

## Carbon and nitrogen mineralization in different upland soils of the subtropics treated with organic materials

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### Abstract

Use and management of organic waste/residues is currently an important global issue for attaining sustainability in agricultural production. However, knowledge about the decomposition characteristics and nutrient release pattern of added organic materials in subtropical soils and their interaction with inherent soil properties are lacking. Thus, laboratory incubation studies were carried out under aerobic conditions with crop residues and chicken manure (1%) applied to six contrasting soils. In all cases, CO<sub>2</sub>-C effluxes peaked by day 9 and the active C release phase persisted until day 25, indicating that priming effects might have occurred. The high pH and non-calcareous soils had higher CO<sub>2</sub> effluxes than the acidic soils. The relative loss of added C differed between soils and its magnitude depended on the decomposable characteristics of the added organic materials, with chicken manure > mungbean residue > wheat residue. Rapid ammonification with presumed immobilization occurred up to day 15. Thereafter, NH<sub>4</sub><sup>+</sup> oxidation took place in the high pH and non-calcareous soils, with chicken manure exhibiting the greatest nitrification. By contrast, the acidic soils predominantly accumulated NH<sub>4</sub><sup>+</sup>, thereby showing higher net N mineralization. In the acidic soils, nitrification was either small or stable, with the process being limited by the addition of organic materials with a high C/N ratio. Some disappearances of NO<sub>3</sub><sup>-</sup> also indicated that N immobilization and/or denitrification had taken place. As such, the decomposition rate constant (*k*) correlated well either with pH alone ( $R^2 = 0.59^{***}$ ) or coupled with C/N ratio ( $R^2 = 0.61^{***}$ ) of the organic materials. The net N mineralization and nitrification showed a similar trend ( $R^2 = 0.26-0.42^*$ ), although these processes were mostly regulated by the different soil factors. Our results reveal that the parameters pH and C/N ratio of organic materials should be included in equations to calculate the quality of added organic matter. Our newly proposed equations, incorporated as the organic matter quality index (OMQI), can predict *k*, net N mineralization and nitrification in different soil types under aerobic conditions, and it could be further improved by also considering inherent soil factors.

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### 1. Introduction

Organic matter, as one of the main keys to soil productivity, has received global attention recently. In particular, an appropriate management strategy towards carbon sequestration can improve soil productivity and crop

production as well as help to reduce the atmospheric build-up of carbon dioxide (CO<sub>2</sub>). It is by facilitating the formation of stable soil aggregates and improving the structure, aeration, tilth, moisture-holding capacity and cation exchange capacity of the soil. Thus, the addition of organic materials to agricultural soil (with or without chemical fertilizers) is important for replenishing the annual C losses and for improving both the biological and chemical properties of the soils (Goyal et al., 1999). This can be achieved from the plant biomass that is usually removed from the agricultural field and from the extensive use of animal manure with improved management approaches. The residue bound-nutrients can be available to the plants in a considerable amount over time (Rahman et al., 2001) and

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the readily available N (ammonium–N + uric acid–N) in poultry manure can supply 30–50% of the total N to plants (Nicholson et al., 1996).

Soil properties, and particle size fractions in particular, influence the stability of the microbial biomass and products, the degree to which depends on the type of organic substrate added (Ladd et al., 1996). Indigenous soil properties contribute largely to C and N mineralization, where soil pH can play a dominant role (Jansson, 1996; Wang et al., 2001). Soil microorganisms direct the decomposition process of the organic materials by liberating CO<sub>2</sub> and plant nutrients (Mary et al., 1996). The evolution of CO<sub>2</sub> decreases with time, with the organic matter attaining a chemical composition similar to that of humus. The dead cells of microbes are also readily mineralized by the living microflora and contribute substantially to the pool of mobile plant nutrients in the soil (Haider et al., 1991).

The incorporation of organic materials into microbial-deficient soil results in N immobilization and may bring about N limitation of the microbial biomass (Chapman, 1997). The amended crop residues increase the supply of carbonaceous materials as an energy source for the living microorganisms and the dead microbial biomass provides the substrate (Mengel, 1996), leading to a series of biological N transformations. Organic residues having low C/N ratios show N mineralization more than those with wide C/N ratios, with the latter mostly causing N immobilization during decomposition (Mary et al., 1996). However, the N supplying capacity of certain soils depends mostly on the indigenous soil organic matter, the addition of organic residues, and the various soil environmental factors (Fu et al., 1987).

As such, information on the timing and method of adding organic matter, particularly with respect to its decomposition and nutrient release pattern for a specific soil is vital towards generating effective management strategies. These may reduce the use of chemical fertilizers while offering better crop return and less environmental degradation. Yet, detailed information on the variable responses of organic additives in contrasting upland soils of the subtropics is lacking. Instead, it is generally believed that the decomposition of organic materials is rapid in the tropics due to the high temperatures and favourable environmental conditions. This effect is perhaps greatest in upland situations, where the soil water contents are usually near to field capacity. To meet this goal in general, and for subtropical upland soils in particular, methods for evaluating the soil-specific quality of organic materials and their influence on C and nutrient release are key. Recently, Tian et al. (1995) proposed an empirical model, the plant residue quality index (PRQI), to estimate the decomposition rate constant (*k*) and net N mineralization, with Kumar and Goh (2003) later modifying it to yield PRQIM. However, the biochemical compositions (lignin and polyphenols) used for both estimations are very expensive to determine and time-consuming. As such, we studied the aerobic turnover of various organic materials in

different soils and their resultant effect on N transformations to: (1) elucidate the effects of both the inherent soil properties and the biochemical properties of the added organic materials on these processes, and (2) attempt to adapt PRQI and PRQIM to use readily available/measurable biochemical properties of organic materials.

## 2. Materials and methods

### 2.1. Soil characteristics

Six contrasting upland soils from different regions of Bangladesh, a subtropical country, were collected from a depth of 0–15 cm. The six soils were calcareous, peat, saline, non-calcareous, terrace and acid sulfate, representing the agroecological zones of Low Ganges River Floodplain, Gopalganj-Khulna Beels, Ganges Tidal Floodplain, Old Brahmaputra Floodplain, Level Barind Tract and Chittagong Coastal Plain, respectively. The soil samples were air-dried because of storage constraints under the assumption of long-term maintenance of C and N mineralization (Haney et al., 2004) and sieved (2 mm mesh) to remove roots and other debris. All samples were stored in a cool and dry place until the start of the experiment. The electrical conductivity for the saline soil was 6.6 dS m<sup>-1</sup>. Other selected physical and chemical properties for all soils are presented in Table 1.

