

Mass Loss and C and N Release From Decomposing Fresh and Composted Residues as Affected by Cold Climate Conditions

Moniruzzaman K. Eusufzai¹, Sanjit K. Deb², Takeki Maeda¹ & Katsumi Fujii¹

¹ Department of Environmental Sciences, Iwate University, Morioka, Iwate, Japan

² Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, New Mexico, USA

Correspondence: Moniruzzaman K. Eusufzai, Geotechnical and Environmental Studies Division, River Research Institute, 72 Green Road, Dhaka, Bangladesh. Tel: 88-172-993-0396. E-mail: mzk1973_82@hotmail.com

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Abstract

Information on the decomposition and nutrient release pattern of fresh and composted residues under low temperature field conditions is still limited. A 540-day period litterbag study was conducted in an agricultural field of the northeastern Japan to quantify mass loss and C and N release from fresh (rice straw and sawdust) and composted (compost) residues. Decomposition rates (k) were estimated from mass loss data by fitting a single-pool exponential decay model for actual days of field incubation. The k values were also expressed in degree-days (DGD) and decomposition-days (DCD) time scales to account for the effect of temperature and precipitation on residue decomposition. At any time scales, k values followed the order: compost > straw > sawdust. Daily mass loss, C and N release were significantly affected by residue type and incubation time. Compost showed higher decomposability and potential N source, while a considerable amount of N was immobilized in straw and sawdust decomposition. Mass loss was positively correlated with initial C content and C: N for compost and straw, while it was negatively correlated with initial N content for straw and sawdust. Decomposition exhibited at a slow rate even at sub-zero air temperature during soil freezing conditions, indicating that residue decomposition under cold climate field conditions may be more regulated by moisture availability than temperature *per se*.

Keywords: decomposition rate constant, degree-days, decomposition-days, exponential decay model, sub-zero temperature, residues

1. Introduction

Decomposition of crop and plant residues release carbon and important nutrients to the soil. However, these important sources of carbon and nutrients are often burned or simply buried into the soil as wastes. It is well accepted that decomposition of crop and plant residues are potentially important for arable soils in terms of nutrient cycling and formation of soil organic matter. While recycling of crop and plant residues is suggested as a potential means of sustaining soil fertility over the long-term (Rasmussen & Parton, 1994; Carter, 2002; Singh & Rengel, 2007), a proper management of these residues in a sustainable agriculture requires knowledge of their decomposition and nutrient release pattern under field conditions. Broadly, residue decomposition rates are affected by a number of interacting variables, including characteristics or quality of available residues, which determine its degradability, physicochemical environment, soil micro-climate (i.e., precipitation, moisture, temperature), and composition of the decomposer community that represents the fauna and microorganisms (Heal, Anderson, & Swift, 1997).

A considerable number of studies have been conducted to quantify decomposition and nutrient release pattern of different residues under field conditions. Decomposition and nutrient loss of cereal straw have been reported in many studies (Douglas et al., 1980; Christensen, 1986; Beare, Wilson, Fraser, & Butler, 2002; Lou et al., 2011). Residue quality measures such as carbon-to-nitrogen ratio (C: N) and lignin-to-nitrogen ratio (L: N) were often used as qualitative and quantitative indices of decomposability (Heal et al., 1997). Generally, residues with high C: N ratio or high L: N ratio decompose at slower rates than residues with low C: N. Both C: N and L: N indices are good predictors of residue decomposability in a given set of environmental conditions, especially in the tropics with high temperature and humidity (Tian, Kang, & Brussaard, 1992; Vanlauwe, Dendooven, & Merckx,

1994). It is well recognized that high temperature and moisture favor residue decomposition because of increased microbial activity (McClaugherty, Pastor, Aber, & Melillo, 1985; Cornejo, Varela, & Wright, 1994). However, the C: N and L: N indices are not always regarded as best measures to represent the decomposition rate (Reinertsen, Elliott, Cochran, & Campbell, 1984). Macro- and micro- climate are considered to have even more influence on decomposition than residue quality (Anderson & Swift, 1983). Although climatic variables may best describe decomposition at regional and global scale (Olsen, 1963; Dyer, Meentemeyer, & Berg, 1990), field decomposition of residues is often predicted by the first order exponential decay model using temperature and moisture adjusted time scales such as degree-days (DGD) and decomposition-days (DCD) (Honetcutt & Potaro, 1990, Douglas & Rickman, 1992; Quemada, 2004). The DCD considers both temperature and moisture effects on residue decomposition, while the DGD accounts only temperature effect. These time scales can incorporate temperature and moisture effects on residue decomposition rates without significant variation in location and years (Ruffo & Bollero, 2003).

