Agroforest Syst (2008) 72:137–148
DOI 10.1007/s10457-007-9062-9

Interactions in decomposition and N mineralization between tropical legume residue components

Srisuda Thippayarugs · Banyong Toomsan · Patma Vityakon · Viriya Limpinuntana · Aran Patanothai · Georg Cadisch

Received: 30 August 2006 / Accepted: 26 March 2007 / Published online: 22 April 2007

Abstract In situ produced plant residues contain a mixture of different plant components of varying quality. To assess synergistic or antagonistic interactions occurring during the decomposition and mineralization of such mixtures, individual plant parts (stems, leaves, leaf litter and roots) or the mixture of stems, leaves and leaf litter of the agroforestry species pigeonpea (*Cajanus cajan*) or of crop residues of peanut (*Arachis hypogaea*) or of the weed hairy indigo (*Indigofera hirsuta*) were incubated in pots for 19 weeks. Periodically, remaining plant residues were sieved out (>2 mm), weighed and N content as well as soil mineral N determined. Above- and below-ground residues of peanut decomposed fastest and showed the largest N release in agreement with their high N concentration and low-acid detergent fibre (ADF) : N ratio. Hairy indigo was hypothesized to be of lower quality than pigeonpea because of its high-polyphenol content. However, it decomposed faster than pigeonpea, largely because of the higher N and lower lignin concentration of its components. Ranking of individual plant components for N mineralization resulted in the following pattern, leaves > leaf litter > roots > stems. In mixtures of the different plant components a similar species order in decomposition was obtained, e.g. peanut > hairy indigo > pigeonpea. The amount of N released from the mixture was dominated by stem material that comprised 46–61% of the mixture. The interactions in mixtures were relatively small for peanut (generally high-quality components) as well as for pigeonpea (low proportion of high-quality components, i.e. N rich leaf material). However, a positive interaction occurred during later stages of N mineralization in the mixture of hairy indigo as it had a significant proportion of N rich components and absence of highly reactive polyphenols. Thus, for plants with low to intermediate chemical quality attributes, manipulating plant composition (e.g. by varying harvest age, affecting stem and leaf proportions) will be important to obtain significant interactions during decomposition when its components are mixed.

Keywords *Arachis hypogaea* · Pigeonpea · *Cajanus cajan* · Hairy indigo · *Indigofera hirsuta* · Leaves · Stems · Litter · Roots · Mixture

S. Thippayarugs
Department of Agriculture, Khon Kaen Field Crops Research Centre, Khon Kaen 40000, Thailand

B. Toomsan · P. Vityakon · V. Limpinuntana · A. Patanothai
Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand

G. Cadisch (✉)
Institute of Plant Production and Agroecology, University of Hohenheim, 70593 Stuttgart, Germany
e-mail: cadisch@uni-hohenheim.de

Introduction

Abundant plant biomass production and efficient management of in situ produced organic residues has been suggested as a mean to sustain crop production while maintaining soil fertility. Leguminous plant species, either growing for improved fallow (or green manures, i.e. pigeonpea), economic yields (i.e. peanut), or even weeds (i.e. hairy indigo) are receiving considerable attention in integrated cropping systems for their ability to fix atmospheric N_2 and increase soil N availability during decomposition.

Understanding decomposition and nutrient release patterns of plant materials is an important first step to better manage organic inputs. Rates of N mineralization differ among species having differing leaf chemistry (Palm et al. 2001) and vary among different plant parts (e.g. leaves, stems, roots) within a species (Frankenberger and Abdelmagid 1985). In situ grown plant residues are usually applied as heterogeneous mixtures, containing green leaves, leaf litter and stems that are different in both physical and chemical characteristics (Frankenberger and Abdelmagid 1985; Oglesby and Fownes 1992). Variation in quality in plant components depends partly on plant varieties, age and management that can produce dramatic changes in rates and patterns of decomposition and N release (Oglesby and Fownes 1992).

Most studies of decomposition and nutrient release of plant materials have predominantly examined behaviour of individual plant parts (i.e. mostly leaves) (Constantinides and Fownes 1994; Trinsoutrot et al. 2000; Vityakon and Dangthaisong 2005) and less of mixed plant parts (Cobo et al. 2002; Thomas and Asakawa 1993; Vanlauwe et al. 1997) or without analysing interactions occurring in mixed plant components. On the other hand, it has been shown that mixing of plants of varying quality can be used to regulate the timing of nutrient availability (Handayanto et al. 1997; Vityakon et al. 2000) and has been extensively studied in the forest floor on litter fall of mixed tree varieties. Finzi and Canham (1998) and more recently Gartner and Cardon (2004) reported that there is no clear consensus on the factors responsible for the patterns of litter decomposition observed in multi-species litter bags and in rates of N mineralization in mixed species stands. As a result, extrapolations of the results of litter decomposition in single species litter studies is likely to lead to discrepancies in patterns of N immobilization and mineralization in multi-species stands. Handayanto et al. (1997) suggested that mixed residues of different quality were likely to show strong interactions only when large amounts of reactive, soluble C or polyphenols were present in one of the residues. Chapman et al. (1988) suggested that the rapid decomposition of high-quality leaf litter produced high-ambient N availability, which stimulated the decomposition of lower quality litter by allowing the transfer of nutrients between litters, leading to a more rapid utilization of carbon substrates. Residue quality also directly affects the abundance, composition and activity of the decomposer community, which may thus alter decomposition patterns.

