracy up to a mg) was placed in nylon mesh bags, each of size 11 x 13 cm with a mesh size of 5 x 5 mm. Sixty such nylon mesh bags were prepared and filled with dry leaf litter of each type and placed at respective sites, taking the total number of litter bags used in the present study to 240. At the end of every month (30 days), four litter bags were collected from each of the tree-plantation sites and from the forest. The soil and dirt attached to the litter bags were scraped off and the contents meticulously processed, being washed under a fine soft jet of running water. The contents of decomposed and broken leaf litter were carefully emptied into a dish and dried to constant weight at 65°C. Care was taken to ensure that each and every leaf unit was transferred to the dish without any sand or soil particles. The leaching and fragmentation during the washing phase were minimized by separately washing each individual leaf part using a soft jet of water.

The total monthly rainfall was measured with the help of a rain gauge (Fig. 2) and the daily minimum and maximum temperature (a simple average of both was used) was recorded using an Hg bulb thermometer in the field for the period of study.

Chemical Analysis. A subsample of the collected litter was analyzed for OC (Organic Carbon), N, P, K, Ca, and Mg every month, following the methods given by Jackson (1973). The OC and N contents of the litter that remained in the bags were analyzed using an elemental Auto-analyzer (Skalar Model, The Netherlands). Phosphorus was determined colorimetrically, the other elements (K and Mg) were analyzed using Atomic Absorption Spectrophotometer (GBC model, Australia), and Ca was analyzed using a flame-photometer. C/N ratios were calculated and their possible correlations with remaining litter decomposition rates were established.

Kinetics. The decomposition constant k and the half life $T_{1/2}$ were calculated for each land-use pattern using the exponential decomposition method, the equation given by Olson (1963):

$X_t = X_0 e^{-kt}$ - (1)

$T_{1/2} = \ln(2)/k = 0.69315/k$ - (2)

Where X_t is the remaining weight of the litter at time t, X_0 the initial weight of the litter placed in the litter bags, k the decomposition constant, and $T_{1/2}$ the half-life time of the decomposition.

Data Analysis. The relationship between temporal variations in litter decomposition rates and rainfall were computed using coefficient correlation analysis; t-tests were used to assess the significance of the comparisons. Cluster analysis using Bray-Curtis distance and nearest neighbor clustering was done by using the monthly decomposition rate, percentage of the weight lost. It should be noted that cluster analysis requires additive variables and hence the monthly decomposition rates cannot be directly used. The actual percentage of decomposition every month is a meaningful variable to base the clusters on.

RESULTS

The percentage of weight remaining during the study period in the tree-plantations and the degraded forest presented in Fig. 3 shows that the weight decreased rapidly during an initial period of five months until December, when the NE monsoon started. It

