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Impact of the addition of different plant residues on nitrogen mineralization–immobilization turnover and carbon content of a soil incubated under laboratory conditions

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Abstract. Application of plant residues as soil amendment may represent a valuable recycling strategy that affects carbon (C) and nitrogen (N) cycling in soil–plant systems. The amount and rate of nutrient release from plant residues depend on their quality characteristics and biochemical composition. A laboratory incubation experiment was conducted for 120 days under controlled conditions (25 °C and 58 % water-filled pore space) to quantify initial biochemical composition and N mineralization of leguminous and non-leguminous plant residues, i.e., the roots, shoots and leaves of *Glycine max*, *Trifolium repens*, *Zea mays*, *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata*, incorporated into the soil at the rate of 200 mg residue N $\mathrm{kg^{-1}}$ soil. The diverse plant residues showed a wide variation in total N, C, lignin, polyphenols and C / N ratio with higher polyphenol content in the leaves and higher lignin content in the roots. The shoot of *Glycine max* and the shoot and root of *Trifolium repens* displayed continuous mineralization by releasing a maximum of 109.8, 74.8 and 72.5 mg N $\mathrm{kg^{-1}}$ and representing a 55, 37 and 36 % recovery of N that had been released from these added resources. The roots of *Glycine max* and *Zea mays* and the shoot of *Zea mays* showed continuous negative values throughout the incubation. After an initial immobilization, leaves of *Populus euramericana, Robinia pseudoacacia* and *Elaeagnus umbellata* exhibited net mineralization by releasing a maximum of 31.8, 63.1 and 65.1 mg N $\mathrm{kg^{-1}}$, respectively, and representing a 16, 32 and 33 % N recovery, respectively. Nitrogen mineralization from all the treatments was positively correlated with the initial residue N contents ($r = 0.89$; $p \le 0.01$) and negatively correlated with lignin content ($r = -0.84$; $p \le 0.01$), C / N ratio ($r = -0.69$; $p \le 0.05$), lignin / N ratio ($r = -0.68$; $p \le 0.05$), polyphenol / N ratio ($r = -0.73$; $p \le 0.05$) and (lignin + polyphenol) : N ratio ($r = -0.70$; $p \le 0.05$) indicating a significant role of residue chemical composition and quality in regulating N transformations and cycling in soil. The present study indicates that incorporation of plant residues strongly modifies the mineralization–immobilization turnover (MIT) of soil that can be taken into account to develop synchronization between net N mineralization and crop demand in order to maximize N delivery and minimize N losses.

1 Introduction

Application of organic materials as soil amendments is an important management strategy that can improve and uplift soil-quality characteristics and alter the nutrient cycling through mineralization or immobilization turnover of added materials (Khalil et al., 2005; Campos et al., 2013; Baldi and Toselli, 2014; Novara et al., 2013; Hueso-González et al., 2014; Oliveira et al., 2014). Use of local organic materials derived either from livestock or plants have been attaining worldwide support for improving the fertility and productivity potential of degraded and nutrient-poor soils (Huang et al., 2004; Tejada and Benítez, 2014). Indeed, plant residues and animal manures are potentially important sources of nutrients for crop production in smallholder agriculture. However, the Hindu Kush Himalayan regions, including the state of Azad Jammu and Kashmir, have a wide diversity of leguminous species and non-leguminous plants compared to the livestock production. Hence, use of plant residues as organic nutrient source is relatively simple for the farmers

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compared to the application of manure. Incorporating plant residues into agricultural soils can sustain organic carbon content, improve soil physical properties, enhance biological activities and increase nutrient availability (Hadas et al., 2004; Cayuela et al., 2009). In the short-term, incorporation of plant residues provides the energy and nutrients for microbial growth and activity, acts as a driving force for the mineralization–immobilization processes in the soil and is a source of nitrogen (N) for plants (Jansson and Persson, 1982). In the long-term, incorporation of crop residues is important for the maintenance of organic carbon (C) and N stocks in the nutrient pool of arable soils (Rasmussen and Parton, 1994).