### 2.2. Treatments and incubation

The experiment comprised four treatments in total: *T*<sub>0</sub> = no organic matter added (control), *T*<sub>1</sub> = wheat (*Triticum aestivum* L.) residue added, *T*<sub>2</sub> = mungbean (*Vigna mungo* L.) stover/residue added, and *T*<sub>3</sub> = chicken manure added. Organic materials were applied (1% dry basis) to the soils and mixed thoroughly; both the biochemical properties of and the amount of C and N added for each of the three organic materials are presented in Table 2. Thirty grams of each soil was taken in a PVC bottle (180 ml) for N mineralization study. Two hundred grams of each soil was taken in a glass jar (1200 ml) to determine CO<sub>2</sub> emission. Each treatment consisted of three replicates, with a series of bottles being used for destructive samplings. To initiate microbial activities, all soils were preincubated for 7 days at 30% water-filled pore space (WFPS) by adding deionized water. The treatment bottles and jars were kept open in an incubation room at 27 ± 1 °C and the water losses were corrected at a 2-day interval.

For the incubation, the organic materials were applied to the soils as for the treatments and mixed thoroughly. Deionized water was added to reach 60% WFPS. Various C and N properties were determined at days 0, 2, 5, 9, 15, 25, 40, 60 and 90. Triplicate samples were taken for each treatment and day of determination. The amount of water lost through evaporation was corrected at an interval of 2–3 days and all jars were kept open in an incubation room at

Table 1  
Some physical and chemical properties of the selected soil series from the six Agroecological Zones of Bangladesh

General soil type	Parent material	Soil series	Sand (%)	Silt (%)	Clay (%)	Texture <sup>a</sup>	Bulk density (g cm <sup>-3</sup> )	Soil pH	C (%)	N (%)	C/N	CEC (cmol <sub>c</sub> kg <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N (mg N kg <sup>-1</sup> soil)	NO <sub>3</sub> <sup>-</sup> -N (mg N kg <sup>-1</sup> soil)
Calcareous grey floodplain	Ganges River Alluvium	Gangachara	17.9	70.1	12.0	SiL	1.31	7.4	0.75	0.07	10.7	25.0	13.1	9.2
Peat	Mucky material (Reeds and Grasses)	Pirojpur	10.1	51.2	39.7	SiCL	1.12	7.3	3.84	0.26	13.2	38.0	7.9	30.6
Salt-affected floodplain	Coastal Alluvium	Bajua	48.2	38.0	13.8	L	1.36	7.8	1.14	0.07	14.8	16.6	9.6	57.8
Non-calcareous floodplain	Old Brahmaputra Alluvium	Sonatala	62.2	24.0	11.8	SL	1.38	5.1	1.28	0.07	10.7	10.0	14.4	6.1
Deep red brown Terrace	Modhupur Clay	Kashimpur	20.5	56.0	23.5	SiL	1.34	5.7	0.63	0.05	12.6	25.4	25.4	2.2
Acid sulfate	Coastal Alluvium	Ramgati	19.0	66.5	14.5	SiL	1.29	4.3	1.77	0.12	14.8	24.0	44.6	1.8

<sup>a</sup> SiCL, Silty clay loam; SiL, silt loam; SL, sandy loam; L, loam.

27 ± 1 °C. Tripods holding vials containing 10 ml NaOH (40%) solution were suspended in all jars to determine CO<sub>2</sub> concentrations (Anderson, 1982). The total CO<sub>2</sub>-C evolution over 90 days was calculated by integrating over the area of the daily fluxes. The apparent loss of added organic C was estimated by subtracting the total CO<sub>2</sub>-C released in a given treatment from that measured in the control. The estimated %C of added organic materials that remained in the soils was fitted to a simple exponential decay function to calculate the decomposition rate constant (*k*), with the coefficients of determination (*R*<sup>2</sup>) ranging from 0.81 to 0.99.

### 2.3. Soil analysis

Mineral N (NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N + NO<sub>2</sub><sup>-</sup>-N) was determined by the steam distillation method (Keeney and Nelson, 1982) using a soil:KCl solution ratio of 1:2.5. Net N mineralization/nitrification was estimated by subtracting the accumulated mineral N (NH<sub>4</sub><sup>+</sup>-N + NO<sub>3</sub><sup>-</sup>-N)/NO<sub>3</sub><sup>-</sup>-N at day 90 from that at day 0; subtracting this value for a given treatment from that for the control provided the apparent contribution of organic N to net N mineralization/nitrification. Standard laboratory methods were followed to determine other properties.

### 2.4. Statistical analysis

An *F*-test ( $\alpha=0.05$ ) and multifactorial analyses were carried out to analyze the treatment variations and standard errors. Simple and multiple regression analyses were performed between the *k*/total CO<sub>2</sub> fluxes/net N mineralization/net nitrification and indigenous soil properties (%sand, %clay, pH, %C, %N, C/N and CEC) and biochemical properties of organic materials (pH, %N, C/N, lignin, polyphenols and their ratios to N) using JMP version 4 (SAS Institute). Due to conflicting results, polyphenols were excluded from the multiple regression analysis. Despite this, a best fit for *k*/net N mineralization with coupled pH and C/N ratio of organic materials and net nitrification with the latter together with any other single variable (including polyphenols) was observed.

The plant residue quality index (PRQI) as defined by Tian et al. (1995) is calculated as  $[1/(a \times C/N + b \times \% \text{lignin} + c \times \% \text{polyphenols}) \times 100]$  where *a*, *b* and *c* are coefficients of the relative contributions (CRC) of the input variables. The former were calculated using the *F*-values of the regression analyses and CRC was the value of the given factors/sum of *F*-values of these factors. Kumar and Goh (2003) modified PRQI to PRQIM by regressing the *k* values against C/N, lignin/N and polyphenols/N ratios. We will instead use the term Organic Material Quality Index (OMQI) because both plant and animal residues were used in this study. For OMQI, the pH and C/N ratio of the organic materials were included, with or without soil factors. Both stepwise and 'enter all' for multiple regression systems were

Table 2

Biochemical characteristics of and amount of C and N present in three different organic materials added to six contrasting soils

Type of organic materials	Biochemical properties of the added organic materials						Organic materials added ( $\text{g kg}^{-1}$ soil)	
	pH	%C	%N	C/N	%Lignin	%Polyphenol	C	N
Wheat residue	7.1	47.5	0.63	75.4	10.8	0.92	4.75	0.063
Mungbean residue	7.3	45.3	1.28	35.4	6.5	0.72	4.53	0.128
Chicken manure	7.8	22.8	2.16	10.6	7.2	1.61	2.28	0.216

tested to improve the relations and to minimize the variability among the soils.