The purpose of this study was to examine the rate and pattern of decomposition and N release of different plant components of three contrasting legumes and the resulting interactions in plant component mixtures (leaves, leaf litter and stems), and eventually their contribution to soil N availability. Pigeonpea (*Cajanus cajan*, agroforestry species) and hairy indigo (*Indigofera hirsuta*, natural weed) represent alternative approaches currently used in northeast Thailand for soil fertility restoration. However, their acceptance by farmers is low and the economically more interesting cash crop peanut was included as a more viable alternative. To test occurrence and direction (synergistic or antagonistic) of interactions the actual decomposition data of mixtures was compared to theoretical (weighted) predicted results based on results of individual performance. The relationships between chemical residue characteristics with the rate of decomposition and N mineralization were tested to understand factors affecting N benefits and interactions of organic residues. A better knowledge of the factors controlling interaction effects in mixed residues during decomposition would allow to better target composition of components in the mixture (e.g. by exclusion, variety/ecotype selection, breeding) or by varying age of plants (in the case of pigeonpea and hairy indigo) and thus to increase nitrogen use efficiency of organic residues in farmers' fields.

Materials and methods

An incubation experiment was conducted in a sheltered open greenhouse at the Field Crops Research Centre (16°15′N and 102°50′E) in Khon Kaen province, Northeast Thailand during September 2000 to January 2001. The soil was collected from a depth of 0 to 15 cm at an experimental field. The soil was classified as Yasothon series (Oxic Paleustult), a typical well drained loamy sand soil with high sand (86%) and low clay (6%) content. Soil fertility was low with 0.23% organic C by the Walkley and Black method (Nelson and Sommers 1982), 0.015% total N by Kjeldahl method (Bremner and Mulvaney 1982), pH 5.6 (1:5 w/v in water) and 1.44 cmol kg^{-1}soil cation exchange capacity. The soil was sieved through a 2 mm screen to remove roots and organic debris. The soil was incubated at 60% soil water-holding capacity for 2 weeks prior to the commencement of the experiment.

Legume residue incubation experiment and analysis

Three legumes were grown in an experimental field of Khon Kaen Field Crops Research Centre from May 2000 until harvest in September, 2000. Legumes included the planted fallow pigeonpea (*C. cajan* (L.) Millsp.), the grain legume peanut (*Arachis hypogaea* L.) cultivar Khon Kaen 60-3, and the local weed hairy indigo (*I. hirsuta* Harvey). After harvesting the plants were separated into stems and leaves. Leaf litter was collected from the ground underneath the plants consisting mostly of senesced leaves. Roots (<2 mm) were collected from the soil at 0 to 30 cm depth. All the components were sun dried and chopped to a length of about 2 cm.

About 780 mg (oven dry basis) of individual plant components of each species or their respective (based on field proportions) leaf, stem and leaf litter mixture, was incorporated in 200 g soil in a 2 l pot. A pot without residue amendment was also added as a control treatment. Distilled water was used to keep moisture of the soil-residue mixture at 60% field capacity by weighing the pots every 1–2 days. The treatments were arranged in a factorial randomized complete block design with four replications and the positions of pots were changed randomly within the block after adjusting soil moisture. The air temperature ranged from 16 to 37°C (mainly day-night variation). The remaining weight, nitrogen content of the legume residues and mineral N in the soil were determined at 7, 14, 28, 42, 63, 84, 105 and 133 days. At each sampling date, the remaining residues were separated from soil by sieving through a 2 mm screen (as an alternative to a 2 mm mesh litterbag approach). The retrieved plant residues were washed lightly in water then dried in the oven at 65°C, weighed, ground (<1 mm) and ash content (550°C) determined. Remaining dry weight or N content (Kjeldahl) was calculated on an ash free basis. Mineral N was determined on 10 g fresh soil, i.e. 50 ml 1 N KCl added, shaken, filtered and aliquots analysed for NH_4^+–N and NO_3^-–N colorimetrically using a flow injection analyser (Tecator 1984). The effect of adding residues on the dynamics of soil mineral N was calculated by subtracting values of the control soil.

Initial total C and N concentrations of the residues were determined using an elemental analyser (NA 1500, Carlo Erba, Milan, Italy). The acid detergent fibre (ADF) method was used for determination of lignin content (Anderson and Ingram 1993). Total soluble polyphenols were determined by the Folin–Denis method using tannic acid as a standard (Anderson and Ingram 1993).

Analysing interactions in mixed component residues

Characteristics of decomposition in plant component mixtures that deviated from responses predicted from decomposition of single components alone were designated ‘non-additive’ (Gartner and Cardon 2004). Potential interactions in mixtures of plant components were analysed by plotting actual decomposition or mineral N data for the different harvests versus weighted (based on their proportional contribution) predicted means. The 1:1 line depicted no real interaction (‘additive’ effect) while any significant deviation indicates a positive or negative interaction (‘non-additive’).

Statistical analysis

Decomposition data at each harvest were analysed using a factorial design of three legumes and their five plant components using the MStatC programme

(MSTATC 1990). Two pool exponential decay equations, with a constant recalcitrant pool and a dynamic labile pool with its exponential release rate constant (k), were fitted to the decomposition and N release data (Isaac et al. 2000; Wieder and Lang 1982). The best fit model was determined based on lowest mean square error values using SigmaPlot® (SPSS, Chicago, IL, USA). Correlation and regression between remaining weight and N and mineral N in soil and initial residual chemical characteristics were performed on untransformed data for each time period. Standard error of the difference between treatment means were calculated from the ANOVA and reported with the data.

Results

Initial chemical characteristics

N concentrations were highest in peanut components except for leaves of hairy indigo (Table 1). ADF and lignin were largest in pigeonpea while total extractable polyphenol concentration was highest in hairy indigo components. There was also a large variation in the initial chemical characteristics among the different components within the same legume species. Leaves were highest in N and polyphenol concentration. In contrast, stems and roots had low proportions of these parameters. Leaf litters were generally high in ADF, lignin and the ratios of lignin : N and (lignin + polyphenol) : N.