Incorporation of crop residues provides readily available C and N to soils depending upon the decomposition rates and synchrony of nutrient mineralization (Murungu et al., 2011). The N availability from these residues depends on the amount of N mineralized or immobilized during decomposition. However, previous studies demonstrated that the decomposition and nutrient release rates of residues are often regulated by environmental factors, such as temperature and soil moisture, and biochemical composition of plant materials and their interaction (Abiven et al., 2005; Khalil et al., 2005). The biochemical composition or quality parameters such as total N concentration, lignin (LG), polyphenols (PP), carbon : nitrogen (C / N) ratio, LG / N, PP / N and (LG + PP) / N ratios are considered useful indicators that control decomposition and N release of added residues (Nakhone and Tabatabai, 2008; Vahdat et al., 2011; Abera et al., 2012). However, it has not been clearly established which of these variables correlate best with N mineralization of plant residues (Nakhone and Tabatabai, 2008), as contrasting results have been reported in the literature (Nourbakhsh and Dick, 2005). On the one hand, it has been reported that N released from leguminous tree leaves indicated that the (lignin + polyphenol) : N ratio was the most important factor in predicting N mineralization (Mafongoya et al., 1998). On the other hand, Frankenberger and Abdelmagid (1985) suggested that lignin content of the legumes is not a good predictor of the N mineralization. Handayanto et al. (1994) suggested that the N concentration or lignin : N ratio of the leaves were not good indicators of N release for agroforestry materials. Palm and Sanchez (1991) attributed the differences in N mineralization rates of various tropical legumes to polyphenols. Handayanto et al. (1994) found, however, that the total N content of plant residues was not correlated with rates of N released under non-limiting N conditions.

Earlier studies clearly demonstrated the beneficial effects of plant residues on soil–plant systems (Huang et al., 2004; Cayuela et al., 2009; Khalil et al., 2005; Baldi and Toselli, 2014). However, there is still a scope to explore the possibilities for achieving maximum benefits in term of rate, time and amount of N released. For example, the synchronization of net N mineralization with plant/crop growth is desirable to maximize N delivery for the crop and minimize N losses. Abiven et al. (2005) reported that one of the tools to achieve synchronization is the use of plant residues with different natures and qualities. Application of residues with a high C / N ratio results in immediate net N immobilization while residues with a low C / N ratio result in net N mineralization, showing that mineralization–immobilization turnover (MIT) can be influenced differently by chemical components of added plant materials. To achieve this target, the combination of legumes and non-legumes plant materials or different plant components of the same plant species, i.e., root, shoot and leaves, can be tested.

Keeping in mind the beneficial effects of plant residues on soil–plant systems, especially in the mountainous upland soils vulnerable to soil (water) erosion, the present work aims to (i) examine the initial biochemical composition and quality characteristics of on-farm available plant residues and to (ii) quantify the N-release potential (mineralization) of these residues added to a soil incubated under controlled laboratory conditions (25 °C) in Rawalakot, Azad Jammu and Kashmir, Pakistan.

2 Materials and methods

2.1 Soil sampling

The soil used in this study was collected from an arable field located at the research farm of the Faculty of Agriculture of the University of Poonch, Rawalakot, Azad Jammu and Kashmir, Pakistan. The study site is located at latitude 33°51′32.18″ N, longitude 73°45′34.93″ E and an elevation of 1638 m above sea level. The climate of the region is subtemperate. Mean daily maximum and minimum air temperatures ranged from 27 to 29 °C (June–July) and 1.0 to −3.5 °C (January–February). The mean annual rainfall ranged between 1100 and 1500 mm with more than 50 % of the total precipitation during monsoon each year. The soil in the study site was clay loam in texture, classified as Humic Lithic Eutrudepts (Inceptisols; Ali et al., 2006). The field was bare at the time of sampling but previously maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) were cultivated. The selected field was divided into 10 subplots to ensure proper and representative soil sampling. Soil samples were collected from a depth of 0–15 cm at random from three points in each plot using a soil auger of 5 cm in diameter. The soil samples from all the selected plots were thoroughly mixed to get a composite sample. The field-fresh soil was passed through a 4 mm sieve to eliminate coarse rock and plant material, thoroughly mixed to ensure uniformity and stored at 4 °C before use (not more than 2 weeks). A subsample of about 0.5 kg was taken, air dried, passed through a 2 mm sieve and used for the determination of physical and chemical characteristics. The original soil analysis is presented in Table 1.

Table 1. Selected physicochemical properties of the soil used in the study.

Soil properties	Values
Bulk density ($\mathrm{Mg\,m^{-3}}$)	1.20
Particle density ($\mathrm{Mg\,m^{-3}}$)	2.48
Porosity (%)	48.3
Sand ($\mathrm{g\,kg^{-1}}$)	241
Silt ($\mathrm{g\,kg^{-1}}$)	394
Clay ($\mathrm{g\,kg^{-1}}$)	365
Texture class	clay loam
pH	7.2
CEC ($\mathrm{cmol\,kg^{-1}}$)	7.3
Organic matter ($\mathrm{g\,kg^{-1}}$)	10.4
Organic C ($\mathrm{g\,kg^{-1}}$)	6.03
Total N ($\mathrm{g\,kg^{-1}}$)	0.58
C : N ratio	10 : 1
Total mineral N ($\mathrm{mg\,kg^{-1}}$)	8.7
Total organic N ($\mathrm{mg\,kg^{-1}}$)	591.0
P ($\mathrm{mg\,kg^{-1}}$)	3.4
K ($\mathrm{mg\,kg^{-1}}$)	88.0
Fe ($\mathrm{mg\,kg^{-1}}$)	15.7
Mn ($\mathrm{mg\,kg^{-1}}$)	17.0
Cu ($\mathrm{mg\,kg^{-1}}$)	1.02
Zn ($\mathrm{mg\,kg^{-1}}$)	1.16

