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G. Seneviratne · L. H. J. Van Holm
L. J. A. Balachandra · S. A. Kulasooriya

Differential effects of soil properties on leaf nitrogen release

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Abstract Identifying the determinants of the N dynamics of plant prunings or litter is important for the efficient management of agroecosystems in order to improve their productivity. The plant materials in these ecosystems are managed as soil surface mulches or are incorporated into the soil. Numerous studies have been conducted to investigate which plant chemical parameter best governs N release. In these studies, different plant materials have been incorporated into a soil with a set of known characteristics. The objective of the present study was to examine the effects of different soil properties on N release from plant leaves, when they were incorporated into soils under non-leaching conditions. A laboratory incubation experiment (for 8 weeks) was carried out with dried and ground leaves of six leguminous plants and wild sunflower, which were mixed with three soils (alfisol; ultisol, udult; ultisol, humult). Leaf cellulose was the major chemical parameter that determined leaf N release in the alfisol and ultisol, udult. In the ultisol, humult, the C/N ratio and hemicellulose concentration were better related to N release. Cellulose was not a good indicator of N release in the ultisol, humult, possibly due to a low soil pH which did not favour the activity of the cellulose-degrading enzymes of microbes active in decomposition. Soil pH determined the specific C source that was used to generate energy for microbial action and N mineralization/immobilization. It also had an effect on the nitrification of the mineralized N. The levels of labile soil C fractions governed the mode or nature of N release (i.e. mineralization or immobilization). The levels of labile leaf C fractions incorporated into the soils governed the extent of N release. The soil N concentration in the decomposable organic matter pool, as compared to the leaf N concentration, determined whether leaf N limited its own release. It is recommended from this study that, in grouping different leaf materials as sources of N, the properties of soils into which they are incorporated should also be considered, in addition to leaf quality in terms of its chemical composition. In future studies, the relationships identified under laboratory conditions in this experiment should be verified under field conditions.

Key words Leaves · Decomposition · Nitrogen release · Soil properties

G. Seneviratne (✉) · L. H. J. Van Holm · L. J. A. Balachandra
Sri Lankan-Belgian Project on Biological Nitrogen Fixation (BNF), Institute of Fundamental Studies (IFS), Hantana Road, Kandy, Sri Lanka
Fax: +94-8-232131

S. A. Kulasooriya
Department of Botany, University of Peradeniya, Peradeniya, Sri Lanka

Introduction

Identifying the determinants of the N dynamics of plant prunings or litter is important for the efficient management of tropical agroecosystems in order to improve their productivity. Crop residues play a major role in supplying N and maintaining soil organic matter (SOM) in conventional agroecosystems. In agroforestry systems like alley cropping the prunings of N_2-fixing leguminous trees release N which is taken up by food crops (Kang et al. 1985). In alley cropping, under ideal conditions, nutrients contained in the prunings should be released at rates which are synchronised with the nutrient demand rate of the food crop. The plant materials in these systems are managed as soil surface mulches or are incorporated into the soil. The surface mulches are also subsequently incorporated into the soil after fragmentation due to catabolism and comminution by soil organisms.

Plant chemical parameters which determine N release are apparently ecosystem-specific, because, as was revealed recently, the degree of control of the chemical parameters on N release depends on the moisture level of the leaf-litter layer (Seneviratne et al. 1998), which