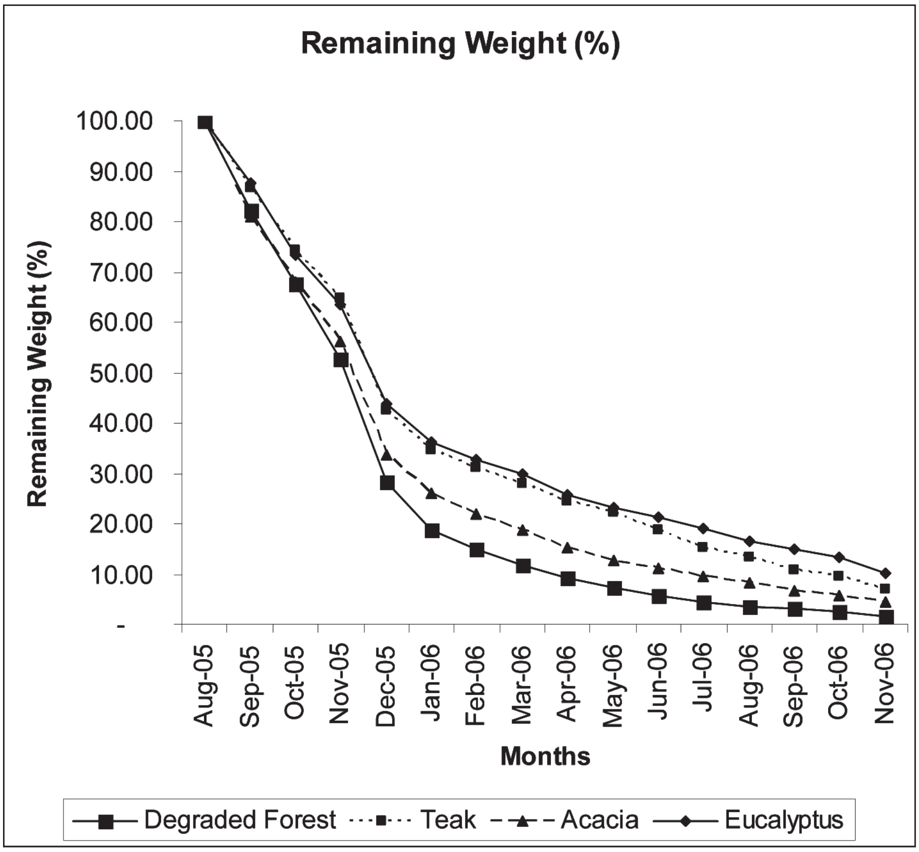


FIG. 3. Weight remaining in the litter-bags across various land-use patterns.

reached a low point (3.62%) after 15 months of decomposition in the natural degraded forest, followed by that of acacia and teak leaf litter, while it was relatively higher (16.53%) in leaf litter in the *Eucalyptus* plantation, indicating that about one-sixth of the initial litter still remained undecomposed in the eucalyptus plantation site even after a year. It showed that the rate of litter decomposition, though higher in all the land-uses in December, was maximum for degraded forest (Fig. 4). It was found that the monthly variation in decomposition rates was significantly positively correlated with that of monthly rainfall (r = >82% and P<0.001) (Table 2).

TABLE 2: Correlation between monthly leaf litter decomposition rate and rainfall.

Vegetation types	Correlation Coefficient (r)*
Natural degraded forest	0.82
Teak Plantation	0.86
Acacia Plantation	0.87
Eucalyptus Plantation	0.93

* All values at significance level P<0.001

The decomposition rate constant was highest in the natural degraded forest at k=3.050 yr^{-1}, while it was lowest in *Eucalyptus* plantation at k=1.699 yr^{-1} (Table 3). The half-life periods corresponding to these were 82 days and 147 days, respectively. ANOVA showed that the decomposition rates are significantly different (P<0.003) across the plantations and forest. Pair-wise comparisons showed that the differences in decomposition rates of teak – *Acacia* plantation and teak – *Eucalyptus* plantation pairs were not statistically significant, while that of *Acacia* – *Eucalyptus* plantation was statistically significant (P<0.06). It was observed that the leaf litter decomposition rate in the degraded forest was significantly different from that of all the plantations to varying degrees: *Acacia* plantation (P<0.09), teak plantation (P<0.008), and *Eucalyptus* plantation (P<0.001).

The cluster analysis using Bray-Curtis distance and nearest neighbor clustering produced a dendrogram (Fig. 5) with initial joining of a teak and *Eucalyptus* plantation pair (at a distance of 44%), instead of the expected degraded forest and Acacia plantation pair that was formed at a distance of 51%. This showed that the similarity of the latter pair in terms of higher rate of decomposition is weaker than the former pair with a lower decomposition rate. The two