2.2 Collection of plant residues

Six predominant on-farm available plant species were selected. These included *Glycine max* shoot, *Glycine max* root, *Trifolium repens* shoot, *Trifolium repens* root, *Zea mays* shoot, *Zea mays* root, and leaves of *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata*. Plant samples/residues were collected at different times during the year 2012. *Glycine max* and *Trifolium repens* samples were collected from the field before flowering (summer) while *Zea mays* samples were taken 1 week before crop harvest. The tree leaves were sampled in late fall. Plant residues were washed with running tap water, rinsed three times with distilled water, dried at 65 °C for 48 h, milled and passed through a 1 mm sieve. Triplicate samples of plant residue were taken and analyzed for their C, N, lignin and polyphenol concentrations. Total N contents of the residues were determined by Kjeldhal digestion, distillation and the titration method (Bremner and Mulvaney, 1982). Wet digestion method was used for organic C analysis (Nelson and Sommers, 1982). The lignin content was determined using Van Soest methods (Van Soest et al., 1991). Soluble polyphenols were extracted in hot water (100 °C, 1 h) and determined by colorimetry using a Folin–Denis reagent (Folin and Denis, 1915).

2.3 Laboratory incubation

The incubation methods used in this study were followed by the methods used in our previous studies (Abbasi et al., 2011; Abbasi and Khizar, 2012). Briefly stated, about 100 g of soil already stored in the refrigerator at 4 °C was weighed and transferred into 200 mL glass jars. The initial moisture content of the soil was 28 % (w/w), which was increased by adding distilled water to achieve a final water-filled pore space of 58 %. The treatments were comprised of a control (no N) and nine plant residues sources, i.e., *Glycine max* shoot, *Glycine max* root, *Trifolium repens* shoot, *Trifolium repens* root, *Zea mays* shoot, *Zea mays* root, and leaves of *Populus euramericana, Robinia pseudoacacia* and *Elaeagnus umbellata*; 10 incubation timings, i.e., 0, 7, 14, 21, 28, 42, 60, 80, 100 and 120 days; and three replications. Altogether, a total of 300 jars (10 treatments × 10 incubation timings × 3 replications) were arranged in a completely randomized design. Plant residues were weighed and added into the jars at a rate equivalent to $200\,\mathrm{mg\,N\,kg^{-1}}$. After adding residues, all the jars were weighed and their weights were recorded. The soil was then incubated under controlled conditions at 25 °C. Soil moisture was checked/adjusted after every 2 days by weighing the glass jars and adding the required amount of distilled water when the loss was greater than 0.05 g.

2.4 Soil extraction and analysis

Samples of all 10 treatments were analyzed for total mineral nitrogen (TMN) as described previously (Abbasi and Khizar, 2012). Initial concentration of TMN ($\mathrm{NH_4^+{-}N + NO_3^-{-}N}$) on day 0 was determined by extracting soil samples with 200 mL of 1 M KCl added directly to the flask immediately after incorporation of each N source. Thereafter, triplicate samples from each treatment were removed randomly from the incubator at different incubation timings and extracted by shaking for 1 h with 200 mL of 1 M KCl followed by filtration. The total mineral N of the extract was determined by using the steam distillation and titration method (Keeney and Nelson, 1982). Net cumulative N mineralized (NCNM) from different plant-residue treatments was calculated following the method described previously (Sistani et al., 2008).

2.5 Statistical analysis

All data were statistically analyzed by multifactorial analysis of variance using the software package MSTATC Version 3.1 (1990). Least-significant differences (LSD) were used as a post hoc test to indicate significant variations within the values of either treatments or time intervals. Correlation (r) between initial quality characteristics of the plant residues (total nitrogen, LG, PP and their ratios) and net N mineralization and the correlation among quality traits were also conducted using SPSS Statistics version 20.0 for Mac (IBM

Table 2. Mean biochemical composition of the plant residues used in the experiment ($n = 3$).