### 3. Results

#### 3.1. Carbon dioxide emissions

$\text{CO}_2\text{-C}$  evolution from the control soils increased with decreasing soil C content (Fig. 1a). For the terrace and calcareous soils, the highest peaks for  $\text{CO}_2\text{-C}$  flux

occurred at day 2 of the incubation. The fluxes decreased thereafter, but still remained higher than those in the remaining soils. Similar trends were also observed for total fluxes during the 90-day incubation (Fig. 1b). The  $\text{CO}_2\text{-C}$  fluxes from the soils with added organic material showed significant variation at the beginning of the incubation period (Fig. 2). Maximum peaks appeared by day 2 for all the soils except the non-calcareous one (by day 9) and the differences between soils were small by day 25 of the incubation. Total  $\text{CO}_2\text{-C}$  emission over the 90-day incubation period also showed significant

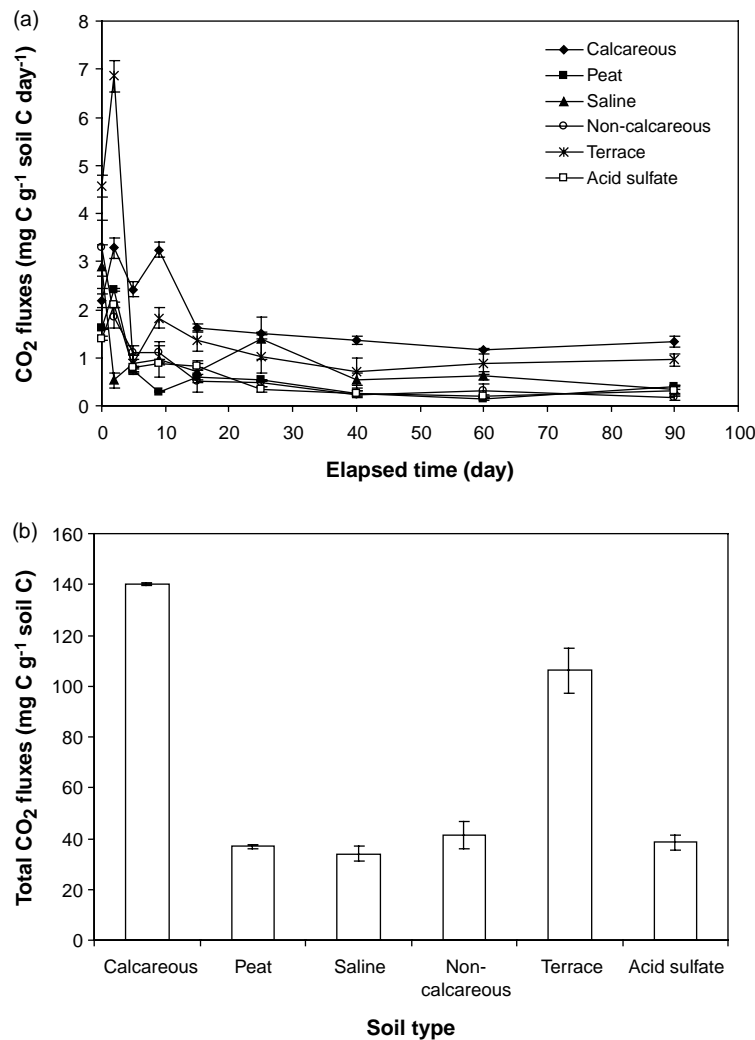


Fig. 1.  $\text{CO}_2\text{-C}$  fluxes (a) and its total release per gram of soil C (b) during the 90-day incubation period from six contrasting non-amended soils. The vertical bars indicate standard errors.

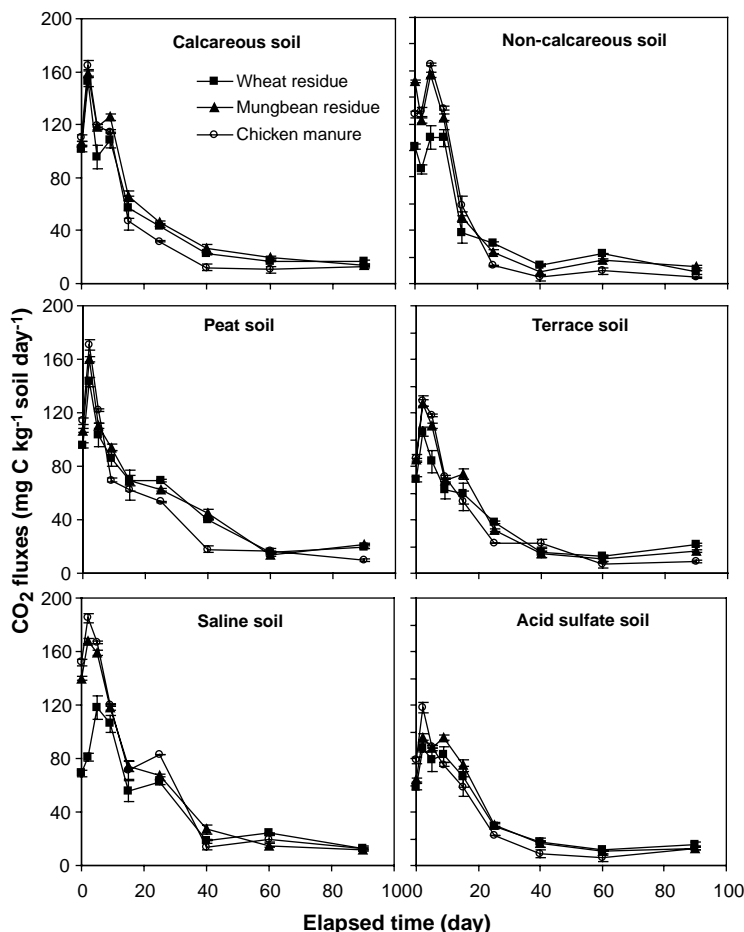


Fig. 2. Evolution of  $\text{CO}_2\text{-C}$  during the 90-day incubation period from six contrasting soils to which three different organic materials were added. The vertical bars indicate standard errors.

