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Influence of leaf litter quality on N mineralization in soils of subtropical humid forest regrowths

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Abstract Laboratory net N mineralization as influenced by leaf litter quality of several subtropical tree species was studied in soils of forest regrowths of three different age groups. Concentrations of NH_4^+ and NO_3^- in the soil generally increased with age of forest regrowth. However, during incubation concentrations fluctuated markedly. In the "soil only" treatment, the cumulative N mineralization, ammonification and nitrification rates were highest in soils of the 13-year-old regrowth, followed by those of the 16- and 7-year-old regrowths. Soils from all three regrowths planted with *Quercus dealbata* had greater N mineralization rates than soils planted with *Pinus kesiya*. Overall, leaf litter of *Schima khasiana* showed the highest release of N, followed by leaf litter of *Q. griffithii*; greatest immobilization of N was recorded for *Rhododendron arboreum* leaves and *P. kesiya* needles. The percentage of N accumulated/depleted from the leaf litter correlated positively with the initial N concentration, and correlated negatively with the lignin content and C/N ratio.

Key words N mineralization · Leaf litter · Forest regrowths · *Schima khasiana* · *Quercus dealbata*

Introduction

Typically, 70–90% of nutrients needed annually for forest growth are derived from the decomposition of organic detritus (e.g. Vogt et al. 1991). Decomposition is a complex microbe-fauna mediated process which is accelerated by environmental conditions that enhance faunal and microbial activity (Swift et al. 1979). Substrate quality (initial chemical composition of decomposing material) is a critical factor in determining the rate of litter decay and nutrient release (Bloomfield et al. 1993). Chemical indices of the residue quality are concentrations of C, N, P, hemicellulose, cellulose, lignin, polyphenols etc., and C/N and lignin/N ratios.

Loss of nutrients is minimal in undisturbed forests and any deficit is balanced by inputs from various sources. This dynamic equilibrium is often disturbed by various anthropogenic activities. The resulting losses of nutrients can, however, be minimized by synchronizing the supply of nutrients with plant growth demand (Myers et al. 1994). One way of achieving this synchrony is through manipulating the quality and quantity of organic inputs on the forest floor. In order to examine this, the initial chemical composition of litter from tree species growing in three different age groups of forest regrowths was determined, and their effects on N mineralization were studied under laboratory conditions.

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Materials and methods

Study sites

Soil and leaf litter samples were collected from 7-, 13- and 16-year-old forest regrowths located at high altitude (1850–1900 m asl) in Meghalaya, India (25° 34′N, 91°56° E). The average annual rainfall is 2500 mm in this region and the mean maximum and minimum air temperatures are 26°C and 14°C, respectively. Detailed vegetation and soil analysis are summarized in Arunachalam et al. (1996a, b) and Maithani et al. (1996). In brief, the soil of the area is lateritic (oxisol), which is slightly acidic (pH 5.12–5.26) and rich in organic matter (6.2–10.7%). The main vegetation is subtropical wet hill forest (Champion and Seth 1968) and the dominant species of the region are *Quercus* spp., *Schima* spp., *Rhododendron* spp. in the virgin forests and *Pinus kesiya* in the degraded ones.

Soil and litter sampling and analysis

Surface soil (0–10 cm) from the 7-, 13- and 16-year-old forest regrowths was collected in bulk during April 1996. The field soil was

Table 1 Major soil properties (0–10 cm depth) in the three forest regrowths

Parameters	Forest regrowth		
	7-year-old	13-year-old	16-year-old
Physical			
Textural class	Sandy loam	Sandy clay loam	Clay loam
Bulk density (g cm^3)	1.3	1.3	1.4
Water holding capacity (%)	53.6	64.5	78.6
Chemical			
Cation exchange capacity (mEq 100 g^{-1})	9.2	16.3	17.7
pH (H_2O)	5.2	5.3	5.1
Organic matter (%)	6.2	9.3	10.7
Total Kjeldahl N (%)	0.4	0.5	0.6
Available P[a] (μg g^{-1})	7.0	12.0	14.2
Microbial[b]			
Biomass C (μg g^{-1})	386	729	1189
Biomass N (μg g^{-1})	62	105	126