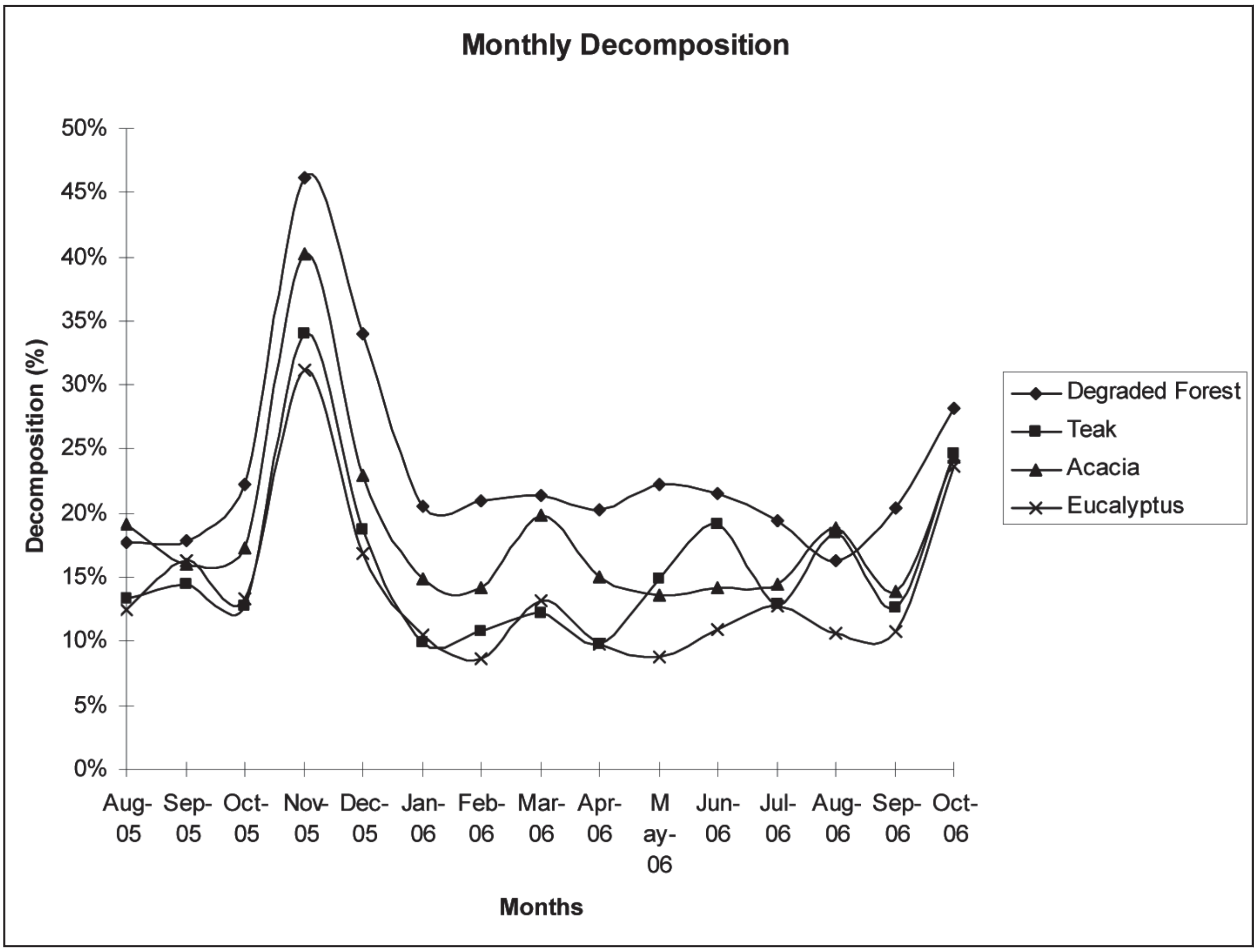


FIG. 4. Monthly leaf litter decomposition rate across various land-use patterns.

pairs joined later at a distance of 61% because of the nearness of *Acacia* plantation to teak plantation.

The temporal variation in N concentrations and C/N ratios in leaf litter of the tree-plantations and degraded forest showed that there was a continuous increase in the N concentration in the leaf litter in the degraded forest and *Acacia* plantation. In the other plantations, there were alternate periods of increase and decrease in N concentration in the leaf litter during decomposition. But overall, in the forest and the plantations, there was mineralization of nitrogen instead of immobilization. The leaf litter in the *Acacia* plantation had the highest initial N concentration of 2.2%, which increased to 4.4% at the end of study (Fig. 6a). The nitrogen content of litter continuously decreased in the acacia plantation from the initial level of 222 mg to 19 mg at the end of the study period (Fig. 7a). The N concentration in the leaf litter in natural degraded forest increased from 2.03% to 3.93%. Teak leaf litter had the lowest N

TABLE 3: Leaf litter decomposition constants for various land-use patterns based on Exponential Decomposition Model.