differs considerably in managed ecosystems as compared to natural ecosystems. Numerous studies have been conducted to investigate these chemical parameters in tropical agroecosystems (Jensen 1929; Vallis and Jones 1973; Melillo et al. 1982; Fox et al. 1990; Palm and Sanchez 1991; Oglesby and Fownes 1992; Handayanto et al. 1994; Constantinides and Fownes 1994; Seneviratne et al. 1998). Early studies showed the influence of the C/N ratio on N release of organic materials; those with low C/N ratios release N faster (Jensen 1929). However, Vallis and Jones (1973) observed a slow rate of N release from leguminous plant materials, though they had low C/N ratios; this was attributed to the presence of polyphenols, which bind proteins, reducing N release. Melillo et al. (1982) reported the importance of the lignin/N ratio in leaf litter decomposition dynamics, and Palm and Sanchez (1991) found that the polyphenol/N ratio was a better parameter than lignin and N concentrations alone for predicting leaf N release. But later on, Constantinides and Fownes (1994) observed that in a wide range of plant materials polyphenols were secondary to N in controlling N release, and that the N concentration explained most of the variation in the latter. Polyphenols are important only when they are in low concentrations under leaching conditions (Handayanto et al. 1994; Seneviratne et al. 1998), and also under non-limiting conditions of leaf N (Seneviratne et al. 1998). In the absence of leaching, some polyphenols are bound to proteins, thus delaying decomposition and N release (Handayanto et al. 1994). Thus, although there is no consensus in these studies regarding which chemical parameter is the best determinant of decomposition and N release, initial concentrations of C, N, lignin, polyphenols and their ratios with N are considered to be the major determinants.

In all previous studies, a soil with a set of known characteristics and a single moisture regime that is optimal for microbial decomposition has been used to study N release from plant materials. Our recent study demonstrated the influence of changes in soil moisture on leaf N release (Seneviratne et al. 1998). The present study illustrates the effect of changes in soil properties on the N release from plant leaves incorporated into soils under non-leaching conditions.

Materials and methods

Soils and plant materials

One alfisol from the dry zone and two ultisols (udult and humult) from the wet zone of Sri Lanka were collected at 0–30 cm depth from abandoned croplands colonized by herbaceous communities. The monthly average range of the minimum (coldest month) and maximum (warmest month) air temperatures of the dry and wet zones are 21–34 °C and 18–31 °C, respectively. The mean annual rainfall of the dry and wet zone is 1300 mm and 2300 mm, respectively. The soils were air-dried and sieved (<2 mm) to remove roots, stones and organic debris and analysed for basic chemical parameters (Table 1). SOM was fractionated to give cellulose, hemicellulose and lignin (Van Soest and Wine 1968) and soluble polyphenols (Anderson and Ingram 1989).

Fresh leaf material from six mature leguminous plants (*Gliricidia sepium, Cassia siamea, Crotolaria juncea, Flemingia congesta, Erythrina lithosperma* and *Acacia auriculiformis*) and wild sunflower (*Tithonia diversifolia*) were collected, oven-dried (65 °C for 72 h) and ground (<1 mm) before use. They were analysed for total N (Kjeldahl), organic C (Walkley and Black 1934), cellulose, hemicelluloses, lignin and soluble polyphenols (Table 2).

Laboratory experiment

An incubation experiment was carried out using 450-ml jars with screw caps. The prepared soils were mixed separately with ground leaf materials at a rate of 3 t dry weight ha^{-1} (ca. 0.24 g dry matter 100 g^{-1} dry soil), an average rate of organic material recycling in the tropics. Each jar was filled with 150 g of the mix-

Table 1 Initial characteristics of the three soils used in the study. WHC water-holding capacity

Characteristics	Alfisol	Ultisol, udult	Ultisol, humult
Organic C (%)	0.63	1.89	5.11
pH (H_2O)	6.02	6.23	4.47
Total N (%)	0.07	0.15	0.37
WHC (%)	54.3	45.3	66.8
Polyphenols (%)	0.40	0.63	0.31
Cellulose (%)	0.11	0.17	0.66
Hemicelluloses (%)	1.28	1.70	2.98
Lignin (%)	1.16	1.50	2.52
Sand (%)	64.2	51.7	55.8
Clay (%)	4.20	3.65	4.45
Silt (%)	31.7	44.7	39.4

Table 2 Initial concentrations of organic C, total N, polyphenols, cellulose, hemicelluloses and lignin in leaf materials used in the study

Species	C	N	Polyphenol	Cellulose	Lignin	Hemicelluloses
				g kg^{-1}		
Gliricidia sepium	342	28	19	159	142	112
Tithonia diversifolia	291	33	23	143	111	261
Erythrina lithosperma	293	41	26	182	117	361
Flemingia congesta	316	30	29	196	303	135
Crotalaria juncea	301	34	13	180	72	111
Cassia siamea	353	28	21	185	73	235
Acacia auriculiformis	321	22	23	191	201	62

ture. The mixtures in the jars were supplied with 35–50 ml of deionized water, depending on the water holding capacities (WHC) of the soils in order to adjust the moisture content to 50% of WHC. Each jar was supplied with ca. 3 ml of a minus-N solution (Stanford and Smith 1972) to optimize microbial action. The soils without the leaf materials served as the controls. Each mixture had four replicates. The jars were closed to minimise soil moisture loss and incubated at 27–30 °C for 8 weeks, during which time they were opened every other day to flush and refresh the gas phase.