[a] Extracted with 0.5 M potassium bicarbonate
[b] Determined according to chloroform-fumigation extraction procedure given in Anderson and Ingram (1993)

sieved through a 2-mm mesh, homogenized separately for each stand, and initial pH, moisture content and NH_4^+-N and NO_3^--N were determined according to Anderson and Ingram (1993). The remaining soils were stored at 4 °C until use. Care was taken to remove the smaller organic matter like fine roots, etc. from the soil before analysis. Fresh leaf litter samples of dominant tree species were collected from five randomly placed litter traps (1 m×1 m) on the forest floor of the three regrowths during the peak litterfall period (March–April). The leaf samples were sorted according to species, air-dried and chopped approximately into 1-mm sections using sterilized scissors. Though it is generally accepted that such finely chopped litter provides a uniform substrate when added to soil incubations, the fact that litter decay and mineralization rates may not compare to the field situation could not be completely ruled out. Subsamples of leaf litter were oven-dried at 80 °C in order to determine their dry weights. The ash content of plant material was determined by igniting the sample in muffle furnace at 550 °C for 6 h. The C content was taken as 50% of the ash-free weight. Total Kjeldahl N (TKN) was determined using a TECATOR 1030 autoanalyzer. Total P was estimated colorimetrically according to the molybdenum blue method (Anderson and Ingram 1993). Lignin content of the samples was determined by the standard technique given by Peach and Tracey (1955). All analyses were done using three replicats for each sample. The physico-chemical and microbial properties of the soils used in the incubation study have been reported previously (Arunachalam et al. 1996a; Maithani et al. 1996) and are summarized in Table 1.

Laboratory N mineralization

One-hundred-gram samples of field-moist soil from each forest regrowth were placed into 250-ml polyethylene beakers, and adjusted to 60% of their water-holding capacity. Soil was incubated for 7 days at room temperature to allow microbial activity to settle down. The leaf litter from each forest regrowth was then added to their respective soils at a loading rate of 0.01 g plant material g^{-1} oven-dried soil and was mixed thoroughly. The beakers were sealed with polythene sheets and incubated for 90 days at 25±1 °C in a temperature- and light-controlled BOD incubator (SICO).

For the 7-year-old regrowth soil, the leaf litter treatments were soil plus *P. kesiya* (needles), and soil plus *Quercus dealbata.* For the 13-year-old regrowth soil, soil plus *P. kesiya* and soil plus *Q. dealbata* treatments were set up. Five treatments were executed for the soils of the 16-year-old regrowth: (1) soil plus *P. kesiya,* (2) soil plus *Q. dealbata,* (3) soil plus *Q. griffithii,* (4) soil plus *Schima khasiana* and (5) soil plus *Rhododendron arboreum.* For all three stands, a "soil only" treatment served as the control.

About 27 replicates for each treatment were set up for the experiment. The moisture content of the incubated soil samples was kept constant throughout the experiment by periodic addition of deionized water. The concentrations of NH_4^+-N and NO_3^--N in soil were measured photometrically at 2, 4, 8 and 12 weeks, according to Anderson and Ingram (1993).

The net N mineralization rate was calculated by subtracting the initial inorganic N (NH_4^+ plus NO_3^-) present in the soil from the N accumulated in the soil during the respective incubation period:

$$\text{N mineralization rate}\,(\mu g\,g^{-1}\,day^{-1}) = \frac{\text{Final concentration} - \text{Initial concentration}}{\text{Incubation time (days)}}$$

By subtracting the total extractable N in the control from that of the leaf litter plus soil treatment, accumulation or depletion of inorganic N attributable to the presence of leaf litter was calculated. The difference in concentration was then divided by the initial concentration of leaf N added to each incubation, and the fraction thus obtained was multiplied by 100 to express the result as a percentage of the total, initial leaf N added.