Land-Use	Rate Constant k (yr^{-1})	Half Life Period $T_{1/2}$ (days)	Wt remained (%) (12 months)
Natural degraded forest	3.050	82	3.62
Teak Plantation	1.892	132	13.24
Acacia Plantation	2.368	105	8.15
Eucalyptus Plantation	1.699	147	16.53

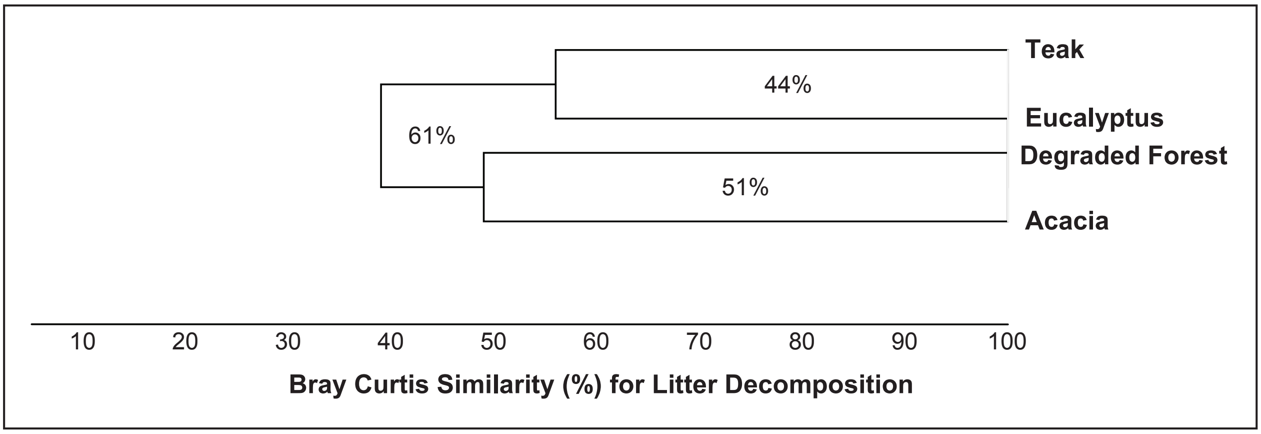


FIG. 5. Bray-Curtis Similarity (%) for litter decomposition.

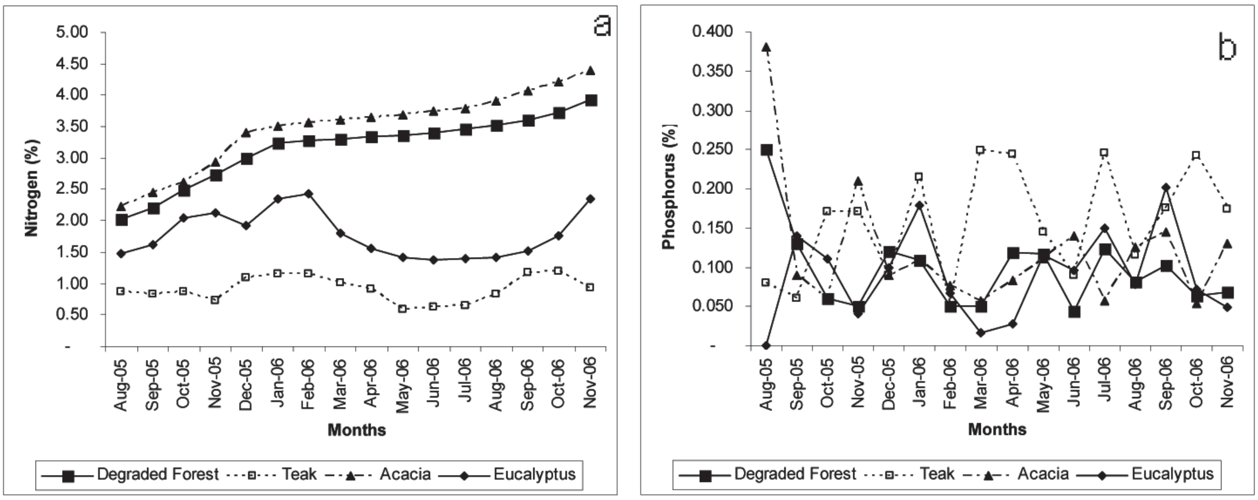
concentration of 0.88% while it was highest at 2.2% in acacia leaf litter. There was a continuous fall in the C/N ratios from 26.28 to 12.75 in the leaf litter of natural degraded forest, and from 24.67 to 11.95 in *Acacia* leaf litter (Table 4). While the initial C/N ratios of leaf litter across the tree-plantations were relatively higher, the leaf litter of the teak plantation showed the highest initial C/N ratio of 60. 29 while the lowest initial C/N ratio of 24.67 was recorded in acacia leaf litter.