Plant residues (treatments)	Plant organs	Total N	Total C (LG)	Lignin (PP)	Polyphenols	C / N	LG / N	PP / N	LG+PP / N
			$\mathrm{g\,kg^{-1}}$						
Glycine max	shoot	35.2a	447c	11f	13.1f	12.7	0.3	0.4	0.7
Glycine max	root	12.8e	466b	29d	26.9d	36.4	2.3	2.1	4.4
Zea mays	shoot	9.6f	472ab	41b	29.5cd	49.2	4.3	3.1	7.3
Zea mays	root	4.0g	486a	48a	31.4c	121.5	12.0	7.9	19.9
Trifolium repens	shoot	27.4b	397g	13f	18.0e	14.4	0.4	0.6	1.1
Trifolium repens	root	16.0d	423de	21e	20.2e	26.4	1.3	1.2	2.5
Populus euramericana	leaves	20.8c	435cd	34c	53.8a	20.9	1.6	2.6	4.2
Robinia pseudoacacia	leaves	33.3a	404fg	28d	32.3c	12.1	0.8	1.0	1.8
Elaeagnus umbellata	leaves	34.7a	418ef	32cd	38.7b	12.1	0.9	1.1	2.0
LSD ($p \leq 0.05$)	–	3.14	14.16	4.53	3.77	–	–	–	–

Note: different letters in each column show significant differences among treatments with $p \leq 0.05$

Corp., 2011). A probability level of $p \leq 0.05$ was considered significant (Steel and Torrie, 1980).

3 Results and discussion

3.1 Chemical composition of the residues – residue quality

A significant difference ($p \leq 0.05$) among different residue treatments was observed for different components of the plant residues presented in Table 2. The total N ranged from a minimum of 4.0 to a maximum of $35.2\,\mathrm{g\,kg^{-1}}$. Shoots of *Glycine max* and leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata* displayed the highest N compared to the remaining treatments (Table 2). The total C contents varied between $397\,\mathrm{g\,kg^{-1}}$ in the *Trifolium repens* shoot and a maximum of $486\,\mathrm{g\,kg^{-1}}$ in the *Zea mays* root. *Zea mays* (both shoot and root) displayed the highest C contents compared to the remaining plant-residue treatments. The C : N showed a similar trend recorded for residue C content. The LG content varied between a minimum of $11\,\mathrm{g\,kg^{-1}}$ in the *Glycine max* shoot and a maximum of $48\,\mathrm{g\,kg^{-1}}$ in the *Zea mays* roots. Similarly, a minimum PP content ($13.1\,\mathrm{g\,kg^{-1}}$) was recorded in the *Glycine max* shoot while a maximum PP ($52.8\,\mathrm{g\,kg^{-1}}$) was found in the *Populus euramericana* leaves. The LG / N, PP / N and LG+PP / N ratios were highest in the *Zea mays* root while the lowest values were recorded in the *Glycine max* shoot. Generally, total N contents of the legume residues were higher compared to the non-legumes. Similarities could be observed between the same organs of the different species, i.e., all the roots were characterized by high C, LG and PP contents and lower N concentration. Leaves were particularly rich in PP and total N. The differences in the concentration of quality characteristics of residues according to plant components, i.e., shoot, root and leaves, have been reported previously (Abiven et al., 2005; Nourbakhsh and Dick, 2005). It has been reported that high lignin content in root was due to the presence of suberin in the roots and its ability to form complex barriers when associated with lignin (Abiven et al., 2005). Plant residues used in this study provided a wide range of contrasted chemical composition and significant variation in quality characteristics because of the difference in (i) type of species, i.e., leguminous and non-leguminous, trees and crops, and (ii) plant components/organs, i.e., shoot, root and leaves.

3.2 Nitrogen mineralization

Analysis of variance showed that N mineralization was significantly ($p \leq 0.05$) affected by the treatments and the incubation timings, while the interaction between the treatments and the timings was also significant. Results indicated that the control soil without any amendment released a maximum of $77.7\,\mathrm{mg\,N\,kg^{-1}}$ on day 100 compared to $13.7\,\mathrm{mg\,kg^{-1}}$ at the start, showing a substantial release of N into mineral N pool (Table 3). Expressed as the total N initially present, the net N mineralized during the incubation was 14 %. The mineralization of native soil N observed here was in accordance with our previous study where a maximum of $90\,\mathrm{mg\,kg^{-1}}$ mineral N was released from the control soil, representing 16 % of the initial N of the soil (Abbasi and Khizar, 2012). Among different plant materials added, the legumes, i.e., the shoot of *Glycine max* and shoot and root of *Trifolium repens*, exhibited significantly higher TMN compared to the non-legumes. The maximum TMN released from these amendments varied between 150 and $189\,\mathrm{mg\,kg^{-1}}$. The mean values indicated that these legumes were collectively able to release $85\,\mathrm{mg\,N\,kg^{-1}}$ compared to $20\,\mathrm{mg\,kg^{-1}}$ by maize and $58\,\mathrm{mg\,N\,kg^{-1}}$ by leaves of the non-legumes trees. As expected, the plant organs also affected N mineralization and, in general, roots displayed significantly lower TMN compared to the shoot and leaves. Incorporation of *Glycine max*

Table 3. Mean changes in the concentration of total mineral N of a soil amended with different plant residues and incubated at 25 °C under controlled laboratory conditions during a 120-day period ($n = 3$).