( $P < 0.0001$ ) variation between treatments (Fig. 3a). The  $\text{CO}_2\text{-C}$  flux was highest in the peat and calcareous soils containing high and low soil C, respectively. Flux values were lowest in the saline soil and intermediate and identical for the low pH non-calcareous, terrace and acid sulfate soils. In all cases, there was initial increase of soil pH, with the high pH soils demonstrating large buffering capacities at the later periods (data not shown). Among the added organic materials, chicken manure had a greater initial influence on  $\text{CO}_2\text{-C}$  evolution than either mungbean or wheat residues.

The relative loss of SOC also varied significantly ( $P < 0.0001$ ) among the treatments (Fig. 3b). The non-calcareous, peat, calcareous and terrace soils lost significantly higher amounts of C (60–67%) than the other soils, in which the amount of loss (50–54%) was identical. The loss of C differed significantly between the added organic materials, with chicken manure (83%) > mungbean residue (52%) > wheat residue (46%). The added C lost from the latter two materials, however, was not significant in either the high pH soils or the non-calcareous one. As such, the non-calcareous and peat soils treated with chicken manure had the highest C reductions (85–95%). By contrast,

the saline soil showed the lowest loss with the addition of either wheat (30%) or mungbean residues (39%).

The decomposition rate constants ( $k$ ) varied significantly ( $P < 0.0001$ ) between soils and organic materials (Table 3). Rates were faster in the non-calcareous soil (0.0213) than in the peat and calcareous soils (0.0129–0.0154). The  $k$  values for the remaining three soils were lower and identical. Chicken manure treated soils showed a significantly higher  $k$  (0.0247) than those treated with either mungbean or wheat residues (0.0070–0.0085). Considering only the fast phase (data not shown), similar but increased  $k$  values were obtained between soils (0.0182–0.0301) and between organic materials (0.0133–0.0454). During the subsequent slow phase, differences between soils were narrower (0.0046–0.0114), and chicken manure displayed significantly higher  $k$  values (0.0171) than either mungbean (0.0060) or wheat residues (0.044).

### 3.2. Nitrogen mineralization and nitrification of added organic material

Initial ammonification took place in all soils until day 15 of the incubation, together with generally probable

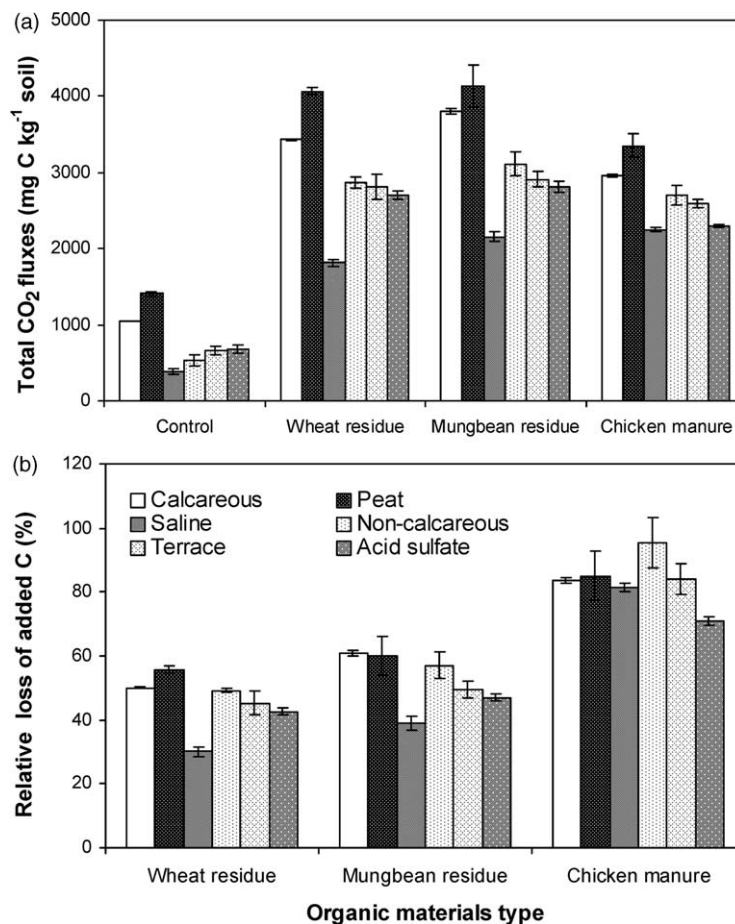


Fig. 3. Total CO<sub>2</sub> evolution (a) and relative loss of added C (b) during the 90-day incubation period from various treatments of six different soils. The vertical bars indicate standard errors.

concurrent immobilization (Fig. 4). Thereafter, oxidation of NH<sub>4</sub><sup>+</sup> occurred and was greater in the high pH and non-calcareous soils than in the acidic soils. Net N mineralization during the 90-day incubation period varied significantly between the soils ( $P < 0.0001$ ; Table 4). It was highest in the acid sulfate soil (74.38 mg N kg<sup>-1</sup> soil) but still similar to the calcareous soil, which showed a faster oxidation of NH<sub>4</sub><sup>+</sup>. The remaining four soils had identically low net N mineralization, however, the values were still greater than the respective ones for the control treatment (42.84 mg N kg<sup>-1</sup> soil). Irrespective of the soils, both chicken manure and mungbean residue have a larger significant ( $P < 0.0001$ ) influence on net N mineralization (68.76–72.59 mg N kg<sup>-1</sup> soil) than wheat residue (54.88 mg N kg<sup>-1</sup> soil), indicating wheat residue might

have more of an effect on N immobilization. The interaction between the soils and organic materials also varied significantly ( $P < 0.0001$ ), but response differences were identical.