Statistical analysis

Tukey's test was used to determine the statistical significance of variations among the chemical properties of the leaf litter when added, including the mineral N concentration. Linear regressions were done following Zar (1974), wherever necessary.

Results

Chemical composition of leaf/needle litter

Concentrations of C and lignin and C/N and lignin/N ratios gradually increased in litter samples of the commonly occurring species (*P. kesiya, Q. dealbata*); these increases were generally statistically significant ($P<0.05$); nevertheless, C and lignin concentrations in litter of these species in the field remained more or less the same in the 13- and 16-year-old regrowths. The P concentration generally decreased with regrowth age, while N concentrations did not show significant variation between stands. *P. kesiya* generally had significantly ($P<0.05$) greater concentrations of C and lignin than *Q. dealbata,* and C/N and lignin/N ratios were also significantly ($P<0.05$) higher in *P. kesiya* needles. However, N and P concentrations were lower in *P. kesiya* compared to *Q. dealbata*. Among the tree species selected from the 16-year-old regrowth, *S. khasiana* had the highest concentration of N and P followed by *Q. griffithii, Q. dealbata* and *R. arboreum* in descending order. Lignin content was lowest in *Q. dealbata* and *S. khasiana* and highest in *P. kesiya* and *R. arboreum* litter (Table 2). C/N and lignin/N ratios were lowest for *S. khasiana* and highest for *R. arboreum* leaf litter.

Table 2 Initial chemical composition of the leaf litter of dominant tree species in the three forest regrowths. Values followed by the same letter are not significantly different at $P < 0.05$

Sources of litter in different regrowths	Chemical properties (%)					
	C	N	P	Lignin	C/N	Lignin/N
7-year-old regrowth						
Pinus kesiya litter	40.80a±0.16	0.80a±0.01	0.098a±0.001	36.2a±1.3	51.0a	45.3a
Quercus dealbata litter	36.08b±0.29	0.84a±0.01	0.121b±0.008	18.3b±0.2	42.9b	21.8b
13-year-old regrowth						
P. kesiya litter	47.60a±3.21	0.73a±0.01	0.068a±0.003	43.3a±2.9	65.2a	59.4a
Q. dealbata litter	37.30b±1.09	0.87b±0.02	0.089b±0.001	24.4b±1.3	42.9b	28.0b
16-year-old regrowth						
P. kesiya litter	47.90a±2.87	0.70a±0.02	0.054a±0.001	45.1a±2.9	68.4a	64.4a
Q. dealbata litter	39.30b±1.62	0.78a±0.06	0.079b±0.001	24.0b±1.1	50.4b	30.8b
Quercus griffithii litter	36.40bc±0.81	0.83b±0.01	0.058ac±0.002	36.8c±1.3	43.9c	44.3c
Schima khasiana litter	32.10d±0.87	1.09c±0.01	0.087d±0.003	23.2bd±0.9	29.5d	21.3d
Rhododendron arboreum litter	42.30e±1.87	0.60d±0.01	0.044e±0.001	41.3ae±1.7	70.5ae	68.8ae

Mineral N flux in soil during incubation

Initially, the concentration of total inorganic N was 8.25, 13.49 and 16.54 μg g^{-1} in the soils of the 7-, 13- and 16-year-old forest regrowths, respectively. NH_4^+ and NO_3^- concentrations tended to be higher in soil from the older stands at the start of the experiment and reduced with stand age. NO_3^- levels in the controls remained almost constant for the initial 30 days. In the controls, after day 30, there was a two-fold increase in NO_3^- levels in the soil of the 13-year-old regrowth, and about a three-fold increase in the soils of 7- and 16-year-old regrowths by day 60. Subsequently, the NO_3^- level remained more or less the same for the next 30 days, except in soil of the 13-year-old regrowth, where an increase in the NO_3^- level was recorded during this period (Fig. 1).