At the end of the incubation period, subsamples (10 g) of soil were taken from the jars and analysed for exchangeable NH_4^+-N and NO_3^--N (Anderson and Ingram 1989).

Data analysis

Correlations and linear and non-linear regression analyses were carried out for leaf chemical parameters and percentage N released from the leaf materials. The regression analyses were confined to the data sets which showed high correlation coefficients. In the regression analyses, outliers were excluded to improve the goodness-of-fit. Significant differences in the amounts of NH_4^+-N, NO_3^--N and mineral N (NH_4^+-N plus NO_3^--N) released from different plant materials in the three soils were calculated using ANOVA and Duncan's multiple range test. All the statistical analyses were performed using SAS software (SAS 1987).

Results and discussion

E. lithosperma, *C. juncea* and *T. diversifolia* contained relatively high N concentrations (mean 36 g kg^{-1}), whereas *A. auriculiformis* showed the lowest N concentration (22 g kg^{-1}) of the species examined (Table 2). *F. congesta* and *A. auriculiformis* had high cellulose and lignin concentrations. *F. congesta* and *E. lithosperma* contained relatively high pholyphenol concentrations of 29 g kg^{-1} and 26 g kg^{-1}, respectively.

Table 3 shows the amounts of net mineral N produced from different leaf materials in the three soils during incubation. In these results, the amounts of NH_4^+-N do not reflect net NH_4^+-N produced during N release from the leaf materials, because nitrification converts a fraction of the NH_4^+-N to NO_3^--N. Therefore, the amounts of net N mineralized should be considered as net NH_4^+-N produced from the leaf materials.

In the alfisol, *F. congesta* and *C. juncea* showed the highest net NH_4^+-N concentrations after incubation (Table 3). Although *T. diversifolia* showed the lowest net NH_4^+-N concentration in the alfisol, the same species showed the highest concentration in the ultisol, udult. This was caused by differential responses of N release of the two soils to cellulose added through the leaf materials (Table 4). N release from the leaf materials incorporated into the alfisol was correlated positively with their cellulose concentrations, whereas in the ultisol, udult it correlated negatively with cellulose. Hence, in the alfisol, any increase in cellulose levels increased the percentage N release whereas in the ultisol, udult the inverse was found (Fig. 1). This could have been due to the utilisation of cellulose as the energy source for the basically microbial decomposition and N mineralization in the organic-matter-depleted alfisol compared to its use as the C source mainly for the growth of the microbial population in the ultisol, udult which had a medium SOM level (Table 1). In the ultisol, udult, therefore, a fraction of mineralized N was immobilized in the microbial biomass, thus reducing the amount of N released. These contrasting relationships of the two soils with different cellulose concentrations indicate that there may be a critical concentration of cellulose at which N release is maximized. It is worthwhile investigating this effect further, because it can have very important implications for the management of N release. Cellulose has been found to influence litter N mineralization in tropical alfisols (Mtambanengwe and Kirchmann 1995), because its availability determines the rate of N release in aqueous media poor in labile C (Bary et al. 1992). These results indicate that cellulose plays an important role as a C source in microbial decomposition and N mineralization/immobilization in tropical soils. Polyphenols were not important in determining N release (Table 4), because they were

Table 3 Net NH_4^+-N, NO_3^--N and mineral N (NH_4^+-N + NO_3^--N) release from leaf materials in the three soils during 8 weeks. Minus values show net immobilization. Values are the means of four replicates. LSD Least significant difference, CV coefficient of variation