Treatments	Days after plant-residue addition										LSD ($p \leq 0.05$)
	0	7	14	21	28	42	60	80	100	120	
	mg N kg^{-1} soil										
Control	13.7	13.9	12.9	17.1	30.9	65.9	63.1	75.6	77.7	51.7	2.88
T_1	14.8	39.2	49.2	76.8	96.7	158.1	165.2	174.1	188.7	160.9	7.90
T_2	13.7	8.1	5.2	8.3	11.8	13.8	28.4	50.4	49.4	27.7	8.15
T_3	13.7	7.4	6.2	6.9	10.5	23.1	21.2	36.1	46.7	21.0	5.34
T_4	14.3	7.4	9.4	7.7	8.8	15.3	22.2	21.4	32.4	26.4	4.30
T_5	14.1	19.0	21.6	55.5	62.5	86.8	127.6	150.8	145.8	93.3	7.31
T_6	15.5	8.2	5.2	23.9	34.0	85.3	98.0	149.9	130.2	85.8	9.46
T_7	13.0	5.7	4.1	8.6	22.6	55.5	73.1	106.8	87.3	66.9	8.39
T_8	13.9	7.4	9.2	23.6	46.6	91.3	111.0	138.9	127.8	93.7	7.83
T_9	12.9	9.4	14.5	25.3	51.1	80.1	92.7	140.0	116.4	93.5	6.88
LSD ($p \leq 0.05$)	2.43	4.77	3.12	5.11	7.63	8.23	6.87	9.23	8.27	7.34	

T_0 is the control; T_1 is *Glycine max* shoot, T_2 is *Glycine max* root; T_3 is *Zea mays* shoot, T_4 is *Z. mays* root; T_5 is *Trifolium repens* shoot; T_6 is *Trifolium repens* root; T_7 are *Populus euramericana* leaves; T_8 are *Robinia pseudoacacia* leaves; T_9 are *Elaeagnus umbellata* leaves. LSD represents the least significant difference ($p \leq 0.05$) among incubation periods (within rows) and among the treatments (within column).

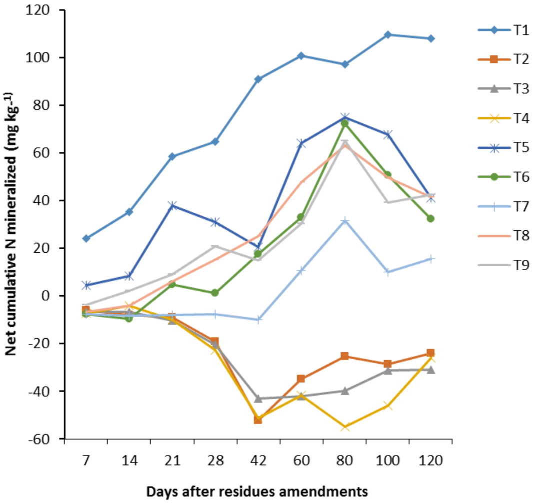

Figure 1. Net cumulative N mineralized from the added plant residues at different incubation periods. Legend: T_1 is *Glycine max* shoot, T_2 is *Glycine max* root; T_3 is *Zea mays* shoot, T_4 is *Zea mays* root; T_5 is *Trifolium repens* shoot; T_6 is *Trifolium repens* root; T_7 are *Populus euramericana* leaves; T_8 are *Robinia pseudoacacia* leaves; T_9 are *Elaeagnus umbellata* leaves.

root and *Zea mays* shoot and root resulted in a constant decrease in TMN, and the maximum values ranged between 32 and 49 mg kg^{-1} compared to 78 mg kg^{-1} in the control treatment. However, after initial negative values until day 14 and 21, leaves of *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata* continuously increased TMN until reaching between 107 and 140 mg kg^{-1} (highest values).