Both the soils and organic amendments had a remarkable effect on the accumulation of NO<sub>3</sub><sup>-</sup>-N (i.e. nitrification; Fig. 5). Nitrification was faster in the high pH and non-calcareous soils than in the two acidic soils. In the beginning of the incubation period and again after day 25, disappearance of NO<sub>3</sub><sup>-</sup>-N was observed. Nitrification was rapid in the calcareous and non-calcareous soils and occurred earlier than in the peat, saline and terrace soils, where it occurred by day 25. This process was either stable or very slow in the terrace and acid sulfate soils. Net nitrification varied significantly ( $P < 0.0001$ ) and was highest in the saline

Table 3

Decomposition rate constants ( $-k$ ) of the different organic materials added to six contrasting soils during the 90-day incubation period

Soils treatment	Calcareous	Peat	Saline	Non-calcareous	Terrace	Acid sulfate	Mean
Wheat residue	0.0077	0.0098	0.0040	0.0074	0.0068	0.0063	0.0070
Mungbean stover	0.0106	0.0111	0.0053	0.0090	0.0077	0.0073	0.0085
Chicken manure	0.0203	0.0253	0.0189	0.0476	0.0225	0.0138	0.0247
Mean	0.0129	0.0154	0.0095	0.0213	0.0123	0.0091	

LSD<sub>0.05</sub>: soils, 0.0062; organic amendment, 0.0044; soils × organic amendment, 0.0108.

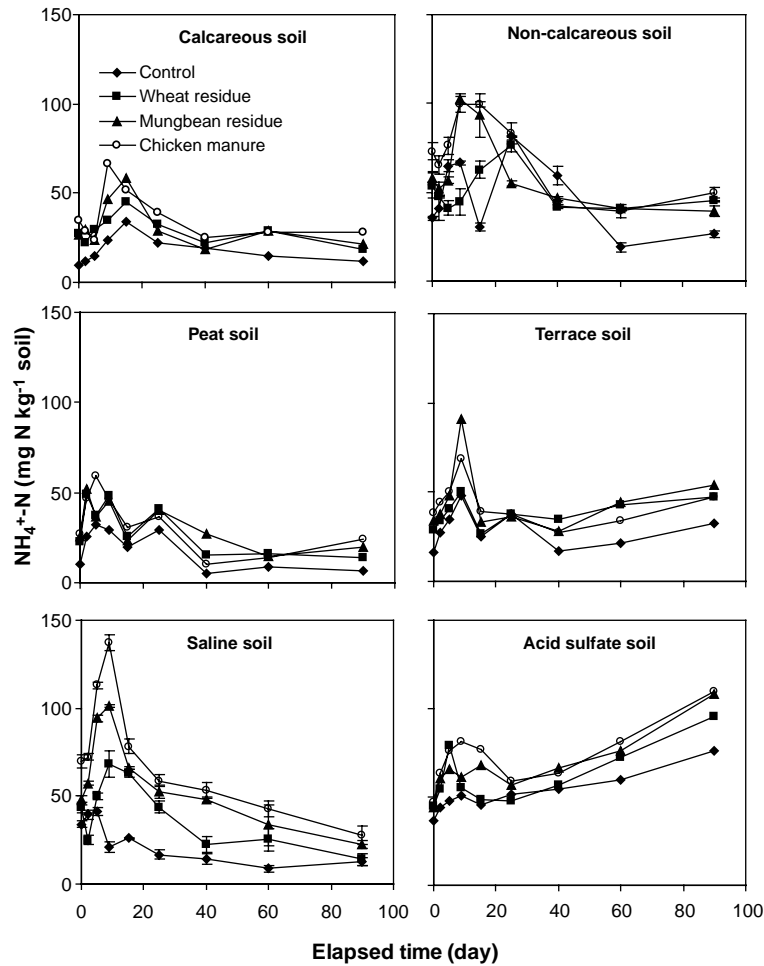


Fig. 4. Changes in  $\text{NH}_4^+\text{-N}$  content during the 90-day incubation period in six contrasting soils treated with various organic materials. The vertical bars indicate standard errors.

soil ( $85.31 \text{ mg N kg}^{-1}$  soil) followed by the calcareous soil (Table 4). It was identical, and lower, between the non-calcareous and peat soils as well as between the acid sulfate and terrace soils. The C/N ratio of the organic amendments

largely regulated the accumulation/disappearance of  $\text{NO}_3^- \text{-N}$  (Fig. 5). Application of chicken manure dominated the nitrification process more so than for mungbean and wheat residues, with some disappearance of  $\text{NO}_3^- \text{-N}$  occurring

Table 4

Net nitrogen mineralization and net nitrification ( $\text{mg N kg}^{-1}$  soil) of six contrasting soils to which various organic materials were added during the 90-day incubation period

Soils treatment	Calcareous	Peat	Saline	Non-calcareous	Terrace	Acid sulfate	Mean
<b>Net N mineralization</b>							
Control (No N)	43.43	39.54	35.65	20.35	44.72	53.15	39.47
Wheat residue	70.64	45.37	48.61	45.37	53.15	66.11	54.88
Mungbean stover	86.85	57.69	72.27	52.50	58.34	84.91	68.76
Chicken manure	90.10	64.81	66.11	53.15	68.05	93.33	72.59
Mean	72.75	51.85	55.66	42.84	56.07	74.38	
<b>Net nitrification</b>							
Control (No N)	41.48	43.42	57.04	29.10	28.52	12.96	35.42
Wheat residue	79.72	53.80	78.10	54.12	34.35	15.56	52.61
Mungbean stover	92.04	63.52	97.87	70.97	38.89	20.74	64.00
Chicken manure	97.22	68.05	108.25	76.48	58.98	31.11	73.35
Mean	77.62	57.20	85.31	57.67	40.18	20.09	

LSD<sub>0.05</sub>: soils, 5.62; organic amendment, 4.59; soils × organic amendment, 11.24