Initial chemical characteristics of the mixtures were calculated according to the weight ratios of the individual components that were observed in the field of 4–5-month-old plants (see ratios at the bottom of Table 1). The mixtures revealed that the initial N concentration was largest in the peanut mixture but the peanut mixture was lowest in the other chemical characteristics except polyphenol. In contrast, the mixture of pigeonpea components was highest in most of the chemical characteristics determined here, except N, polyphenol and its ratio to N, which was higher in the mixture of hairy indigo.

The plant materials were added to the incubation vessels at the same dry matter rate (3.9 g kg^{-1}soil) which was equivalent to about 10 Mg ha^{-1}. Due to the difference in nutrient content the amounts of N added varied considerably between plant components (33–147 mg N kg^{-1} soil) and between species (43–82 mg N kg^{-1} soil for mixtures).

Table 1 Initial chemical concentration of individual plant components and the mixture[a] of stems, leaves and leaf litter of three legume species

Species	Component	% N	% C	% ADF	% Lignin (L)	% Polyphenol (P)	C : N	ADF : N	Lignin:N	Polyphenol:N	(L + P) : N
Peanut	Stem	1.59	41	43	8.9	1.43	26	27	5.6	0.89	6.5
	Leaf	3.16	42	23	5.5	1.84	13	7	1.7	0.58	2.3
	Leaf litter	2.68	40	43	22.7	0.94	15	16	8.5	0.35	8.8
	Root	1.93	40	43	11.0	0.99	21	22	5.7	0.51	6.2
	Mixture[a]	2.12	41	40	11.6	1.38	21	19	5.5	0.65	6.2
Pigeonpea	Stem	0.85	44	60	12.6	1.06	52	71	14.7	1.24	16.0
	Leaf	2.88	49	25	10.3	2.31	17	9	3.6	0.80	4.4
	Leaf litter	1.09	43	57	26.8	1.30	39	52	24.6	1.19	25.8
	Root	0.77	45	59	31.3	1.17	58	77	40.4	1.51	41.9
	Mixture	1.10	44	56	16.6	1.24	38	51	15.0	1.12	16.2
Hairy indigo	Stem	1.31	42	51	9.7	1.92	32	39	7.5	1.46	8.9
	Leaf	3.78	45	19	7.8	4.99	12	5	2.1	1.32	3.4
	Leaf litter	1.63	40	57	22.0	2.19	24	35	13.5	1.34	14.9
	Root	0.97	43	58	12.1	1.23	45	59	12.5	1.27	13.7
	Mixture	1.81	42	48	14.2	2.49	23	27	7.8	1.38	9.2

ADF acid detergent fibre

[a] Mixture ratio of stem : leaf : leaf litter of 4—5-month-old field grown plants: peanut = 0.59:0.17:0.24, pigeonpea = 0.61:0.09:0.29 and hairy indigo = 0.46:0.15:0.38

Residue decomposition

Overall, peanut residues showed initially the fastest dry weight loss (Fig. 1). During early decomposition stages, weight loss of leaves of both peanut and pigeonpea was faster than that of the other components. With pigeonpea however, the weight loss of leaves was strongly retarded in later stages of the experiment. While stems of peanut decomposed relatively fast, loss of dry weight of stems of pigeonpea and hairy indigo was retarded during the early stages of incubation. Dry weight loss of leaf litter material of peanut and pigeonpea was slowest among the plant parts tested. However, leaf litter of hairy indigo did not follow this pattern and decomposed similar to the respective mixture.

The mixture of stems, leaves and leaf litter was composed according to their production ratio (Table 1) in the field. The main component of the mixture was stems, i.e. 59, 61 and 46% in peanut, pigeonpea and hairy indigo, respectively. The smallest component in the mixture was leaves with 17, 9 and 15% in peanut, pigeonpea and hairy indigo, respectively. The weight remaining of the mixture mostly followed the pattern of decomposition of stems, as they represented the majority component in the mixture.

A 2-pool model with a recalcitrant pool and a labile pool with an exponential decay best described the decomposition patterns ($R^2 \geq 0.93$) (Table 2). The decomposition model confirmed that peanut components differed little in the pattern of dry weight loss, i.e. from 20 to 29% of initial weight in the recalcitrant pool and from 0.033 to 0.053 day^{-1} for the rate constants (being highest in leaves and lowest in roots) of the labile pools. The estimated recalcitrant pool of the peanut mixture was lower than those of their individual component, respectively, suggesting an interaction effect during decomposition of the mixed components. The respective rate constants of decomposition (k_w) of hairy indigo were lower than those of peanut. The decomposition rate constant of pigeonpea leaves was higher, 0.060 day^{-1}, than those of the other components (0.025–0.030 day^{-1}) but with an associated large recalcitrant pool. The model of the mixtures of pigeonpea and hairy indigo were similar to that of their stems.

Predicted dry weight losses of the mixtures of the three species showed small but significant deviations from the observed data (Fig. 2). For peanut and pigeonpea mixtures, the slopes of the linear relationships between observed and predicted data were <1. The mixture of hairy indigo showed a nearly constant deviation of about 3.5% from the 1:1 line.

Nitrogen loss from legume residues

Overall, peanut material exhibited the largest N losses in the recovered residue materials (Fig. 3a). After 133 days of incubation N remaining was highest in leaf litter (29%), which was significantly higher than N remaining in leaves (17%) and in the mixture (12%) ($P < 0.05$). In pigeonpea the pattern of N loss was strongly different among the components (Fig. 3b). All the components, except leaf litter, lost N sharply during the first 7 days. At the end of the incubation period, N recovered was lowest in leaves (27%), but largest in leaf litter (45%) and roots (48%). In hairy indigo N loss was lowest in roots (47% recovered) at the end of incubation, significantly less than from leaves, leaf litter and the mixture (Fig. 3c).