3.3 Net cumulative N mineralization

Nitrogen mineralization of added plant residues was determined on the basis of net cumulative N mineralized. The N mineralization from *Glycine max* and *Trifolium repens* shoot showed positive values throughout the incubation, ranging from 24 to 110 mg kg^{-1} for *Glycine max* and 5 to 75 mg kg^{-1} for *Trifolium repens* (Fig. 1). Considering the NCNM at the end day 120, the net N mineralized as percentage of total N applied from *Glycine max* and *Trifolium repens* shoot was 54 and 21 %, respectively. The percent of N mineralized from *Glycine max* shoot had been reported previously and ranged from 39 to 43 % of applied N residues (Nakhone and Tabatabai, 2008). However, the NCNM from *Glycine max* roots, *Zea mays* shoot and *Zea mays* roots exhibited negative values throughout the incubation, indicating net immobilization. Among the three residues, *Zea mays* roots displayed higher negative values leading to higher immobilization. Roots of *Glycine max* and leaves of *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata* showed four phases of mineralization–immobilization turnover: initial negative values from days 7 to 21, slow mineralization from days 21 to 60, a rapid mineralization between days 60 and 80 and a decline in net between days 100 and 120. The net N mineralized as percentage of total N applied from roots of *Glycine max* and leaves of *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata* was 16, 8, 21 and 21 %, respectively. Net nitrogen mineralization (% of added N) from different organic materials during 110 days of incubation was in the range of −35 % in *Triticum aestivum* (wheat) residues to 81 % in *Trifolium repens* (white clover) residues (Kumar and Goh, 2003). Similarly, a 44, 38 and 35 % of N added had been released from

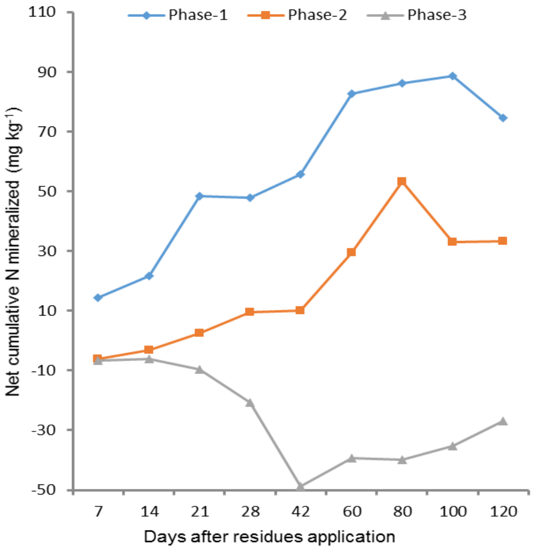

Figure 2. The mineralization–immobilization turnover of added plant residues representing three phases during 120 days incubation.

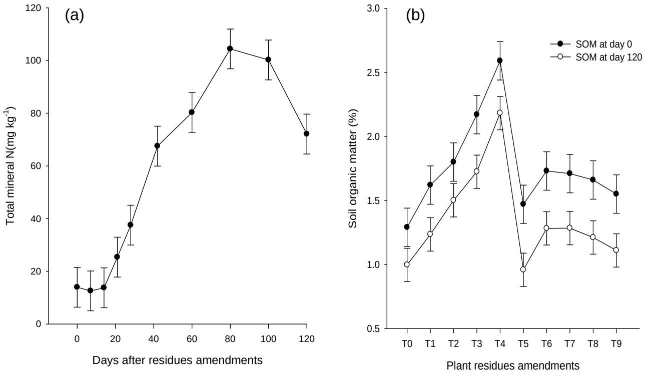

Figure 3. Mineralization trend of added plant residues across timings **(a)** and soil organic matter (SOM) turnover of different plant residues recorded at the start of the experiment on day 0 and at the end of incubation on day 120 **(b)**. The hanging bar on each major line represents the LSD ($p \leq 0.05$) between incubation periods and between each treatment.

the leaves of peanut, pigeon pea and hairy indigo, respectively (Thippayarugs et al., 2008).

All legumes (except *Glycine max* root) exhibited the highest NCNM (average 30 % of added plant N residues) compared to non-legumes (17 %). Similarly, the cereal crop *Zea mays* shoot and root exhibited net immobilization compared to net mineralization observed in the legumes and tree leaves. The plant components also showed variation in NCNM. For example, shoots of *Glycine max* and *Trifolium repens* mineralized an average of 74 mg N kg^{-1} compared to 4 mg N kg^{-1} from the roots. Likewise, leaves of forest trees showed higher NCNM compared to the roots of legumes and non-legumes crop.