Species	NH_4^+-N (g 100 g^{-1} N applied)			NO_3^--N (g 100 g^{-1} N applied)			N mineralized (g 100 g^{-1} N applied)				
	Alfisol	Ultisol, udult	Ultisol, humult	Alfisol	Ultisol, udult	Ultisol, humult	Alfisol	Ultisol, udult	Ultisol, humult	LSD (0.05)	CV (%)
Gliricidia sepium	37.8	67.0	−114	6.03	17.8	12.4	43.8	84.8	−102	8.02	40.1
Tithonia diversifolia	23.0	128	− 11.9	2.91	28.8	13.2	25.9	157	1.28	9.05	6.52
Erythrina lithosperma	41.1	53.7	121	7.43	14.9	14.2	48.5	68.6	135	9.37	4.92
Flemingia congesta	59.4	69.8	− 52.6	7.54	16.4	15.0	67.0	86.2	− 37.7	23.2	26.6
Crotalaria juncea	57.7	98.4	−128	9.73	29.3	14.2	67.4	128	−114	153	49.7
Cassia siamea	48.9	82.0	−209	8.77	21.2	−7.47	57.7	103	−217	22.6	53.5
Acacia auriculiformis	29.3	58.4	−117	2.13	17.9	7.36	31.4	76.3	−110	13.3	46.3
LSD (0.05)	4.05	2.54	74.0	0.43	1.40	2.12	4.20	3.40	73.5	–	–
CV (%)	5.37	3.58	56.9	7.60	3.78	12.1	6.69	3.74	65.3	–	–

Table 4 Pearson's correlation coefficients (r) between initial chemical parameters of leaf materials and their percentage N release in three soils. Values within parentheses indicate probability levels

Chemical parameters	N release (%)		
	Alfisol	Ultisol, udult	Ultisol, humult
C	0.173 (0.711)	−0.339 (0.452)	−0.772 (0.042)
N	0.241 (0.601)	0.135 (0.769)	0.736 (0.059)
Polyphenols	−0.136 (0.773)	−0.391 (0.386)	0.503 (0.250)
Cellulose	0.609 (0.147)	−0.620 (0.136)	−0.184 (0.692)
Hemicelluloses	−0.109 (0.816)	0.080 (0.864)	0.610 (0.145)
Lignin	0.088 (0.850)	−0.436 (0.329)	0.157 (0.738)
C/N	−0.209 (0.653)	−0.310 (0.496)	−0.729 (0.063)
Polyphenol/N	−0.295 (0.521)	−0.428 (0.337)	−0.083 (0.860)
Cellulose/N	−0.034 (0.942)	−0.441 (0.320)	−0.576 (0.176)
Lignin/N	−0.055 (0.907)	−0.458 (0.302)	−0.040 (0.932)
Hemicellulose/N	−0.141 (0.762)	0.160 (0.733)	0.356 (0.432)

not limiting under the non-leaching conditions imposed (Seneviratne et al. 1998).

In the ultisol, humult, C and N (hence the C/N ratio) correlated negatively and positively, respectively with the percentage N released from the leaf materials (Table 4). As the C/N ratios of the leaf materials increased, N release decreased, finally resulting in net N immobilization in the ultisol, humult (Fig. 2). This was due to an abundance of C relative to N (Mtambanengwe and Kirchmann 1995) in leaf materials incorporated into the soil rich in organic matter (Table 1). The C/N ratio has been identified as a good predictor of litter N release (Thomas and Asakawa 1993; Mtambanengwe and Kirchmann 1995; Vanlauwe et al. 1995). Although the cellulose concentration was not a good indicator of leaf N release, hemicelluloses correlated positively with the former in the ultisol, humult. This could have been a result of the low pH of the very acidic ultisol, humult (Table 1). The pH optima for the activity of cellulose-degrading enzymes in most terrestrial fungi lie between 4 and 7 (average, 5.5), whereas those of their hemicellulose-degrading enzymes range from 3.5 to 5 (average, 4.3. Wood and Kellogg 1988). Therefore, there is a tendency for microbes in ultisol, humults to utilize hemicelluloses to a greater extent than cellulose. This was proven by high, net NH_4^+-N and total N mineralization in this soil with *E. lithosperma* (Table 3), which was rich in hemicelluloses (Table 2), and was confirmed by the positive relationship between hemicelluloses and N release (Fig. 3). Leaf materials with hemicellulose concentrations >22% showed net N mineralization.