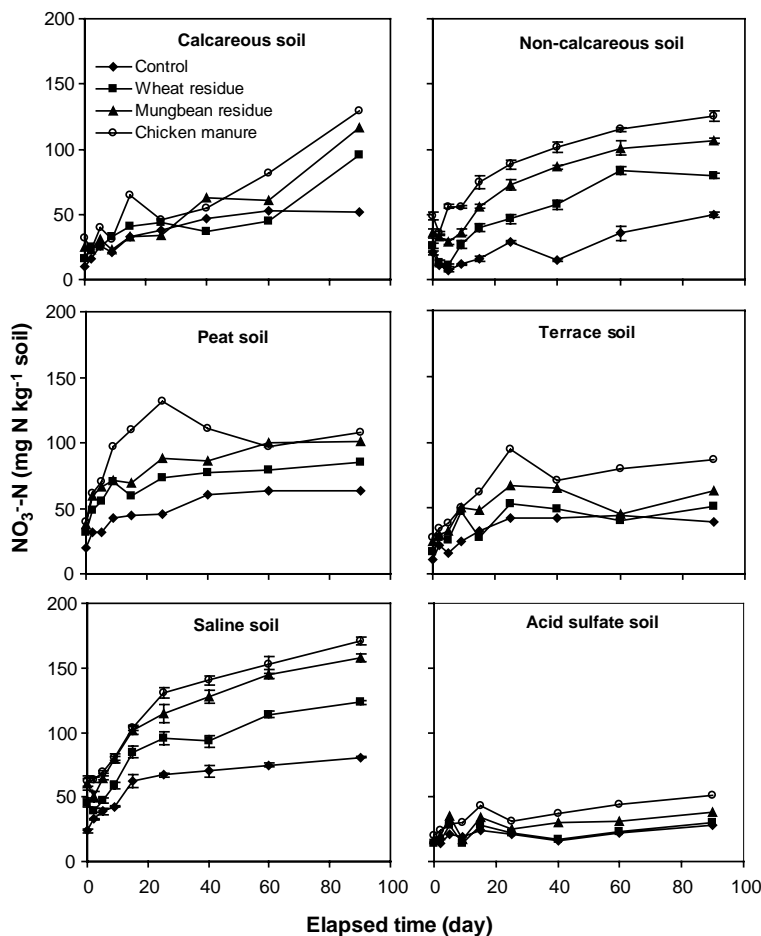


Fig. 5. Changes in  $\text{NO}_3^-$ -N content during the 90-day incubation period in six contrasting soils treated with various organic materials. The vertical bars indicate standard errors.

during the early part of the incubation period. Accordingly, chicken manure depicted significantly ( $P < 0.0001$ ) higher net nitrification ( $73.35 \text{ mg N kg}^{-1} \text{ soil}$ ) than either mungbean or wheat residues (Table 4). The saline soil supplied with chicken manure/mungbean residue and the calcareous soil applied with chicken manure demonstrated the highest, and identical, values of net nitrification, ranging from  $97.22$  to  $108.25 \text{ mg N kg}^{-1} \text{ soil}$ . Values were lowest for the control treatment and for the acid sulfate soil treated with wheat residue ( $12.96 \text{ mg N kg}^{-1} \text{ soil}$ ).

### 3.3. Relationships

The total  $\text{CO}_2$ -C flux of the added organic materials showed a significant negative ( $R^2 = 0.33^*$ ) relationship to the C/N ratio of the soils ( $P < 0.01$ ) and a positive one to %N ( $P < 0.05$ ), with a predictive level of 33 and 52%, respectively (data not shown). The indigenous soil properties separately did not affect any of the  $k$  values, net N mineralization or net nitrification. Only net N mineralization displayed a significant relationship to %clay, either negatively alone ( $R^2 = 0.21$ ) or coupled positively with CEC ( $R^2 = 0.33$ ). Similarly, net nitrification demonstrated

a significant relationship with the combination of pH, C/N ratio and clay content of the soils (with the latter two variables being inversely related to one another), with a predictive level of 67% ( $P < 0.001$ ).

The biochemical properties of the organic materials did not influence the total  $\text{CO}_2$  fluxes (Table 5), but were all significantly related to the means of  $k$  ( $P < 0.05$ ). As single factors, both pH and polyphenols of the organic materials influenced  $k$  significantly and positively ( $R^2 = 0.59^{***}$ ); they were followed by significant positive and negative relationships for %N and C/N ratio, respectively. Both net N mineralization and nitrification resulting from the added organic materials were correlated significantly ( $P < 0.05$ ) to various biochemical compositions of the materials, albeit poorly explained (0.23–42%). Two parameters, pH and C/N ratio, showed the best fit for  $k$  (61%) when all the independent variables were entered (Table 6). The corresponding prediction levels improved to 67% by including the soil property  $1/\text{CEC}$ , which by itself responded better than any of the other soil variables. Similarly, net N mineralization and net nitrification showed a good fit to C/N ratio and pH of the organic materials ( $R^2 = 0.42^*$  and  $0.11$ ) and inclusion of soil properties  $1/\text{clay}$  and  $1/\text{soil pH}$



Table 5

Coefficients of determination ( $R^2$ ) of the simple linear regressions relating several independent variables to the biochemical composition of the organic materials added to six contrasting soils

Parameters independent variables	N (%)	$\sqrt{N}$ (%)	pH	C/N	Lignin (%)	Polyphenol (%)	Lignin/N	Polyphenol /N	(Lignin + polyphenol)/N
Total CO <sub>2</sub> -C fluxes	0.10	0.08	0.11	0.03	0.05	0.15	0.02	0.01	0.02
Decomposition rate constant ( $k$ )	0.53***	0.50**	0.59***	-0.43**	-0.41**	0.59***	-0.31*	-0.28*	-0.31*
Net N mineralization	0.36**	0.12	0.10	-0.41**	-0.41**	0.30*	0.42**	-0.42**	-0.42**
Net nitrification	0.25*	0.26*	0.25*	-0.26*	-0.25*	0.23*	-0.24*	-0.23*	-0.24*

\*, \*\*, \*\*\*Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 6

Regression coefficients and statistics for the equations fit on the decomposition rate constant ( $k$ ) of the organic materials (OM) applied to six contrasting soils vs. biochemical composition of the organic materials with or without soil factor

Number of population/soil	Biochemical composition of the OM /soil factor	Regression coefficient	Standard error	Probability (individual)	F-value	$R^2$ /probability/ F-value (multiple)	Coefficient of relative contribution (CRC)
All soils ( $n=18$ )	Intercept	-0.2939	0.1196			0.61	
	pH	0.0406	0.0153	0.02	7.06	$P < 0.001$	0.880
	C/N ratio	0.0002	0.0002	0.34	0.96	11.71	0.120
With soil factor (1/CEC) ( $n=18$ )	Intercept	-0.2993	0.1140			0.67	
	pH	0.0406	0.0146	0.02	7.76	$P < 0.01$	0.686
	C/N ratio	0.0002	0.0002	0.32	1.06	9.43	0.093
	1/CEC	0.1043	0.0659	0.14	2.50		0.221

improved the fit greatly ( $R^2=0.65^{**}$  and  $0.89^{***}$ , respectively) (data not shown).