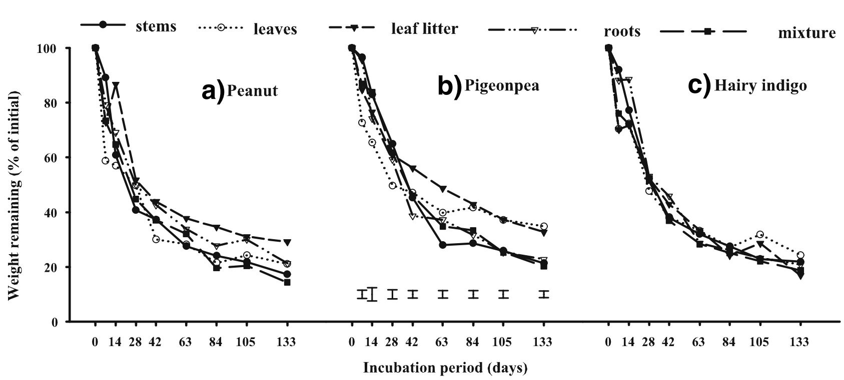

Fig. 1 Per cent weight remaining in fraction >2 mm of the initial total weight added of five legume components of **a** peanut, **b** pigeonpea and **c** hairy indigo. *Vertical bars* represent SED of combined analysis

Table 2 A 2-pool model with a recalcitrant pool and a labile pools with an exponential decay rate describing weight or N loss as per cent of initial amount remaining (Y) of individual plant components and the mixture of stems, leaves and leaf litters of three legume species at different times (t = day^{-1})

Species	Components	Dry weight loss (%)		N loss (%)	
		Model	R^2	Model	R^2
Peanut	Stem	$Y = 20 + 80^{-0.043t}$	0.981***	$Y = 24 + 76^{-0.140t}$	0.988**
	Leaf	$Y = 24 + 76^{-0.053t}$	0.937***	$Y = 19 + 81^{-0.140t}$	0.990**
	Leaf litter	$Y = 29 + 71^{-0.033t}$	0.935***	$Y = 31 + 69^{-0.095t}$	0.976**
	Root	$Y = 25 + 75^{-0.036t}$	0.992***	$Y = 26 + 74^{-0.180t}$	0.989**
	Mixture	$Y = 18 + 82^{-0.036t}$	0.983***	$Y = 21 + 79^{-0.118t}$	0.956**
Pigeonpea	Stem	$Y = 17 + 83^{-0.025t}$	0.981***	$Y = 38 + 62^{-0.271t}$	0.979**
	Leaf	$Y = 39 + 61^{-0.060t}$	0.981***	$Y = 28 + 72^{-0.092t}$	0.997***
	Leaf litter	$Y = 34 + 66^{-0.027t}$	0.989***	$Y = 35 + 65^{-0.016t}$	0.935**
	Root	$Y = 22 + 78^{-0.030t}$	0.981***	$Y = 45 + 54^{-0.110t}$	0.972**
	Mixture	$Y = 17 + 83^{-0.023t}$	0.990***	$Y = 35 + 65^{-0.138t}$	0.988**
Hairy indigo	Stem	$Y = 20 + 80^{-0.032t}$	0.990***	$Y = 29 + 71^{-0.195t}$	0.998***
	Leaf	$Y = 27 + 73^{-0.042t}$	0.964***	$Y = 26 + 74^{-0.071t}$	0.994***
	Leaf litter	$Y = 20 + 80^{0.030t}$	0.966***	$Y = 24 + 76^{-0.028t}$	0.922*
	Root	$Y = 16 + 84^{-0.026t}$	0.973***	$Y = 43 + 57^{-0.170t}$	0.961**
	Mixture	$Y = 19 + 81^{-0.033t}$	0.992***	$Y = 27 + 73^{-0.104t}$	0.966**

* Significant at $P < 0.05$

** Significant at $P < 0.01$

*** Significant at $P < 0.001$

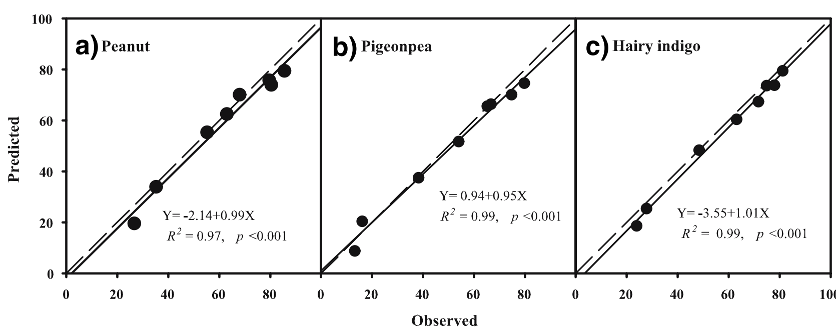

Fig. 2 Relationship between predicted (weighted mean) and observed dry weight loss (% of initial) of the mixture (leaves, leaf litter and stems) of **a** peanut, **b** pigeonpea and **c** hairy indigo. *Dashed line* indicates 1:1 line along which observed and predicted values are equal (additive effect)

Similar to the dry weight loss model, the recalcitrant pool of the components of peanut ranged from 19 to 31% and was lowest in leaves (Table 2). The mixture of peanut had a recalcitrant N pool of 21%, similar to that of leaves, as well as a rate constant of N loss of 0.118 day^{-1} intermediate among the individual components. The recalcitrant N pools in pigeonpea and hairy indigo were mostly higher than those in peanut and were highest in roots. In all species the decay rate of the labile pool was lowest in leaf litters. The recalcitrant pool of pigeonpea mixture was close to stems while the mixture of hairy indigo was close to leaf material. However, the mixture of those two species had a decay rate, which was intermediate to their individual components.