In the alfisol, all leaf materials showed net N mineralization, ranging from 25.9% for *T. diversifolia* to 67.4% for .*C juncea* (Table 3). Although net N mineralization was common in the ultisol, udult too, >100% net N mineralization was measured with *T. diversifolia, C. juncea* and *C. siamea.* This suggests that a fraction of native soil N was also released in addition to the whole amount of added leaf N mineralized. This could be attributed to a positive interaction between the added N and soil N, leading to a decrease in the size of the soil-derived N pool (the "priming effect"; Jenkinson et al. 1985). In the ultisol, humult, negative values of net N release were recorded with *G. sepium, F. congesta, C juncea, C. siamea* and *A. auriculiformis,* which indicated net N immobilization with these types of litter.

NO_3^--N production (nitrification) was higher in the ultisol, udult than in the alfisol (Table 3), because it was proportional to the supply of NH_4^+-N in the two soils (Table 3, Fig. 4). In general, NH_4^+-N availability

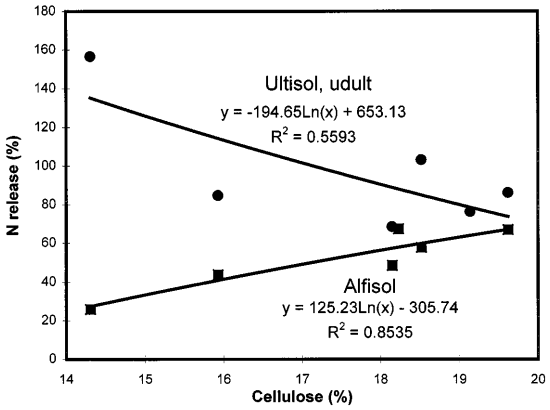

Fig. 1 Relationship between cellulose concentration of the leaf materials and their percentage N release, when incubated in alfisol and ultisol, udult for 8 weeks

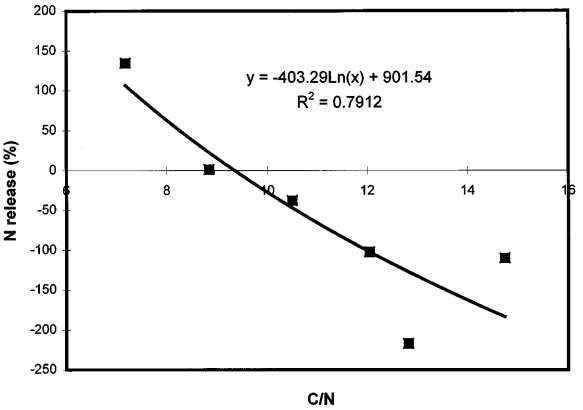

Fig. 2 Relationship between C/N ratio of the leaf materials and their percentage N release, when incubated in ultisol, humult for 8 weeks

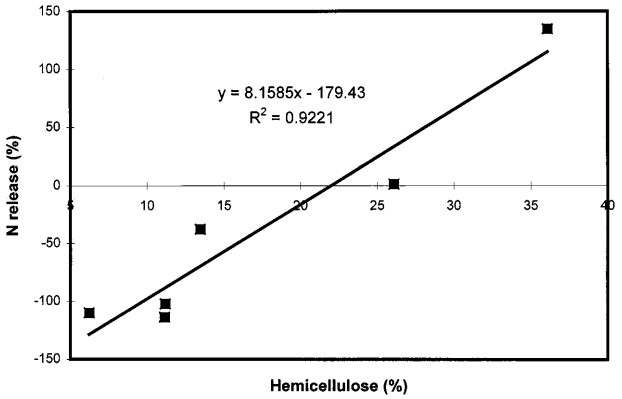

Fig. 3 Relationship between hemicellulose concentration of the leaf materials and their percentage N release, when incubated in ultisol, humult for 8 weeks