The concentration of NH_4^+-N in the control as well as in the litter-amended soils showed a gradual increase during the initial 15 days of incubation. Subsequently, a sharp decline was observed in the levels of NH_4^+-N in soils of the 7- and 16-year-old regrowths between day 15 and day 30, followed by a gradual increase up to day 60 of the incubation. The NH_4^+ level tended to increase, however, until day 90 in the soil of the 7-year-old regrowth. Two peaks were observed in the concentration of NH_4^+-N in the soil of the 16-year-old regrowth: one after 15 days and another after 60 days of incubation. In the soils of the 13-year-old regrowth, the level of NH_4^+-N showed a steady increase during the initial 60 days of incubation, after which it dropped significantly in both control and litter-amended soils.

N mineralization or immobilization in soil

The net N mineralization rate (μg g^{-1} day^{-1}) was generally lower in the litter-amended soils when compared to controls after 15 days of incubation. In control as well as litter-amended soils of the 7- and 16-year-old regrowths, im-

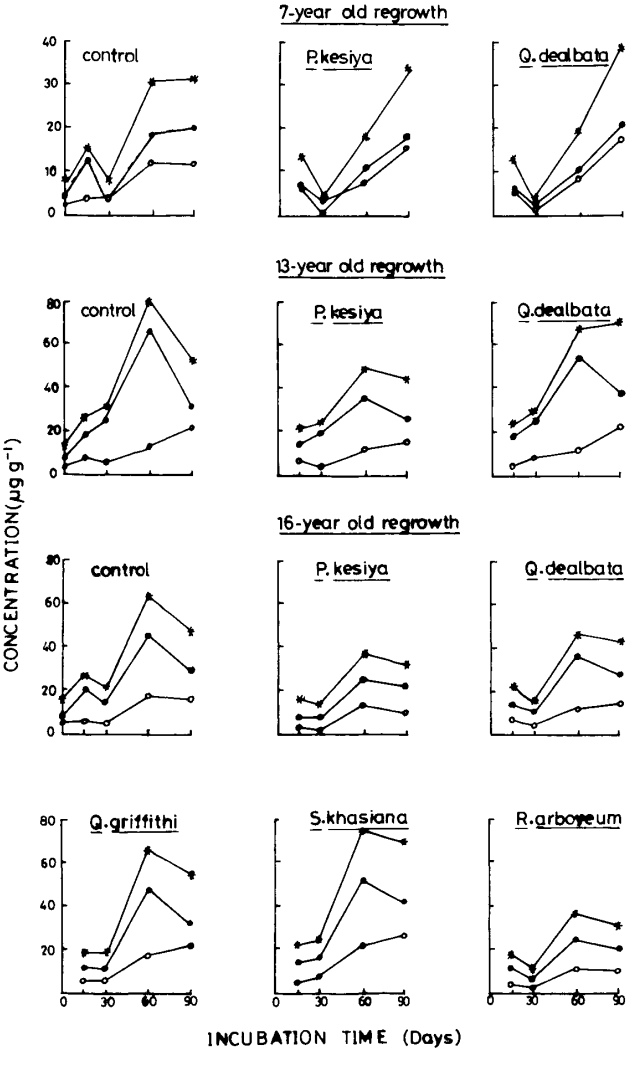

Fig. 1 Changes in soil inorganic N (μg g^{-1} dry soil) during 90 days of incubation (25 °C, 60% water holding capacity). ○ NO_3^--N, ● NH_4^+-N, * total-N (NO_3^--N plus NH_4^+-N)