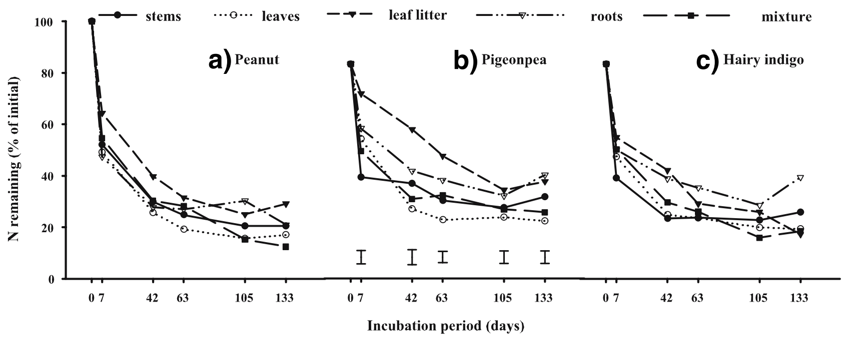

Fig. 3 Per cent of N remaining in fraction >2 mm of the initial total N added of five legume components of **a** peanut, **b** pigeonpea and **c** hairy indigo. *Vertical bars* represent SED of combined analysis

N mineralization

Net N mineralization (mineralized N–control soil) in the peanut treatments was always positive while net mineralization of some of the plant materials of pigeonpea and hairy indigo resulted in negative values indicating immobilization of mineral N relative to the control (Fig. 4). Amount of net N mineralization was greatest from leaves in all species (data not presented). At the end of the experiment 44, 38 and 35% of N added had been released from leaves of peanut, pigeonpea and hairy indigo, respectively. In peanut, net mineral N release was lowest for stem material. While leaf material of pigeonpea resulted in a continuous positive net N release all other components, at least initially, strongly immobilized soil mineral N. Towards the end of the experiment, a positive net N mineralization was also observed from stem material; however its contribution in absolute terms was low (e.g. 6 μgN g^{-1} compared to 40 μgN g^{-1} from leaves). Roots and the mixture showed continuous immobilization during the experiment. With hairy indigo, leaves, leaf litter and the mixture also led to a positive net mineralization towards the end of the experiment resulting in 35, 45 and 20% N release, respectively. Root and stem material of hairy indigo resulted in mineral N immobilization throughout the experiment.

When observed per cent net mineral N data of the mixture of peanut were compared to their predicted values a small positive interaction emerged during later stages of incubation (Fig. 5a). Mineral N in the mixture of pigeonpea plant materials showed a very close relationship between observed and predicted values from the beginning to 84 days. Nevertheless, after 133 days of incubation mineral N in this mixture was much lower than that in the predicted model (Fig. 5b) resulting in a non-significant relationship between observed and predicted data. Per cent net mineral N in the mixture of hairy indigo showed a good correlation between predicted and observed values with the strongest trend to an increasing positive interaction effect with ongoing mineralization (Fig. 5c).

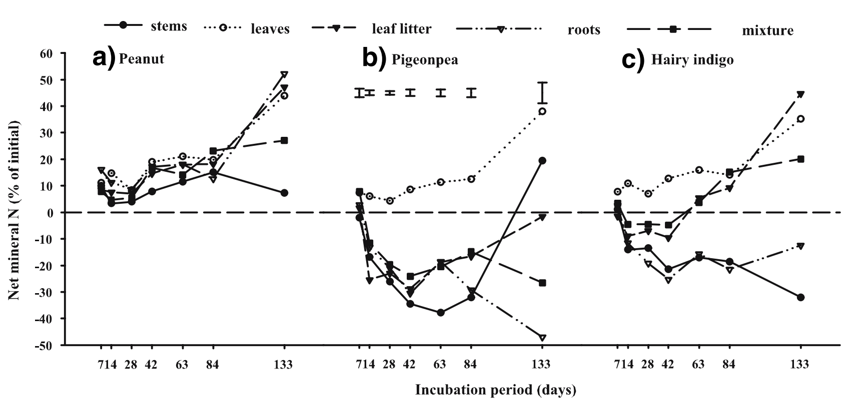

Fig. 4 Per cent of net mineral released in fraction >2 mm of the initial total N added of five legume components of **a** peanut, **b** pigeonpea and **c** hairy indigo. *Vertical bars* represent SED of combined analysis

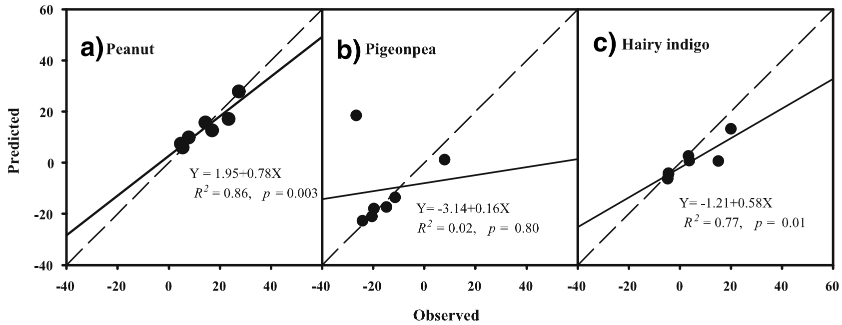

Fig. 5 Relationship between predicted (weighted mean) and observed per cent net mineral N of the mixture (leaves, leaf litter and stems) of **a** peanut, **b** pigeonpea and **c** hairy indigo. *Dashed line* indicates 1:1 line along which observed and predicted values are equal (additive effect)

Relationship between plant quality and decomposition

Rate constants of dry weight loss (k_w) of the labile pool showed highly significant correlations ($P < 0.01$) with N and ADF concentration and the ratios of ADF- and C to N (Table 3). Lignin concentration and the ratios of lignin : N, and (lignin + polyphenol) : N also showed a significant correlation with k_w ($P < 0.05$) while their recalcitrant pool did not show any correlation to the initial chemical characteristics.