Studies concerning residue decomposition in low temperature arable field conditions are still limited (Cochran, 1991; Koenig & Kochran, 1994). Efforts have been made to measure decomposition across the climatic gradients or ecosystems, but are mostly focused on leaf litter (Meentemeyer, 1978; Aerts, 1997). The importance of residue and livestock recycling farming system has long been recognized in many Asian countries including Japan (Ikumo, 2005). However, limited information on residue decomposition and nutrient release can restrict their wide and effective uses as soil amendments. In particular, to the best of our knowledge, there are almost no studies that have quantified in-situ decomposition rates of fresh residue and composted residue biomass in the cold climatic region representing the present study area of northeastern Japan.

The objective of this study was to quantify the decomposition and C and N release for rice straw, sawdust, and composted residue biomasses in an upland agricultural field located in the northeastern part of Japan, characterized by cool and short summer, cold and snow covered winter, and a sub-humid climate.

2. Method

2.1 Experimental Site

The field decomposition study was carried out for a 540-day incubation period (from 01 September 2005 through 22 February 2007) on an upland agricultural field at the Iwate University Experimental Station located in the Northeast Japan (39.72° N latitude, 141.44° E longitude, and 155 m elevation above mean sea level). The field was chosen to be broadly representative of a humic volcanic ash soil (*Andisols*, *Hydric Hapludands*) according to the USDA classification system, which is the major cultivated soil for upland crops in Japan and shares about 50% of upland croplands. Soil physical properties measured at a depth of 0-20 cm soil layer were as follows: loam in texture (43.8% sand, 42.1% silt and 14.1% clay), particle density-2.71 Mg m⁻³, and bulk density-1.20 Mg m⁻³. Soil total carbon (C) and total nitrogen (N) contents measured at 0-20 cm soil layer were 10.6 g kg⁻¹ and 1.68 g kg⁻¹ (dry weight basis), respectively. The study area is characterized by a sub-humid climate, with a short summer, and cold, snow covered winter. Based on a long-term (1924-2007) monthly mean temperature record of the Japan Meteorological Agency (JMA), annual mean air temperature of the study area is 10 °C. The annual mean relative humidity is 75.8%, with the maximum and minimum monthly mean values of 82% and 66.3% for July and April, respectively. The annual mean total precipitation is 1126 mm during the period of 1953-2007. More than one-thirds of this annual precipitation is snow, which generally takes place from November to April. The experimental site is 20 m away from the meteorological station of the Department of Forestry, Iwate University. Meteorological variables such as rainfall and air temperature used in this study were obtained from the meteorological station. Daily rainfall and air temperature during the field decomposition period are shown in Figure 1. Total rainfall observed during the period of September-December 2005, January-December 2006, and January-March 2007 were 491.5, 1222, and 261 mm, respectively. For these periods, daily mean temperature values at the experimental site varied from 31 °C to -10 °C, 32 °C to -8 °C, and 10 °C to -2.3 °C, respectively (Figure 1).

2.2 Experimental Design

Field decomposition of residues was studied using fine mesh litterbag technique (Bocock & Gilbert, 1957). The litterbag technique is based on the loss in mass of a known quantity and chemical composition of residue contained within sealed bags made of non-degradable mesh material and buried in the soil for different incubation period. The technique assumes that all the mass losses from litterbags are mineralized. This technique remains the most widely used method for examining residue decomposition in terrestrial ecosystems (Curtin & Fraser, 2003; Curtin, Francis, & McCallum, 2008).

Three residues, i.e., rice straw, sawdust and composted residues (henceforth referred to as compost) were

categorized according to their source of origin, local abundance and quality. Straw (*Oryza sativa* L. ssp. japonica) was a crop residue biomass, which is either burned or used as fodder. Rice straw, included only above-ground parts of plants, was collected from the local farm in August 2005, and cut into small pieces (1-2 cm lengths). As a woody biomass, sawdust was the by-product (granular fine material) of Japanese cedar “Sugi” (*Cryptomeria japonica* (L. f.) D. Don), which is simply used as dumping materials. Sawdust was collected from local lumber mills and was passed through a 1-mm mesh sieve. Compost used in the experiment was a mixture of dairy manure, rice husk and wood bark biomass with high moisture content. Initial physicochemical properties of straw, sawdust and compost are shown in Table 1.

Table 1. Initial physicochemical characteristics of rice straw, sawdust, and composted residue biomass

Characteristics	Rice straw	Sawdust	Compost
Moisture content (kg kg ⁻¹)*	0.19	0.43	0.75
C (g kg ⁻¹)	38.6	49.6	65
N (g kg ⁻¹)	0.84	0.08	2.2
C:N	46.3	611.8	29.5

*Dry weight basis.