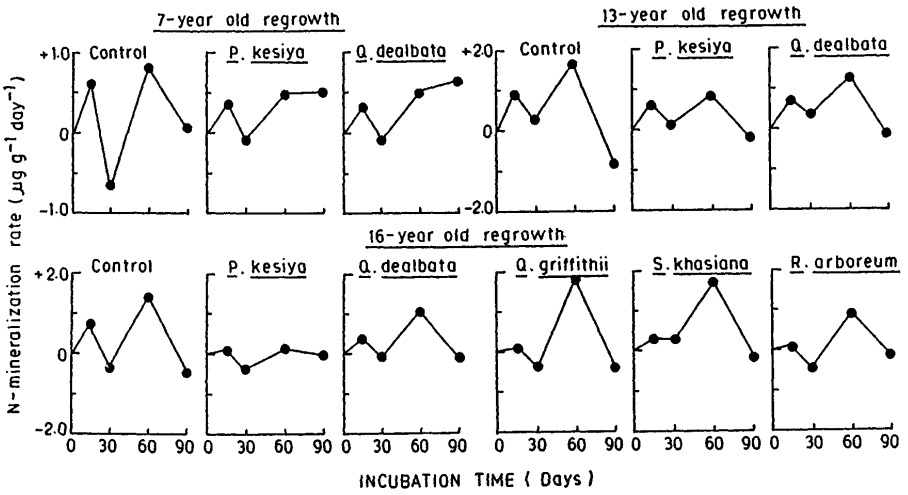

Fig. 2 Net N mineralization rate (µg g^{-1} day^{-1}) during 90 days of incubation of soils of the three forest regrowths

Table 3 Ammonification, nitrification and N mineralization rates of soils from the three forest regrowths amended with leaf litter over 90 days of incubation. For abbrevications, see Table 2

Treatment/litter source	Ammonification (µg g^{-1} day^{-1})	Nitrificaiton (µg g^{-1} day^{-1})	N mineralization (µg g^{-1} day^{-1})
7-year-old stand			
Control	0.172	0.100	0.271
Soil + *P. kesiya*	0.156	0.137	0.287
Soil + *Q. dealbata*	0.183	0.159	0.342
13-year-old stand			
Control	0.254	10.76	0.431
Soil + *P. kesiya*	0.199	0.130	0.330
Soil + *Q. dealbata*	0.342	0.187	0.529
16-year-old stand			
Control	0.226	0.122	0.348
Soil + *P. kesiya*	0.142	0.045	0.187
Soil + *Q. dealbata*	0.209	0.095	0.305
Soil + *Q. griffithii*	0.259	0.162	0.585
Soil + *S. khasiana*	0.370	0.219	0.585
Soil + *R. arboreum*	0.118	0.033	0.152

mobilization was recorded for the period between the 15th and 30th day of incubation, except for *S. khasiana*-treated soil from the latter regrowth. The peak mineralization rate was observed on the 60th day of incubation, both in the controls and litter-treated soils of all the three forest regrowths (Fig. 2). Mineralization rates in the controls were significantly ($P<0.05$) higher in the soils of the 13- and 16-year-old regrowths compared to those of the youngest regrowth. The soils of the 13-year-old regrowth showed net N mineralization up to day 60, after which only immobilization occurred in the control and all the treatments.

Cumulative N mineralization, ammonification and nitrification rates were calculated at the end of the experiment, and the control soils of the 13-year-old regrowth exhibited the highest rates of ammonification, nitrification and net N mineralization, followed by the 16- and 7-year-old regrowths, respectively (Table 3). *Q. dealbata*-amended soils exhibited greater rates of N mineralization than *P. kesiya*-amended soils for all three forest regrowths. *S. khasiana*-amended soils from the 16-year-old regrowth had the highest rates of ammonification, nitrification and net N mineralization, whereas the lowest values were recorded for the *R. arboreum*-treated soils (Table 3).

Accumulation/depletion of N in leaf litter

The treatments which included leaf litter of either *Q. dealbata* or *P. kesiya* generally showed depletion/immobilization of N during the first 60 days of incubation in the soils of all three forest regrowths. There was a net release of N after 30 days of incubation in soils of the 16-year-old regrowth amended with leaf litter of *S. khasiana*. This gradually increased with incubation time. *Q. griffithii* litter also showed net release of N after 60 days of incubation. In contrast, *P. kesiya* litter exhibited N immobilization throughout the 90-day incubation of the soils from the 13- and 16-year-old forest regrowths. In the case of soil from the 7-year-old regrowth, slight mineralization was recorded for *P. kesiya* leaf litter after 60 days of incubation (Fig. 3). Overall, leaf litter of *S. khasiana* showed the highest release of N followed by *Q. griffithii*; greatest immobiliza-