Rate constants of N loss (k_n) showed significant ($P < 0.05$) correlations only with lignin even though the coefficient of determination was very low (0.282). However, the recalcitrant N pools were highly ($P < 0.01$) correlated with N and ADF concentraton and the ratios of C : N and ADF : N and (lignin + polyphenol) : N. Lignin concentration showed a lower but also significant ($P < 0.05$) relationship with the recalcitrant N pool.

The coefficients of determination of linear regressions between the chemical characteristics of plant components and net N mineralization at day 133 of incubation were highest for N concentration (R^2 0.817). All chemical characteristic and their ratio except lignin and polyphenol concentration were the next best plant characteristics to predict net N mineralization. Our results suggest that a C : N ratio of about 17 or lower is required to consistently obtain a net N release.

Table 3 Coefficients of determination (R^2) of linear regression between initial chemical characteristics and rate constants of decomposing weight (k_w) and their recalcitrant pools, rate constants of N release (k_n) and their recalcitrant pools and net mineral N at 133 days of incubation of different components of three legume species

Chemical characteristics	Dry weight		Residue N		Net mineral N at 133 days
	k_w	Recalcitrant pool	k_n	Recalcitrant pool	
N	0.570**	0.239	0.036	0.448**	0.817***
C : N	0.449**	0.156	0.077	0.758***	0.684**
Lignin (L)	0.274*	0.019	0.282*	0.314*	0.147
Polyphenol (P)	0.043	0.045	0.032	0.122	0.174
ADF	0.756***	0.235	0.006	0.433**	0.674**
L : N	0.306*	0.005	0.043	0.582**	0.399*
P : N	0.205	0.107	0.000	0.234	0.420**
(L + P) : N	0.321*	0.007	0.041	0.587**	0.414**
ADF : N	0.563**	0.178	0.055	0.728**	0.693**

* Significant at $P < 0.05$

** Significant at $P < 0.01$

*** Significant at $P < 0.001$

Discussion

Decomposition and mineralization of plant materials from different legume species

The superior decomposition and N release performance of peanut can be accounted for by its better chemical quality characteristics of its components, in particular its high N and low-ADF concentrations. The observed high-potential contribution of peanut residues to soil mineral N supply confirms previous observations (Promsakha et al. 2005). Additionally, being a cash crop makes peanut a more attractive species for farmers than the other green manures tested. The herbaceous weed hairy indigo was hypothesized to be of lower quality than the agroforestry species pigeonpea because of its high-polyphenol content. However, in general it performed better than pigeonpea because of the higher N concentration and lower lignin concentration of its components.

When plant residues are incorporated, the residues of different plant parts become mixed so that plant materials of different quality decompose simultaneously within the same soil volume. The same order (i.e. peanut > hairy indigo > pigeonpea) was obtained when comparing the amount of N released in mixtures compared to single components. The result of the amount of N released from mixtures was dominated by the presence of stem material as its dry weight accounted for 46–61% of the mixture. Field grown mature whole plant residue mixtures commonly contain a high proportion of stems. In contrast, the relative proportion of high-quality leaves contributed only 9–17% to total above ground recycled biomass. The importance of this high proportion of stem material in plant residues is often underestimated, and laboratory or field incubation studies predominantly use only leaf materials when comparing different species (Handayanto et al. 1994; Palm and Sanchez 1991). However, not only the quantity but also the quality of the stem material will largely determine the pattern of net N mineralization in field situations. The importance of the contribution of stems to the overall results will increase with increasing age of field grown material, e.g. Araujo-Febres (2005) found a decrease in the leaf to stem ratio and an increase in ADF with increasing age of hairy indigo. Thus while for peanut residues the current results are representative (sampling at peanut harvest), for pigeonpea and hairy indigo a further decrease of their overall contribution to soil nutrient supply can be expected with increasing age of harvested material.

Decomposition and mineralization of different plant components

The differences in N mineralization among the plant components of peanut, pigeonpea and hairy indigo were closely linked to their residue quality. In all legumes, the components that resulted in immediate net N mineralization were green leaves and all the components of peanut whose N concentrations were larger than 1.5%, C : N ratio <27, and (lignin + polyphenol) : N ratio <9. Similarly, Melillo et al. (1982) suggested that initial N concentration or C : N ratio were important factors influencing the degradability of organic residues. High lignin in pigeonpea or high polyphenol in hairy indigo were expected to influence the rates of N mineralization but they showed very poor correlation to the rate constants of the two parameters. While in other studies the (lignin + polyphenol) : N ratio was a good predictor when dealing with complex materials (Handayanto et al. 1994, 1997) in this study the N concentration or the ADF : N ratio were more suitable predictors. The importance of fibres in decomposition has also been highlighted recently by Cobo et al. (2002) and Tscherning et al. (2006) in their decomposition studies.

Ranking of plant components for amount of N mineralized, when added at the same weight, followed mainly the following pattern: leaves > leaf litter > roots > stems. However, the ranking was not the same between species. In particular, roots of peanut showed surprisingly fast decomposition and net N release patterns mainly due to their high N concentration. This confirms the strong below-ground residual effect after growing peanut in a sandy soil in Thailand (McDonagh et al. 1993).

Leaf residues have generally been described as high-quality litter materials in terms of high N and low-lignin contents (Isaac et al. 2000; Palm and Sanchez 1991; Sakala et al. 2000) thus have been found to decompose easily (Mtambanengwe and Kirchmann 1995) as in our case. A high ADF : N and (lignin + Polyphenol) : N ratio might have caused a slower decomposition of pigeonpea leaves; e.g. Sakala et al. (2000) suggested that N release was low when green pigeonpea leaves contained substantial amounts of recalcitrant materials such as lignin and ADF. Despite a high-polyphenol concentration leaves of hairy indigo did not show significantly lower net mineralization. This is in agreement with the overall regression analysis, which showed only a minor influence of polyphenols in this experiment (Table 3). This was probably due to the fact that polyphenols of hairy indigo were not very active in binding proteins or inhibiting enzyme activities and thus not having a dominant impact (Handayanto et al. 1997).