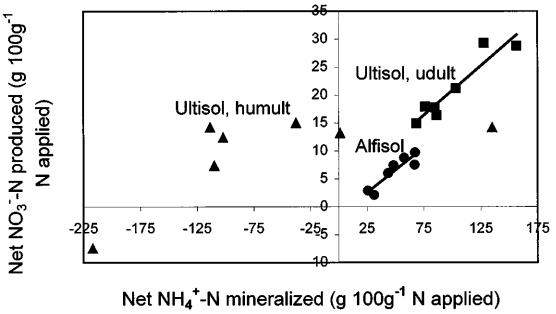

Fig. 4 Scatter plot of net NH_4^+-N mineralized versus NO_3^--N produced by the leaf materials in the three soils, when incubated for 8 weeks

governs the NO_3^--N production in soils that have favourable conditions for nitrification and an adequate supply of C (Tisdale et al. 1995). A similar trend was not observed in the ultisol, humult possibly due to an adverse pH for nitrification, i.e. less than 4.5 (Tisdale et al. 1995).

In the present study, it was clearly shown that different soil properties changed the mode and magnitude of N release of the same leaf materials. For example, *C. juncea* and *C. siamea* showed net N mineralization in the alfisol and ultisol, udult whereas the same species showed net N immobilization in the ultisol, humult. Amounts of N mineralized varied between the alfisol and the ultisol, udult, with ranges of 25.9–67.4% and 68.6–157%, respectively, for the same species. This difference in N dynamics was caused by the quality of the substrate in the soil, which affected the metabolic efficiency of the microbial decomposers (Rosswall 1981). In the alfisol and ultisol, udult the decomposable SOM had relatively high C/N ratios compared to that of the ultisol, humult (Table 5). The microbial biomass of the three soils also showed a similar trend, because the C/N ratio of microbes is influenced by the C/N ratio of the substrate (Tezuka 1990). The C/N ratios of the leaf materials incorporated into the soils ranged from 7 to 15,

Table 5 The C/N ratios of the decomposable soil organic matter (SOM) and microbial biomass C and N flushes (based on fumigation-incubation method) of the three soils (LJA Balachandra, unpublished)

Soil	C/N ratio of the decomposable SOM	Biomass flush ($\mu g\ g^{-1}$ soil)	
		C	N
Alfisol	26.0	17.7	7.95
Ultisol, udult	31.8	26.2	6.63
Ultisol, humult	6.36	23.7	27.3

and were higher than that of the decomposable SOM in the ultisol, humult. Thus, in the latter, the amount of leaf N incorporated into the soil was relatively low relative to the soil N level, hence the percentage of N release was limited (Seneviratne et al. 1998), as was revealed by the high positive correlation between the leaf N concentration and N release (Table 4). In the other two soils, N release was not limited by leaf N due to the relatively high concentration of the latter compared to that of the soil. The leaf C/N ratio also changed the C/N ratio of the substrate of the soils and hence affected the mode and magnitude of N release. This is because the C/N ratios of the substrate and microbial biomass are crucial parameters that determine the amount of N mineralized or immobilized (De Ruiter et al. 1993). These factors could have caused the basic differences in the N dynamics in the three soils, although further changes were possible in each soil type due to the modification of microbial action caused by the differences in the chemical composition of different leaf materials (Seneviratne et al. 1998), as was seen for the different species (Table 3). Therefore, in grouping different leaf materials as sources of N, the properties of the soils into which they are incorporated should also be considered, in addition to the leaf quality in terms of its chemical composition.

In conclusion, soil pH determines the specific C source that is used to generate energy for microbial action and N mineralization/immobilization. It also affects the nitrification of mineralized N. The levels of labile soil C fractions govern the mode or nature of N release (i.e. mineralization or immobilization). The levels of labile leaf C fractions incorporated into the soil govern the extent of N release. The N concentration of the decomposable organic matter pool of the soil relative to the leaf N concentration determines whether the latter limits the release of leaf N. In future studies, these relationships identified under laboratory conditions should be verified under field conditions.

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