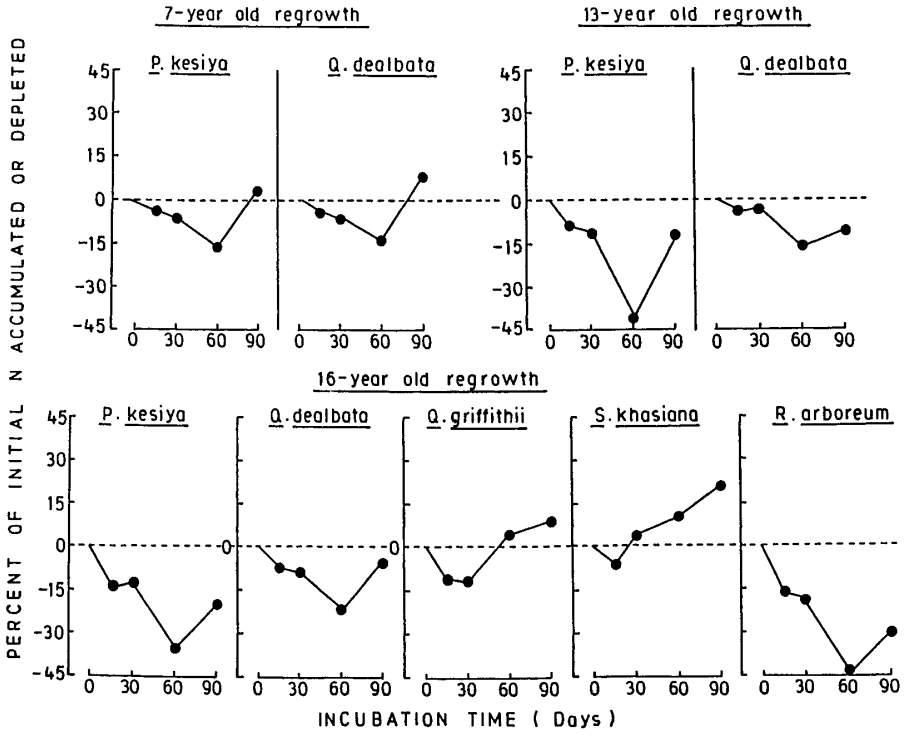

Fig. 3 Net N accumulated or depleted from leaf litter of various species during 90 days of laboratory incubation

Table 4 Correlation coefficients (r) of correlations between initial chemical compositon of litter and fraction of leaf litter N mineralized/immobilized during different time intervals ($n=9$). *N. B.* Data were correlated irrespective of species and stand

Incubation time (days)	Chemical properties (%)					
	C	N	P	Lignin	C/N	Lignin/N
15	–0.438	0.604	0.887**	–0.678*	–0.654*	–0.766**
30	–0.680*	0.922***	0.766**	–0.760**	–0.872**	–0.877**
60	–0.871**	0.872**	0.441	–0.604	–0.937***	–0.759**
90	–0.831**	0.928***	0.673*	–0.728**	–0.973***	–0.868**

* $P<0.05$; ** $P<0.01$; *** $P<0.001$

tion occurred in the leaf litter of *R. arboreum*, followed by that in the needles of *P. kesiya.*

Relationship between accumulation/depletion and initial leaf N

There were positive correlations between the percentage of N accumulated in, or lost from, leaf litter and the initial N concentration (Table 4). The P concentration in litter showed a very weak, positive correlation with both the percentage of N accumulated and that lost, but these relationships were not significant. C, lignin, C/N and C/P ratios showed significant ($P<0.001$) negative correlations with N accumulation/depletion.

Discussion

Residue quality

The initial chemical composition of litter determines the turnover rate of organically bound nutrients. The initial total N concentrations (0.60–1.09%) and lignin concentrations (23–45%) of leaf litter of the study species are well within the range (0.36–3.90% and 4.5–46%, respectively) reported by Vogt et al. (1986, 1991), Van Vuuren et al. (1992) and Myers et al. (1994) for various tropical and subtropical tree species. Species with more sclerenchymatous cells (e.g. *P. kesiya* and *R. arboreum*) also had greater lignin concentrations and lower nutrient levels. The C/N ratio, which varied between 29.5 and 70.0, indicated a wide range of litter qualities.