The shoots of *Glycine max* and *Trifolium repens* exhibited the highest NCNM without any negative value during incubation because of high N concentration and a low C / N ratio. However, it is interesting to note that the total N concentration of the leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata* was higher and C / N ratio was lower compared to the *Trifolium repens* shoot, but the net mineralization (averaged) of *Trifolium repens* shoot was higher (47 and 58 %) compared to the leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata*, respectively. The low mineralization in leaves in spite of high N content and low C / N ratio was attributed to higher concentration of LG, PP, LG / N, PP / N and LG+PP / N. These results demonstrated the effect of other factors in addition to total N and C / N ratio on plant-residue decomposition and N mineralization kinetics. As indicated in a previous study (Trinsoutrot et al., 2000), the net accumulation (whether positive or negative) of mineral N in soil during decomposition of organic residues is directly related to the residue N content. However, our results clearly indicated that N was not the only factor affecting the mineralization of added residues; some additional quality characteristics also influenced MIT of plant residues. Likewise, the total N content and C / N ratio of the leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata* were on par with *Glycine max* shoot but the net mineralization of *Glycine max* shoot was 3-fold higher. It had been reported that organic materials with similar C / N ratios may mineralize different amounts of N because of differences in composition that are not reflected by the C / N ratio (e.g., different lignin contents) (Mohanty et al., 2011).

Similarly, roots of *Glycine max* and *Zea mays* showed net immobilization while roots of *Trifolium repens* displayed fast decomposition and net N-release pattern. This discrepancy in root MIT was mainly due to high N concentration, low C / N ratio and low LG and PP contents of the roots of *Trifolium repens*. The N turnover shown by *Trifolium repens* roots confirmed the strong below-ground N dynamics and residual effect of *Trifolium repens* when grown in the soil.

Among the leaves of different trees tested, leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata* released a substantial amount of N into the mineral N pool. Leaf residues have been described as high-quality litter materials in terms of high N and low lignin contents (Thippayarugs et al., 2008) and have been found to decompose easily and release mineral N substantially (Mtambanengwe and Kirchmann, 1995) as observed in our study. However, *Populus euramericana* leaves exhibited higher net immobilization (for a longer period) and lower net mineralization. The variation was again due to disparity in the biochemical composition. The low N content, high C / N ratio and high PP content may have been largely responsible for the slow decomposition and low net mineralization of *Populus euramericana* leaves. These results inferred that the same plant components may not necessarily show similar decomposition and

Table 4. Pearson linear correlation coefficients between initial quality characteristics of the plant residues and net N mineralization and correlation within plant-quality characteristics.

	N_{min}	TN	LG	PP	C : N	LG : N	PP : N
TN	0.89^{**}						
LG	-0.84^{**}	-0.66^{*}					
PP	-0.42ns	-0.10ns	0.62^{*}				
C : N	-0.69^{*}	-0.80^{**}	0.73^{*}	0.07ns			
LG : N	-0.68^{*}	-0.76^{**}	0.77^{**}	0.14ns	0.99^{**}		
PP : N	-0.73^{*}	-0.77^{**}	0.82^{**}	0.29ns	0.99^{**}	0.98^{**}	
LG + PP : N	-0.70^{*}	-0.76^{**}	0.79^{**}	0.19ns	0.99^{**}	1.00^{**}	0.99^{**}

** and * represent significant levels at $p \leq 0.01$ and $p \leq 0.05$, respectively; the correlation significance and non-significance level was calculated at $p \leq 0.05$. The abbreviations represent N mineralization ($N_{\text{min.}}$), total nitrogen (TN), lignin (LG) and polyphenols (PP).

mineralization turnover because of the variation in biochemical composition.

In general, the added plant residues increased organic matter stock in soil and thereby increased N mineralization and N transformation processes in soil. Plant or crop residues, when added or incorporated into the soil, increase the organic matter (avoid the climate change), reduce the soil and water losses and increase the biological activity in the soils. Such changes bring a substantial improvement in the physical, chemical and microbial properties of soil and eventually in the soil quality (Giménez Morera et al., 2010; Jiménez et al., 2013; Zhao et al., 2013; Singh et al., 2014; Prats et al., 2014)

3.4 Pattern and trend of N mineralization

The patterns of N mineralization varied among plant residues and plant components. After incorporation into soil and during incubation, the added residues exhibited three main patterns of cumulative net mineralization (Fig. 2): (i) a pattern of the continuous and rapid release of net N throughout the incubation without showing any negative value indicating net mineralization, shown by the *Glycine max* shoot and *Trifolium repens* shoot; (ii) a pattern shown by the *Trifolium repens* roots and *Populus euramericana*, *Robinia pseudoacacia* and *Elaeagnus umbellata* leaves indicated initial negative values of net cumulative immobilization for variable periods followed by slow and then a rapid release of N, indicating immobilization–mineralization turnover; (iii) a pattern of continuous negative values throughout the incubation, indicating net N immobilization as seen in the case of the *Glycine max* root and the *Zea mays* shoot and root. The MIT and N-release patterns by plant residues observed here were in accordance with those reported previously in both leguminous and non-leguminous plant residues (Kumar and Goh, 2003).