The observed slower decomposition of the stems as compared with leaves was also reported by Isaac et al. (2000) who worked with eight tree species and found that stems (<1 cm diameter) decomposed more slowly than leaves throughout the 48 weeks of incubation. Immediate N mineralization with peanut stems incorporation was probably due to their low C : N ratio (26) compared to that of hairy indigo stems (32) and pigeonpea (52), both of which resulted in N immobilization throughout most of the incubation.

The high lignin and ADF content may have been largely responsible for the slow decomposition of leaf litters of peanut and pigeonpea. Despite the high amount of recalcitrant materials, immediate net N mineralization was obtained from peanut leaf litter likely due to its high N content and hence its lower ADF : N ratio. However, net N immobilization throughout the incubation time was obtained with pigeonpea leaf litter, confirming results of Sakala et al. (2000) who also found prolonged net N immobilization of senesced pigeonpea leaves.

Interactions occurring when mixing different plant components

Mixing organic residues with different chemical characteristics can alter decomposition and N mineralization processes (Handayanto et al. 1997; Kuo and Sainju 1998; Vityakon et al. 2000; Wardle et al. 1997). Mixtures can result in additive effects, representing the weighted mean of single components, or non-additive effects being either synergistic or antagonistic effects. In this study, significant interactions in mixtures were observed at least during some stages of decomposition. However, the interactions were relatively small in mixtures of peanut and pigeopea. Finzi and Canham (1998) found that the presence of low-quality residues (e.g. high lignin : N ratio) held the rate of net N mineralization at a low level until >70% of the residue mixture was dominated by residues of high-litter quality. Similarly, Handayanto et al. (1997) showed a strong non-linear relationship between interactions in function of the proportion of the added materials. The proportional weight of high-quality leaves (9–17%) in our study may thus have been too small to induce larger changes in the decomposition behaviour of low-quality stems and leaf litters. The proportion of leaves in hairy indigo and pigeonpea is determined by harvest age and will decrease with increasing age and hence potential interactions are likely to decrease with age of plants.

Mixing stems, leaves and leaf litter of hairy indigo resulted in consistently positive interaction effects on dry weight loss (around 4%; Fig. 2c) and also N mineralization was increased with ongoing incubation time (Fig. 5c). Plant components of hairy indigo were of intermediate chemical quality compared to the other two legumes and appeared thus to provide the largest opportunities for interactions. Chapman et al. (1988) suggested that the rapid decomposition of high-quality residues produced high ambient N availability, which stimulated the decomposition of low-quality residues by allowing the transfer of nutrients between residues, leading to a more rapid utilization of carbon substrates. Heterogeneous residues may also change the abundance and composition of the soil fauna leading to alterations in residue decomposition and N mineralization (Blair et al. 1990; Chapman et al. 1988). Wardle et al. (1997) suggested that depending on the component species, the effect was either positive or negative. When component species had a high initial N content mixing enhanced the decomposition rate, which was also the case in our experiment with hairy indigo. Other factors such as high-available C content have also been suggested to influence decomposition, leading potentially to increased N immobilization (Quemada and Cabrera 1995). However, the proportion of leaf materials with a large labile C fraction was low in the mixture and thus their impact was probably small. Compounds such as polyphenols in decomposing residues, as found in abundance in hairy indigo, could decrease the rate of litter decomposition and N mineralization by inhibiting the enzyme activity of the decomposer community (e.g. White 1986) or complexation of proteins (Handayanto et al. 1997). However, in our case, it was concluded that the polyphenols in hairy indigo were not highly active and thus did not contribute significantly to interaction effects.

In peanut, observed interactions during decomposition and mineralization were also often positive but smaller than in hairy indigo. These smaller interaction effects in mixtures of peanut residues maybe due to the relative high quality of these materials providing fewer opportunities for nutrient facilitation or competition effects.

Mixing plant components of pigeonpea had the smallest effect on alterations in decomposition. Mixtures of pigeonpea components even led to some negative effects during mineralization, confirming results of Sakala et al. (2000). They suggested that negative interactions resulted from a general N limitation in the residue mixtures rather than any specific interaction between components of the residues. Indeed, also in our case, pigeonpea residues led to the largest N immobilization events due to their low N concentration. Additionally, pigeonpea materials had the highest ADF and lignin concentrations and thus highest ADF : N and (lignin + polyphenol) : N ratios. These attributes thus increased the potential for negative interactions in net N mineralization with time.

Conclusions

Above- and below-ground residues of peanut decomposed fastest and showed the largest N release in agreement with their quality characteristics [high N; low (lignin + polyphenol) : N or ADF : N ratio]. Hairy indigo, despite its high-polyphenol content, performed better than pigeonpea because of the higher N and lower lignin concentration of its components. Ranking of individual plant components for N mineralization resulted mostly in the following pattern, leaves > leaf litter > roots > stems. When plant residues are incorporated, the residues of different plant parts become mixed so that residues of different quality decompose simultaneously within the same soil volume. The amount of N release from the mixture was dominated by stem material that comprised 46–61% of the mixture. Interactions in plant component mixtures were small when the plant quality was generally high (as in case of peanut) or the proportion of N rich leaf material was low (as in the case of pigeopea). A positive interaction for N mineralization occurred in the mixture of hairy indigo, which had an intermediate quality with a significant proportion of N rich components and absence of highly reactive polyphenols. Thus, for plants with low to intermediate chemical quality attributes manipulating plant composition (e.g. harvest age, affecting stem and leaf proportions) in agroforestry species will be important to obtain significant interactions during decomposition in the mixtures of plant components.

Acknowledgements The research was funded by the Royal Golden Jubilee Ph.D. Programme of Thailand. Additional support was provided by a senior research fellow grant to Prof. Aran Patanothai by the Thailand Research Fund in Thailand.