Because both crop and animal residues were examined in this study, we have suggested a modification of Tian et al. (1995) that uses pH and C/N ratio of the organic materials (organic material quality index, OMQI) (Table 7). We compared the values of this index to those of the plant residues quality index (PRQI) as proposed by them and its modification (PRQIM) by Kumar and Goh (2003). PRQI produced higher values than PRQIM for wheat residue (15.8 vs. 2.18), mungbean residue (30.3 vs. 4.81) and chicken manure (39.7 vs. 14.7). Our OMQI values for wheat residue (6.54), mungbean residue (9.37) and chicken manure (12.29) for all the six soils were comparable to those for PRQIM. However, the linear and quadratic functions provided by Kumar and Goh (2003) either under- or overestimated our

data for net N mineralization. The parametric replacement of pH and C/N ratio of the organic materials in PRQI/M with the calculated CRC provided us a good estimate of OMQI. The proposed OMQI also correlated significantly with  $k$ , net mineralization and nitrification in the soils treated with organic materials (Table 7). Inclusion of soil factors further improved the equations considerably.

## 4. Discussion

### 4.1. Mineralization of organic carbon

Our results indicate that soils with low C and N content influenced C mineralization, even with the addition of organic materials (Aulakh et al., 2000; Thönnissen et al.,

Table 7

Correlation/regression coefficients with respective  $R^2$  values to estimate  $k$ , NM and NN using the OMQI as an independent variable with or without soil factor

Independent variable(s)	Correlation/regression coefficient to calculate $k$ , NM and NN		$R^2$ (probability)
	Intercept $\pm$ SE	Correlation/regression coefficients $\pm$ SE	
OMQI without soil factor ( $n=18$ )	$k = -0.0157 \pm 0.0075$	$0.0031 \pm 0.0008 \times \text{OMQI}$	0.50 ( $P < 0.001$ )
	$\text{NM} = -2.94 \pm 9.50$	$3.07 \pm 0.98 \times \text{OMQI}$	0.38 ( $P < 0.01$ )
	$\text{NN} = -5.99 \pm 14.93$	$3.61 \pm 1.54 \times \text{OMQI}$	0.26 ( $P < 0.05$ )
OMQI with soil factor ( $n=18$ )	$k = -0.0392 \pm 0.0130$	$0.0031 \pm 0.0007 \times \text{OMQI} + 0.2802 \pm 0.1221 \times 1/\text{CEC} + 0.1880 \pm 0.1077 \times 1/\% \text{ sand}$	0.64 ( $P < 0.01$ )
	$\text{NM} = -55.19 \pm 11.59$	$3.07 \pm 0.49 \times \text{OMQI} + 566.08 \pm 91.33 \times 1/\% \text{ clay} + 0.72 \pm 0.23 \times \text{CEC}$	0.86 ( $P < 0.0001$ )
	$\text{NN} = 5.32 \pm 8.62$	$3.61 \pm 0.58 \times \text{OMQI} + 522.68 \pm 63.63 \times 1/\% \text{ clay} - 263.86 \pm 36.38 \times 1/\text{soil pH}$	0.91 ( $P < 0.0001$ )

Calculated organic material quality index (OMQI) in relation to the pH and C/N ratio of the added organic materials: wheat residue = 6.54, mungbean residue = 9.37 and chicken manure = 12.29.  $R^2$ , coefficients of determination;  $k$ , decomposition rate constant; NM, net N mineralization; NN, net nitrification;  $n$ , number of population; OM, organic materials; SE, standard error.

2000). The maximum peaks for CO<sub>2</sub>-C from days 2 to 9 implied that the active phases of organic C release occurred at this time, showing the priming effect of the added organic materials (Krieft et al., 1987; Curtin et al., 1998). The slow phase (i.e. recalcitrant process) probably occurred by day 25. It appeared earlier in the chicken manure treated soils, signifying the rapid mineralization of hydrolyzable C under aerobic conditions. The response differences for total CO<sub>2</sub>-C emissions were clear, as was its relative loss between the high and low pH soils. The distinctiveness of the non-calcareous soil was likewise clear, denoting the importance of microbial adaptability (Lal et al., 2000).

The added organic materials regulated the CO<sub>2</sub>-C effluxes, with chicken manure > mungbean residue > wheat residue: the latter results are in agreement with those of Yadav et al. (1989). Addition of the organic materials also caused pH levels to rise, with the exact amount depending on their biochemical composition and extent of microbial respiration (Khalil et al., 2001). The increase in soil pH might enhance C mineralization in the acidic soils and probably concealed the variable effects of the biochemical properties of organic materials. The relative loss of added C supports the above explanations. This implies that slowly decomposing organic materials might result in a reduced C loss under aerobic conditions, depending on the amount of soil C present and extent of added C released. However, the mineralization of non-hydrolyzable C might be independent of organic materials over the long-term and become slowly available to microbes (Paré et al., 1997).

The decomposition rate constant (*k*) was lower for the saline, terrace and acid sulfate soils than for the other soils, presumably due to the lack of relevant microbes in the former. Its value for the soils with the added organic materials was related to the availability of hydrolysable C and the chemical composition of the materials. Irrespective of the soils, the overall *k* for wheat residue, mungbean stover and chicken manure was 0.0070, 0.0085 and 0.0247, respectively. The *k* value for treatments with wheat residue, even in the initial fast rate (0.0133), was lower than that reported by Kumar and Goh (2003), which ranged from 0.055 to 0.060. The value we obtained for mungbean residue (leguminous) was similar to that found by Thönnissen et al. (2000) with incorporated soybean (0.0099), but lower than that reported for peas/white clover (0.095–0.148) by Kumar and Goh (2003). In comparison to our values, Gale et al. (2004) reported a similar *k* (0.050) for rapid phase with chicken manure. The above differences might derive from the slightly different methodologies in the respective studies and/or differences in biochemical properties that are particularly pertinent in legume residues.