There was little significant correlation between the N concentration of the leaf litter and the rate of litter decomposition in the teak and *Eucalyptus* plantations. However, the temporal variation in N concentration in the leaf litter was significantly correlated with the litter weight in natural degraded forest as well as that of Acacia plantations ($r^2 = 0.94$ and $P<0.001$ for both).

The P concentration decreased from 0.250 to 0.068% in leaf litter in natural degraded forest, and from 0.380 to 0.130% in acacia leaf litter in the

TABLE 4: N and C/N of leaf litter across the three tree-plantations and the degraded forest.

Years and months	Degraded forest		Teak plantation		Acacia plantation		Eucalyptus plantation	
	Nitrogen (%)	C/N Ratio	Nitrogen (%)	C/N Ratio	Nitrogen (%)	C/N Ratio	Nitrogen (%)	C/N Ratio
2005 - Aug	2.03	26.28	0.88	60.29	2.22	24.67	1.47	34.42
- Sep	2.21	24.73	0.82	63.32	2.45	22.16	1.62	32.03
- Oct	2.48	21.23	0.87	58.59	2.62	19.72	2.04	26.01
- Nov	2.72	19.60	0.73	69.59	2.94	17.03	2.12	25.51
- Dec	3.00	16.98	1.10	49.38	3.41	14.90	1.93	27.12
2006 - Jan	3.24	16.74	1.15	46.71	3.50	14.46	2.35	23.10
- Feb	3.28	15.94	1.15	47.77	3.56	14.90	2.42	20.89
- Mar	3.30	15.67	1.02	49.19	3.61	14.18	1.80	29.10
- Apr	3.34	16.13	0.90	57.62	3.65	13.73	1.56	34.05
- May	3.36	15.13	0.60	85.62	3.69	13.71	1.42	37.50
- Jun	3.41	14.82	0.62	84.91	3.74	13.86	1.38	38.01
- Jul	3.46	15.18	0.64	83.55	3.79	13.56	1.40	38.95
- Aug	3.52	15.36	0.83	64.57	3.91	13.59	1.41	38.02
- Sep	3.61	14.73	1.18	44.52	4.07	12.88	1.52	33.73
- Oct	3.73	13.81	1.20	43.86	4.21	12.01	1.76	28.85
- Nov	3.93	12.75	0.94	56.24	4.40	11.95	2.34	22.95