Mineral-N dynamics

NH_4^+-N was the dominant form of inorganic N in the soils of all the three regrowths. It was 1.4% higher than NO_3^--N in the field soil. The higher concentration of NH_4^+-N compared to NO_3^--N in this study may be attributed to the slightly acidic nature of the soils (ca. pH 5.2) which might have inhibited the growth and activity of autotrophic nitrifiers in the soils (Chao et al. 1993). NH_4^+-N and NO_3^--N together constituted only 0.21%, 0.27%, and 0.28% of the

TKN in soils of the 7-, 13- and 16-year-old regrowths, respectively. This range is in agreement with that reported by Singh et al. (1981) who found that most of the N in the soils they studied was organically bound. However, the NH_4^+/NO_3^- ratio generally increased during the laboratory incubation. There were situations when the ratio went even below the initial value, i.e. mostly in the residue-added and control soils of the 7-year-old regrowth, indicating a low rate of ammonification and/or possible immobilization of NH_4^+ in the microbial biomass. This ratio fluctuated greatly in soils of the 7- and 13-year-old regrowths during the experiment, and a maximum value of 5.17 was observed in soil of the latter stand. In general, the ratio was higher during the first 30 and 60 days of incubation. This gives an indication of the optium duration for studies which examine mineral-N dynamics using laboratory incubations of soil. For example, after 60 days of incubation, a two- to six-fold increase was observed in the NH_4^+ and NO_3^- concentrations.

Laboratory net N mineralization

The cumulative ammonification and nitrification rates recorded after 90 days of incubation ranged between 0.12–0.37 μg g^{-1} day^{-1} and 0.045–0.219 μg g^{-1} day^{-1}, respectively. These rates are slightly greater than those measured for the same soils in situ (0.14–0.21 μg g^{-1} day^{-1} and 0.12–0.15 μg g^{-1} day^{-1}, respectively; Maithani 1997, unpublished). This is understandable, as in the field leaching is predominant as this area has a high rainfall; other factors also contribute, like immobilization and moisture limitations. Owing to the greater potential of the needles of *P. kesiya* to immobilize N, a 10–59% decrease in the net ammonification rate was observed, in the treatment which included this litter when compared to the control. However, immobilization by *P. kesiya* needles was highest when mixed with soil from the 16-year-old regrowth. *Q. dealbata* addition increased the cumulative ammonification rates relative to controls by 6% and 25% in the treatments employing soil from the 7- and 13-year-old regrowths, respectively, while it resulted in a 8% decrease in treatments where soils of the 16-year old forest were used. In the soils of the oldest regrowth, addition of *S. khasiana* litter, however, resulted in a ca. 38% increase in the ammonification rate relative to the control, while that of the *Q. griffithii* treatment only increased by 12%. The highest decrease (91%) in the ammonification rate was observed in the *R. arboreum*-amended treatment followed by that of the *P. kesiya*-amended treatment (59%).

On average, the ammonification, nitrification and net N mineralization rates in soil increased with stand age up to 13 years of regrowth (as shown by results of the *P. kesiya* and *Q. dealbata* treatments) and then dropped sharply. The low rate of N mineralization and, in particular, nitrification, in soils from the 16-year-old regrowth could be due to a ready supply of available C to soil microbes resulting in increased rates of internal N cycling, and excessive heterotrophic immobilization. This would reduce N availability to nitrifiers which may lead to low activity of the nitrifier population (Adams and Attiwill 1986). Despite decreased net N mineralization in the oldest regrowth, the inorganic N pool showed a steady increase during forest recovery (as shown by the control soils). This could be due to higher in situ net N mineralization in the older stands (152–173 kg ha^{-1} $year^{-1}$) than in the 7-year-old stand (142 kg ha^{-1} $year^{-1}$), reduced uptake by plants and/or low leaching losses of inorganic N (Maithani 1997, unpublished).