References

Anderson JM, Ingram JSI (eds) (1993) Tropical soil biology and fertility: a handbook of methods, 2nd edn. CAB International, Wallingford, UK, p 221

Araujo-Febres O (2005) Evaluation of yield and nutritive value of Hairy indigo (*Indigofera hirsuta* L.) in Venezuela. J Anim Sci 83:147

Blair JM, Parmelee RW, Beare MH (1990) Decay rates, nitrogen fluxes, and decomposer communities of single- and mixed-species foliar litter. Ecology 71:1976–1985

Bremner JM, Mulvaney CS (1982) Total nitrogen. Methods of soil analysis part 2 chemical and microbiological properties. American Society of Agronomy, Madison, WI, USA, pp 595–624

Chapman K, Whittaker JB, Heal OW (1988) Metabolic and faunal activity in litters of tree mixtures compared with pure stands. Agric Ecosys Environ 24:33–40

Cobo JG, Barrios E, Kass DCL, Thomas RJ (2002) Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant Soil 240:331–342

Constantinides M, Fownes JH (1994) Nitrogen mineralization from leaves and litter of tropical plants: relationship to nitrogen, lignin and soluble polyphenol concentrations. Soil Biol Biochem 26:49–55

Finzi AC, Canham CD (1998) Non-additive effects of litter mixtures on net N mineralization in a southern New England forest. Forest Ecol Manage 105:129–136

Frankenberger WT, Abdelmagid HM (1985) Kinetic parameters of nitrogen mineralization of leguminous crops incorporated into soils. Plant Soil 87:257–271

Gartner TB, Cardon ZG (2004) Decomposition dynamics in mixed-species leaf litter. Oikos 104:230–246

Handayanto E, Cadisch G, Giller KE (1994) Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. Plant Soil 160:237–248

Handayanto E, Giller KR, Cadisch G (1997) Regulating N release from legume tree prunings by mixing residues of different quality. Soil Biol Biochem 29:1417–1426

Isaac L, Wood CW, Shannon DA (2000) Decomposition and nitrogen release of prunings from hedgerow species assessed for alley cropping in Haiti. Agron J 92:501–511

Kuo S, Sainju UM (1998) Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol Fertil Soils 26:346–353

McDonagh JF, Toomsan B, Limpinuntana V, Giller KE (1993) Estimates of the residual nitrogen benefit of groundnut to maize in Northeast Thailand. Plant Soil 154:267–277

Melillo JM, Aber JD, Muratore JF (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63:621–626

MSTATC (1990) A microcomputer program for the design, management, and analysis of agronomic research experiments. Michigan State University, Michigan, USA

Mtambanengwe F, Kirchmann H (1995) Litter from a tropical savanna woodland (miombo): chemical composition and C and N mineralization. Soil Biol Biochem 27:1639–1651

Nelson DW, Sommers LE (1982) Total carbon, organic carbon and organic matter. Methods of soil analysis part 2 chemical and microbiological properties. American Society of Agronomy, Madison, WI, USA, pp 539–579

Oglesby KA, Fownes JH (1992) Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous trees. Plant Soil 143:127–132

Palm CA, Gachengo C, Delve R, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83:27–42

Palm CA, Sanchez PA (1991) Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents. Soil Biol Biochem 23:83–88

Promsakha NSS, Toomsan B, Cadisch G, Baggs EM, Vityakon P, Limpinuntana V, Jogloy S, Patanothai A (2005) Dry season groundnut stover management practices determine nitrogen cycling efficiency and subsequent maize yields. Plant Soil 272:183–199

Quemada M, Cabrera ML (1995) Carbon and nitrogen mineralized from leaves and stems of four cover crops. Soil Sci Soc Am J 59:471–477

Sakala WD, Cadisch G, Giller KE (2000) Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. Soil Biol Biochem 32:699–706

Tecator (1984) Determination of ammonia nitrogen (ASN 65-32/84) or nitrate nitrogen (ASN 65-31/84) in soil samples extractable by 2 M KCl using flow injection analysis. Application notes. Tecator, Höganas, Sweden

Thomas RJ, Asakawa NM (1993) Decomposition of leaf-litter from tropical forage grasses and legumes. Soil Biol Biochem 25:1351–1361

Trinsoutrot I, Recous S, Bentz B, Lineres M, Cheneby D, Nicolardot B (2000) Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. Soil Sci Soc Am J 64:918–926

Tscherning K, Lascano C, Barrios E, Schultze-Kraft R, Peters M (2006) The effect of mixing prunings of two tropical shrub legumes (*Calliandra houstoniana* and *Indigofera zollingeriana*) with contrasting quality on N release in the soil and apparent N degradation in the rumen. Plant Soil 280:357–368

Vanlauwe B, Sanginga N, Merckx R (1997) Decomposition of four Leucaena and Senna prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. Soil Biol Biochem 29:131–137

Vityakon P, Dangthaisong N (2005) Environmental influences on nitrogen transformation of different quality tree litter under submerged and aerobic conditions. Agroforest Syst 63:225–236

Vityakon P, Meepetch S, Cadisch G, Toomsan B (2000) Soil organic matter and nitrogen transformation mediated by plant residues of different qualities in sandy acid upland and paddy soils. Neth J Agric Sci 48:75–90

Wardle DA, Bonner KI, Nicholson KS (1997) Biodiversity and plant litter: experimental evidence which does not support the view that enhanced species richness improves ecosystem function. Oikos 79:247–258

White CS (1986) Volatile and water-soluble inhibitors of nitrogen mineralization and nitrification in a ponderosa pine ecosystem. Biol Fertil Soils 2:97–104

Wieder R, Lang G (1982) A critique of the analytical methods used in examining decomposition data obtained from litter-bags. Ecology 63:1636–1642