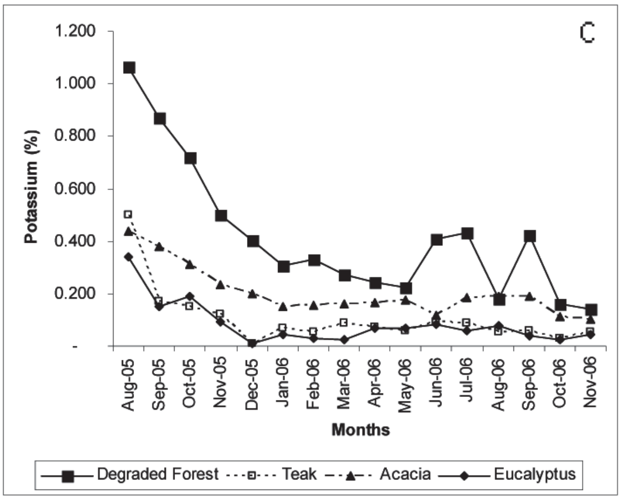


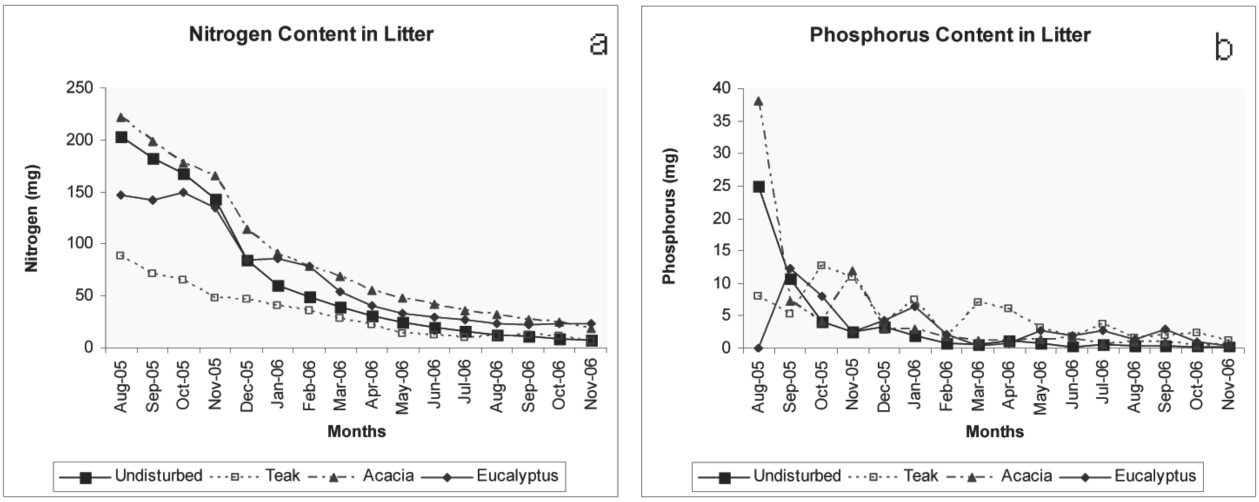
FIG. 6. Nutrient concentration in leaf litter across various land-use patterns
(a) Nitrogen concentration in litter
(b) Phosphorus concentration in litter
(c) Potassium concentration in litter

plantation (Fig. 6b). P concentration in teak leaf litter ranged from 0.080% to 0.174%, while it increased from nil to 0.048% in eucalyptus leaf litter. There was a net release of P in the leaf litter in natural degraded forest and that of litter in *Acacia* plantation, while there was alternate release and accumulation of P in the leaf litter of teak and eucalyptus in their respective plantations (Fig. 7b). The C/P ratios ranged respectively from 144 in acacia leaf litter in August to 3224 in eucalyptus leaf litter in March.

Potassium is a nutrient that is released faster, and its concentration fell by 95% in natural degraded forest and by 92% in *Acacia* plantation in the first six months, while it dissipated completely in teak and *Eucalyptus* plantations in the first five months. The final concentrations of K in teak and eucalyptus leaf litter were 0.052% and 0.044%, while those in degraded forest and *Acacia* plantation were 0.142% and 0.102%, respectively (Fig. 6c). The K release in leaf litters of the natural degraded forest and the plantations is shown in Fig. 7c.

DISCUSSION

Leaf litter decomposition has been mathematically modeled in the various ways possible, like single exponential, double exponential, straight line, asymptotic, power models; the most commonly used being the single exponential model, where the relative decomposition rate is constant. As decomposition proceeds, the decomposers utilize the soluble components and relatively easily degradable components like sugars, starches, and proteins. Thus during the initial phases, the decomposition rate is higher than in the later phases, the more recalcitrant materials like lignin, tannins, celluloses, and hemicelluloses being decomposed at much slower rates (Loranger *et al.* 2002). While the absolute decomposition decreases as time increases, it is possible to have a constant relative decomposition rate (Wieder & Lang 1982). But in the present study the constant rate of decomposition was not observed, even though the best fit mathematical model was the single rate ex-