Role of residue quality in N-release dynamics

Compared to the controls, the net N mineralization rate increased by about 6% and 20% with the addition of *P. kesiya* needles and *Q. dealbata* leaf litter, respectively, in the 7-year-old regrowth soil. Whereas in the 13-year-old forest soil, there was a decrease in N mineralization by about 31% and 19%, and in the 16-year-old regrowth by 87% and 14%, in the *P. kesiya* and *Q. dealbata* treatments, respectively (Table 3). This latter trend could well be explained by the decrease in initial N levels, and increase in lignin concentrations, in the needles of *P. kesiya* and leaf litter of *Q. dealbata* with stand age. A relatively greater initial N concentration and lower lignin content in the needles of young *P. kesiya* present in the 7-year-old regrowth caused rapid mineralization. With the progression of understorey regrowth vis-a-vis tree growth, the lignin content in the residue increased, and this led to lower N-release rates. This appeared to be the case with *Q. dealbata* litter from the 7-year-old regrowth when compared to the other two, older, regrowth.

The immobilization or depletion of N observed in the present study can be explained on the basis of the N content of the litter samples used. However, the possibility that C added in fresh, ground leaf litter affected soil microbial activity (due to a "priming effect"), and hence the net mineralization of soil N, could not be ruled out completely. As the N content of the litter was less than 2%, the initial immobilization observed was expected. Nevertheless, the rapid release of N from *S. khasiana* leaves into the soil of the 16-year-old regrowth is attributed to its low lignin content. Though the initial N content of these leaves was less than 2%, the low lignin and low C/N ratio might have contributed to the release of N after 15 days of incubation (Fig. 2). Evidently, a strong positive relationship was observed between initial N levels and the percent age of leaf N accumulated/depleted during incubation (Table 4).

Significant negative correlations between the initial lignin content and percentage of N accumulated/depleted in the litter during different intervals of incubation suggest that, in addition to N content, lignin also exerts a strong effect on N release from leaf litter. For example, leaves of *R. arboreum* which had high lignin levels and low N contents decomposed slowly, while *S. khasiana* and *Q. griffithii* leaves, which had high N levels and low lignin contents, decomposed at a faster rate and released N rapidly.

The relatively slow rate of N release from the leaf litter of *R. arboreum* and *P. kesiya* is due mainly to the sclerophyllous nature of the leaves. The sclerenchymatous tissue, and the thick cuticle of these leaves are reported to resist the enzymatic attack of microbes and physically interfere with the degradation of complex chemicals in the cell walls and thus exert some control over decay and nutrient release rates (Bloomfield et al. 1993). These findings are in accordance with the results of the field studies reported here on leaf litter decomposition and N mineralization, where the lowest N mineralization constant (0.62) was recorded for *R. arboreum* and the highest for *Q. griffithii* (1.28). Melillo et al. (1982) found a significant, negative relationship between initial lignin/N and net decay rate. The present study confirms this observation, as both C/N and lignin/N ratios showed a significant ($P<0.001$) negative correlation with percentage of N accumulated/depleted.

In conclusion, the laboratory N mineralization in soil was significantly related to the residue quality of the litter, as the release of N from the leaves was regulated mainly by their initial N and lignin contents. Data on N immobilization or mineralization in various plant species and soils can readily be used in modelling studies to evaluate the long-term effects of organic inputs on soil fertility. Therefore, we recommend the following: (1) the forest floor litter should be protected from fire, predation and any other disturbances as it is a major source of soil organic matter and, of course, checks soil erosion to a great extent in natural forest ecosystems, especially in hilly regions; (2) N-poor soils should be amended with high-quality residues in order to sustain soil productivity. However, in order to reach any definite conclusion regarding residue management for the improvement of soil fertility, long-term in situ and laboratory studies are essential because, as shown in this study, plant materials may immobilize N initially and release it slowly.

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