The N mineralization trend over time showed wide variation (Fig. 3a). These results highlighted the time taken for releasing N into the mineral N pool by the added plant residues. Results showed an initial lag phase where most of the applied residues endured immobilization with little mineralization; only the *Glycine max* and *Trifolium repens* shoots showed mineralization during 0 to 21 days of incubation. The rapid mineralization phase occurred from day 28 to day 80. Thereafter a declining phase of mineralization started toward the later part of the incubation from day 100 to day 120.

3.5 Changes in soil organic matter

In order to examine the changes in soil organic matter (SOM) in response to added plant residues, a comparison between the SOM at the start of day 0 and the end of incubation on day 120 has been shown (Fig. 3b). Soil organic matter contents of all the treatments recorded on day 120 were lower than those recorded on day 0. The unaccounted SOM ranged between 32 and 67 % compared to that recorded on day 0. The decreasing trend of SOM was substantially higher for the treatments showing mineralization (54–67 %) compared to those showing immobilization (32–38 %). By the end of day 120, the loss of SOM was in the following order: *Trifolium repens shoot* > *Elaeagnus umbellata* leave > *Trifolium repens* root = *Robinia pseudoacacia* leaves > *Populus euramericana* > *Glycine max* shoot > *Zea mays* shoot > *Zea mays* root = *Glycine max* root. The SOM turnover observed here coincided with net mineralization. In the initial lag phase when mineralization was either very low or displayed negative values, on average only 8 % of the initial SOM had been utilized (7–21 days). The SOM utilization during days 28–80 when mineralization was rapid was 31 % of the initial amount, while 43 % of initial SOM was utilized in the later part of incubation (between days 100 and 120) when mineralization start showing a declining trend.

3.6 Relationship between cumulative N mineralization and residue-quality characteristics

Results of the study showed highly significant positive correlation between N mineralization and plant-residue N concentrations ($r = 0.89$; $p \leq 0.01$) (Table 4). In contrast, a negative significant correlations existed between net cumulative N mineralized and LG ($r = -0.84$; $p \leq 0.01$), NCNM and

C / N ratio ($r = -0.69$; $p \leq 0.05$), NCNM and LG / N ratio ($r = -0.68$; $p \leq 0.05$), NCNM and PP/N ratio ($r = -0.73$; $p \leq 0.05$) and NCNM and LG + PP / N ratio ($r = -0.70$; $p \leq 0.05$). The correlation between N mineralization and PP was nonsignificant with $p \leq 0.05$. The significant positive correlation between net rates of N mineralization and residue N concentration observed is consistent with other studies (Nourbakhsh and Dick, 2005; Vahdat et al., 2011). It has been reported that N availability may control the decomposition of plant residues, particularly those with low N content such as cereals, when the N requirements of the soil decomposers are not met by the residue or soil N contents (Vahdat et al., 2011). A negative correlation was also observed between net N mineralization and C / N ratio of the plant materials. Previously, total N contents and C / N ratio were considered adequate for predicting the net N mineralization of crop residue. However, the latest studies, including the present work, highlight the role of other quality characteristics, including LG and PP, that affect net mineralization of plant residues. The closer relationship between net mineralization and residue lignin contents ($r = -0.84$; $p \leq 0.01$) than that of the C / N ratio ($r = -0.69$; $p \leq 0.05$) recorded in this study was in accordance with previous findings (Vahdat et al., 2011). The highly significant positive correlation between net N mineralization and the residue N content ($r = 0.89$; $p \leq 0.01$) confirms the previous results (Nourbakhsh and Dick, 2005; Vahdat et al., 2011), indicating that residue N concentration can be considered a better tool to predict mineralization of added organic residues compared to the C / N ratio.

4 Conclusions

The experiment showed that soil amended with plant residues displayed wide variation of N mineralization depending on the plant species and plant components/organs. The decomposition and N-release potential of added materials were largely related to their biochemical composition. In addition to residue N concentration and C / N ratio, LG contents of plant residues also appeared to be an important factor in predicting the net N mineralization of plant residues. Shoots of *Glycine max and Trifolium repens* and leaves of *Robinia pseudoacacia* and *Elaeagnus umbellata* exhibited a substantial mineralization potential, demonstrating that legumes and trees of these two plant species can produce high-quality residues and thus have the potential to promote N cycling in agroecosystems. This study suggested that plant residues showing rapid mineralization can be used for early N demands of a crop, while residues with high C : N and LG contents immobilize N and thus can help to counter the N loss generally observed due to rapid ammonification–nitrification turnover. Use of such plant materials in our cropping systems, especially in the regions subjected to land degradation, may be a useful management strategy to restore these soils for agriculture production.

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