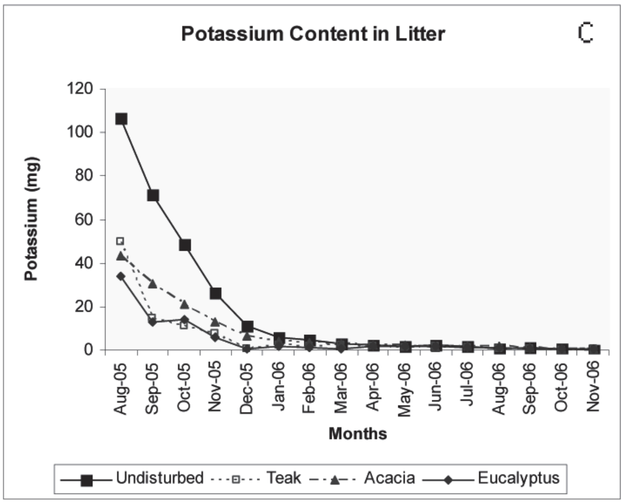


FIG. 7. Nutrient content in leaf litter across various land-use patterns
(a) Nitrogen content in litter
(b) Phosphorus content in litter
(c) Potassium content in litter

ponential model. In the present study, it was noted that leaf litter decomposition rate constants depended on the type of land-use, and was highest for the natural degraded forest and lowest for eucalyptus plantation, which was probably because of the presence of more recalcitrant materials in the eucalyptus leaf litter. In the present study, the type of land-use is synonymous with the leaf litter contained in it, hence the effects of the land-use and the effects of the litter type are inseparable.

The higher rate of weight loss is observed across the tree-plantations and the degraded forest during monsoon seasons, particularly during the NE monsoon, which can be very clearly observed in the significant positive correlations of temporal variations in leaf litter decomposition rates with rainfall levels. The mechanisms by which more rapid decomposition occurred during the monsoon season are many, mainly including the leaching of water-soluble components from the litter mass (Parsons *et al.* 1990, Tietema & Wessel 1994, Couteaux *et al.* 1995, Reddy 1995a). Many earlier studies have shown increased rates of decomposition with increased rainfall and decreased decomposition under drier conditions (Reddy 1995a, Lensing & Wise 2007), which could have indirectly affected the rate of decomposition through direct influence on the associated micro-organisms and decomposer fauna (Tietema & Wessel 1994, Reddy 1995b, Vanlauwe *et al.* 1995). This correlation has been demonstrated in temperate deciduous forests, tropical forests, and grasslands (Knutson 1997, Austin & Vitousek 2000, Salamanca *et al.* 2003). Rainfall directly impacts litter breakdown in the initial stages of decomposition through leaching of soluble compounds (Couteaux *et al.* 1995). Tietema and Wessel (1994) found that leaching accounted for 21% of the mass loss of oak litter during the initial six weeks of decomposition. Aspen leaves also exhibit rapid initial losses due to leaching (Parsons *et al.* 1990). In addition to the direct effect of precipitation via leaching, rainfall can also indirectly affect decomposition through direct impacts on the microbes and fauna (Reddy 1995b, Vanlauwe *et al.* 1995). It has been found that many different kinds of soil micro-arthropods, particularly Collembola and Acarina, become abundant during availability of greater and favorable moisture conditions, thus increasing comminution of leaf litter and enlarging its surface area for more microbial activity and release of nutrients (Reddy 1995a, Frampton *et al.* 2000, Blackburn *et al.* 2002, Lindberg *et al.* 2002, Wiwatwitaya & Takeda 2005).

A higher *k* value indicates a greater decomposition rate and it was highest in natural degraded forest. Although the decomposition rate of leaf litter in the forests was significantly higher than that of tree-plantations, as has been pointed out in many earlier studies (Lisanework & Michelsen 1994, Loranger *et al.* 2002, Attignon *et al.* 2004) as well as in the present one, it was observed that acacia plantation came closer to the degraded forest in terms of leaf litter decomposition in the present study. The dendrogram also revealed that the teak and eucalyptus plantations, and the degraded forest and acacia plantation, are closer in terms of monthly leaf litter decomposition rates. Hence, *Acacia* plantation may be a better and preferred pattern of land-use compared to the other two tree-plantations from a reforestation point of view.