#### 4.2. Mineralization and nitrification of added organic-N

Ammonification and C mineralization were closely coupled in all soils and were predominant until day 15 of the incubation period, a finding that is in agreement with

those of many researchers (Fu et al., 1987; Khalil et al., 2001, 2002). Net N mineralization over the 90-day incubation period differed between the soils. It was highest in the acid sulfate soil, which has been shown to display a high degree of ammonification (Wickramasinghe et al., 1985; Khalil et al., 2001) and also in the calcareous soil, probably as a result of either small N immobilization or rapid remineralization over time. Ammonia volatilization and/or immobilization during large heterotrophic microbial activities could result in similar or lesser N to be mineralized in the other soils. The recalcitrant organic fractions might slow down N mineralization over time, contributing to the formation of humus. Application of chicken manure increased ammonification markedly, and could be attributed to the increase in pH, higher amounts of N, and lower C/N ratio and lignin content. Its application presumably stimulated all the microbial groups (including the ammonium-producers), even in the acidic soils (Acea and Carballas, 1996). By contrast, mungbean residue showed a lower net N mineralization followed by wheat residue, in agreement with Aulakh et al. (2000) and Thönnissen et al. (2000). Application of wheat and mungbean residues apparently enhanced N immobilization (Ehaliotis et al., 1996; Curtin et al., 1998), perhaps over the long-term (Trinsoutrot et al., 2000), although this process might have occurred simultaneously with N mineralization. Our results suggest that the high pH and microbiologically active soils in combination with the smaller C/N ratio organic materials can increase net N mineralization. However, the soils are subject to rapid nitrification, enhancing denitrification loss and/or immobilization (Aulakh et al., 2000; Khalil et al., 2002). This N loss can be less in the highly acidic soils, but immobilization can be important for all soils treated with high carbonaceous materials.

The magnitude of nitrification depended mostly on the soil type. The high pH and non-calcareous soils displayed higher net nitrification than the acidic soils. The salinity level (6.6 dS m<sup>-1</sup>) did not limit net nitrification in the salt-affected soil. The oxidation of NH<sub>4</sub><sup>+</sup> corroborated these findings, indicating the importance of available nitrifiers being present in the soils and high pH levels to facilitate the process (Fu et al., 1987). Nitrification in the acidic soils was either small due to the initial increase in soil pH through microbial respiration or inhibited, particularly in the acid sulfate soil (Wickramasinghe et al., 1985; Khalil et al., 2001). Addition of chicken manure enhanced net nitrification remarkably due to its favourable chemical composition. Khalil et al. (2002) reported similar results, with the inherent microbes potentially accelerating the process (Cordova et al., 2001). In some instances, net nitrification was higher than net mineralization, indicating immobilization/fixation and other N loss phenomena (Haney et al., 2004). Fu et al. (1987) also observed that the application of organic residues produced more mineral N in the form of NO<sub>3</sub><sup>-</sup> under neutral and slightly alkaline conditions.

The mungbean and wheat residues, which have larger C/N ratios, showed smaller nitrification, which can be attributed to the denitrification from anaerobic microsites (Scott, 1992; Ehaliotis et al., 1996). A temporal, but strong interaction between general heterotrophs and autotrophic nitrifiers with the quality of added C might also be responsible for these effects (Wheatley et al., 2001).

Our findings indicate small response differences between the chicken manure treated calcareous and non-calcareous soils, and the other soils receiving mungbean and wheat residues. Similarly, the saline soil responded equally with both chicken manure and mungbean residue, indicating the impact of high N content and low C/N ratio (Aulakh et al., 2000). In the acidic soils, nitrification was further constrained by the addition of organic material with larger C/N ratios. This may be ascribed to the slow decomposition and immobilization of N released subsequently in the presence of high carbonaceous materials. Altogether, these results signify the importance of pH and C/N ratio for N immobilization and rapid nitrification. Furthermore, our results suggest that some specific soil properties might influence the nitrification process more than the biochemical composition of added organic materials.

#### 4.3. Relationships

The soil factors examined did not have a significant effect on either C mineralization or nitrification, probably because of the soil heterogeneity. However, soils with high sand, high CEC and low clay contents might stimulate the N mineralization process. Generally, high clay content in a soil temporarily limits microbial activities due to sorption of the decomposition products/residue substrate onto mineral particles and incorporation of them into soil aggregates (Christensen, 1996; Thomsen et al., 2001). The medium-textured soils could enhance N mineralization by providing immediate physical access of both microbes and its metabolites. In contrast to the soil factors, the  $k$  values correlated well to the biochemical composition of the organic materials, as observed by many researchers (Vigil and Kissel, 1991; Tian et al., 1995; Kumar and Goh, 2003). Gaillard et al. (2003) also emphasized a strong interaction between the initial quality of the crop residue and the resulting heterogeneity of the decomposing microbes and C within the soil. Although the  $k$  values found here demonstrated a positive relationship with polyphenols, it was avoided because of conflicting findings. In this, our results are similar to those of Bending et al. (1998) who mentioned the influence of polyphenols in the early phase and in contrast to the findings of others (Tian et al., 1995; Kumar and Goh, 2003).

Our study emphasizes the utility of the pH and C/N ratio of the organic materials to predict  $k$  values, N mineralization, and nitrification, with the best fit provided when all are entered collectively instead of stepwise or both. The impact of the C/N ratio is in agreement with Vigil and

Kissel (1991); Trinsoutrot et al. (2000) and Wang et al. (2004). The low  $R^2$  value is probably related to the variability of N transformations among the different soils. The PRQI or its modification as PRQIM can also be good predictors for  $k$  values of organic materials, but, as shown by our findings, are soil specific. As such, the prediction capabilities of such indices could be improved greatly by considering soil factors, as shown our proposed equations for OMQI, which successfully estimated  $k$  values, net N mineralization and net nitrification. Moreover, our equations may be improved still further by increasing the number of soils and contrasting organic materials underlying them.

In conclusion, our results reveal that the decomposition of the added organic materials was soil specific and largely related to their chemical composition. The high pH and microbiologically active soils stimulated C and N transformations. The release of active pools of added C continued up to 25 days. A similar pattern was noted for N mineralization, but immobilization and/or denitrification seemed to have a lesser contribution. The acidic soils showed significant ammonification; nitrification was either small or stable and the addition of organic matter with larger C/N ratios further slowed the process. The soil properties pH, CEC and texture could influence C and N mineralization, although the pH and C/N ratio of the added organic materials played a more important role in the regulation of these two processes. Our proposed equations for indexing organic material quality and for the subsequent estimation of  $k$ , net N mineralization and net nitrification show good performance under subtropical conditions, but further improvement is still possible.

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