Nitrogen concentration in leaf litter during decomposition determines microbial activity and influences mineralization of the organic carbon. It is, therefore, one of the key limiting factors in litter decomposition. The C/N ratio of less than 20, or N concentration of more than 2.5%, indicate the mineralization of N leading to a faster decomposition of leaf litter in the soil-litter system. By contrast, in cases of higher C/N ratios N tends to be immobilized and litter decomposition is retarded (Heal *et al.* 1997, Torreta & Takeda 1999, Xuluc-Tolosa *et al.* 2003). While the nitrogen content decreased due to a continuous release of nitrogen, there was an increase in N concentration in the leaf litter throughout the study period in natural degraded forest and *Acacia* plantation, which could be due to the interplay of the mechanisms of nitrogen fixation, absorption of atmospheric ammonia, and microbial immobilization along with the mineralization. Many earlier studies have reported an increase in N concentration during leaf litter decomposition across various forest and tree-plantation ecosystems (Blair & Crossley 1988, Reddy & Venkataiah 1989, Bargali *et al.* 1993, Mudrick *et al.* 1994, Couteaux *et al.* 1998, Taylor 1998, Vesterdal 1999, Musvoto *et al.* 2000, Ribeiro *et al.* 2000, Devi & Yadava 2007). However, in a central African rainforest on low-nutrient sandy soils (Chuyong *et al.* 2002), the increase in N concentration was accompanied by actual accumulation of nitrogen instead of the release seen in the current study. Reyes-Reyes *et al.* (2003) reported significant increase in mineralization of N when leaf litter derived from plants like *Acacia* and *Prosopis* with nitrogen-fixing capabilities were used in the central highlands of Mexico. Although the N concentration of the leaf litter increased over time in the teak and eucalyptus plantations, it did not do so uniformly but through sporadic phases of accumulation and release, which agrees with similar patterns observed in some earlier studies (N'goran *et al.* 2006, Goya *et al.* 2008). In the present study, accumulation of nitrogen was observed in the teak plantation during short periods in the final phases of the study, and in eucalyptus plantation during both the NE monsoon seasons of the study.

After a rapid release of relatively large quantities of P (more than 95% of initial concentration) during the first six months, its mineralization in the leaf litter was observed in the degraded forest and the acacia plantation. Its release was less and occurred only after periods of P accumulation in the teak and eucalyptus plantations. The immobilization of P occurred after initial release and depended on the C/P ratio; Stevenson (1986) reported lower than 300 C/P leading to its immobilization, whereas many other studies reported P mineralization at higher C/P ratios, ranging from 360 to over 1000 (Musvoto *et al.* 2000, N'goran *et al.* 2006, Goya *et al.* 2008). However, in a study in Amazonian forests, it was observed that phosphorus (both available P and total P) did not have an impact on the litter decomposition rates (McGroddy *et al.* 2004). In the present study, the leaf litter in the degraded forest had C/P ratios ranging from 213 to 1159, while it ranged from 144 to 932 in the *Acacia* plantation.

There was a rapid initial release of potassium in the leaf litter during decomposition across all the tree-plantations and degraded forest in the present study, which is expected because K is one of the most mobile nutrients in the soil-litter system (Attiwill 1968, O'Connell & Grove 1996). In the teak and eucalyptus plantations, the entire K concentration in the leaf litter was completely released in the first five months of decomposition. Zaharah & Bah (1999) reported a similar pattern, where they found that K was completely released in the first 30 days of litter decomposition in an Ultisol in Malaysia. Many other studies also reported a faster release of K from the leaf litter during decomposition, followed by a post-immobilization phase (Mudrick *et al.* 1994, N'goran *et al.* 2006, Goya *et al.* 2008). However, there are very few studies that reported an accumulation and retention of K in leaf litter during decomposition (Schoenlein-Crusius *et al.* 1999).

Conclusions. It is concluded that the leaf litter decomposition rate was highest in the natural degraded forest compared with afforested sites of teak, acacia, and eucalyptus plantations. The litter decomposition rates of plantations and forest were strongly positively correlated with the temporal variation in rainfall. Cluster analysis of decomposition pattern showed two clusters: a teak and eucalyptus plantation pair and a degraded forest and acacia plantation pair. Acacia plantation was found to be closer to degraded forest in terms of litter decomposition rates and could be recommended as the better land-use strategy. While there was a continuous release of N, the concentration of N increased in the leaf litter. K was released rapidly in all the land-uses while phosphorus was released (more slowly with periods of accumulation in between) across the plantations and the degraded forest.

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