Prior to field incubation all residues were air-dried at 30 °C for 24-48 hours to a constant weight when the moisture content was about 0.10-0.12 kg kg⁻¹ (fresh weight). Two grams of pre-weighed, air-dried samples of straw, sawdust and compost were placed into nylon mesh litterbags (5 cm × 3 cm; 0.5-mm mesh) tagged with identification numbers. The 0.5-mm mesh size was chosen as it is small enough to minimize loss of fragments, but large enough to allow colonization by microorganisms and mesofauna (e.g. mites, springtails, diplurans, enchytraeids) and to reduce alteration of the microclimate (Tian, 1992). Seventy-two litterbags [3 (residue types) 6 (replicates) 4 (litterbags retrieval dates)] were randomly assigned to three experimental plots each comprising an area of 3 m². In each plot, sealed litterbags containing straw, sawdust and compost were placed horizontally in the soil to a depth of 5-8 cm on 01 September 2005. The vegetation of experimental plots was cut close to soil surface and removed before litterbags placement. However, the vegetation was allowed to regenerate in experimental plots during the study period. The position of each litterbag in the plot was secured and marked with a nylon cord tied to a plastic peg. Following the recommendation of Harmon et al. (1999), additional nine litterbags [3 (residue types) 3 (replicates)], referred to as travel bags, were taken to the experimental site and returned to the laboratory to account for small amounts of residue mass loss due to transport and handling.

2.3 Sampling and Analysis

After 90 (on 29 November, 2005), 270 (28 May, 2006), 360 (26 August, 2006), and 540 (22 February, 2007) days of incubation, eighteen litterbags [3 (residue types) 6 (replicates)] were randomly retrieved at each retrieval date from three plots and enclosed in air-tight Ziploc plastic bags for transport to the laboratory. On second and fourth retrieval periods during the winter (December to April), litterbags could not be collected at a regular 3-month interval as all experimental plots were covered with a thick snow layer of approximately 50 cm depth. These sampling periods were extended to a 6-month interval.

Travel bags were handled as the litterbags and retrieved immediately after placement in the plots. Travel bags were air-dried at 30 °C for 24-48 hours, weighed, and recorded as the final mass (30 °C). Travel bags were then oven-dried at 105 °C for 24-48 hours and weighed for the final mass (105 °C). Temperature conversion factor (henceforth referred to as CF), obtained by dividing the final mass (105 °C) by the final mass (30 °C), was used to convert the initial mass (30 °C) of each sample into the initial mass (105 °C). Travel mass loss (105 °C) was then calculated by subtracting the initial mass (105 °C) from the final mass (105 °C) for each residue type sample. All recovered contents in each retrieved litterbag were gently removed and placed on a clean white paper. Considerable care was taken to manually remove foreign materials (e.g. roots, adhering soil, extraneous mineral matters), and mature insects from the contents. Litterbag samples were then air-dried at 30 °C for 24-48 hours and weighed to get the final mass (30 °C). The CF was used to calculate initial mass (105 °C) and final mass (105 °C) for each sample. Mass loss was calculated by subtracting the final mass (105 °C) and the average travel loss (105 °C) from the initial mass (105 °C) for each sample. Following the estimation of mass loss, samples were oven-dried at 105 °C for 24-48 hours and stored at 4 °C until further use for chemical analysis. Subsamples were finely ground to pass a 1-mm mesh sieve and analyzed for C and N by combustion on a NC analyzer (NC 22A,

Sumi Chemical Analysis Laboratory, Tokyo, Japan). The auto analyzer gave the % C, % N and C: N ratio with 0.01% variation.

Considering that mass loss and C and N release over time followed the first order exponential single-pool decay model (Jenny et al., 1949; Olson, 1963), decomposition rates for straw, sawdust, and compost were determined using the following equation:

$$X = X_0 \exp^{-kt} \quad (1)$$

where, X_0 is the % dry weight of mass (C and N content) initially present; X is the % dry weight of mass remaining (C and N content) at time t (day); and k is the decomposition rate constant (day^{-1}). Mass loss and C and N release from residues were also estimated using DGD and DCD time scales, which accumulated with time and incorporated temperature and moisture as driving variables (Stroo et al., 1989; Ruffo & Bollero, 2003; Steiner et al., 1999). Measured daily air temperature and rainfall data during the entire incubation period (Figure 1) were used for DGD and DCD computations. The DGD, expressed as cumulative DGD, was calculated as the average of daily maximum and minimum temperatures. The measured minimum average temperature value of -10°C during the study period was considered as the threshold temperature value for residue decomposition. Following the assumption that the 4 mm rainfall is enough to fully wet the soil surface (Steiner et al., 1999), the daily DCD was considered to be equal to the minimum of moisture coefficient, M_c , or temperature coefficient, T_c , for a given day. The DCD varies from 0 for very cold or dry conditions to 1 for warm and moist conditions, and the corresponding M_c values are given by the following expressions:

$$M_c = \begin{cases} 1 & P_i \geq 4 \\ \frac{P_i}{4} + 0.5M_{c-1} & P_i < 4 \end{cases} \quad (2)$$

where, M_c and M_{c-1} are the moisture coefficients of the day under consideration and the previous day, respectively, and P_i is the rainfall (mm). As suggested by Steiner et al. (1999), if there is no rainfall, the M_c is assumed to decrease by a factor of 0.5 each after the last rainfall. The T_c was estimated using the following equation:

$$T_c = \frac{2 \times (T_{\text{mean}})^2 \times (T_{\text{opt}})^2 - (T_{\text{mean}})^4}{(T_{\text{opt}})^4} \quad (3)$$

where, T_{mean} is the average of daily maximum and minimum air temperatures ($^\circ\text{C}$) and T_{opt} is the optimum temperature (32°C) for residue decomposition. Considering the base temperature of -10°C , T_{mean} had a minimum value of -10°C at the study site.

2.4 Statistical Analysis

Mass loss and C and N release data, expressed as the % of initial values on dry weight basis, allowed for the determination of net C and N dynamics. Data were examined using the two way (residue type and time) analysis of variance (ANOVA) procedures. The % mass (C and N content) remaining after 90, 270, 360 and 540 days of field incubation were regressed against actual days, DGD and DCD to evaluate the decomposition rate and C, and N release pattern from residues. A pairwise comparison among different residue biomasses and with incubation time were performed by Tukey–Kramer test when F-values from ANOVAs were significant ($P < 0.05$). Pearson's correlation coefficients were calculated for the % mass remaining after 540 days of field incubation and initial C, N and C: N ratio for straw, sawdust, and compost.

3. Results

3.1 Accumulation of Degree-Days (DGD) and Decomposition-Days (DCD)

The daily mean air temperature for the studied area varied substantially during the experimental period (Figure 1). For the same time period, year 2005 was much cooler than years 2006 and 2007, and snowfall occurred from December 2005 to March 2006 (data not shown). Monthly cumulative rainfall was relatively higher in 2005 (September–December) than in 2006, particularly in September and December. The average value of daily mean temperature for the first 90 days of incubation period (01 September–29 November, 2005) was 13.84°C , which dropped as low as 3.4°C during 270 days of incubation (30 November 2005–28 May 2006) and then increased to 22.85°C during 360 days of incubation (29 May–26 August, 2006), and again dropped to 8°C during 540 days of incubation (27 August 2006–22 February, 2007).

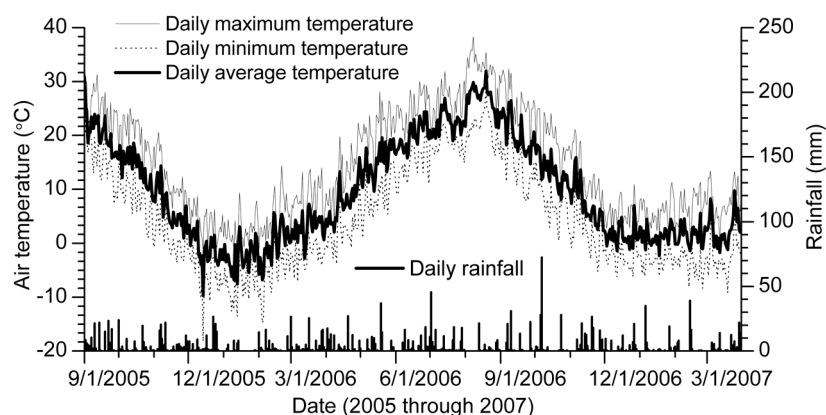


Figure 1. Daily maximum, minimum and mean air temperatures and rainfall during the study period from September 2005 to March 2007 at the experimental site

This fluctuation in temperature was consistently reflected by the cumulative DGD curve (Figure 2a). The accumulation of DGD was higher in 2006 than in 2005 and 2007, which could be explained by the longest sampling period. The cumulative DCD (Figure 2b) also reflected the difference in rainfall between years and varied likewise the DGD. However, the net difference of cumulative DCD was observed lower than cumulative DGD between consecutive sampling periods.

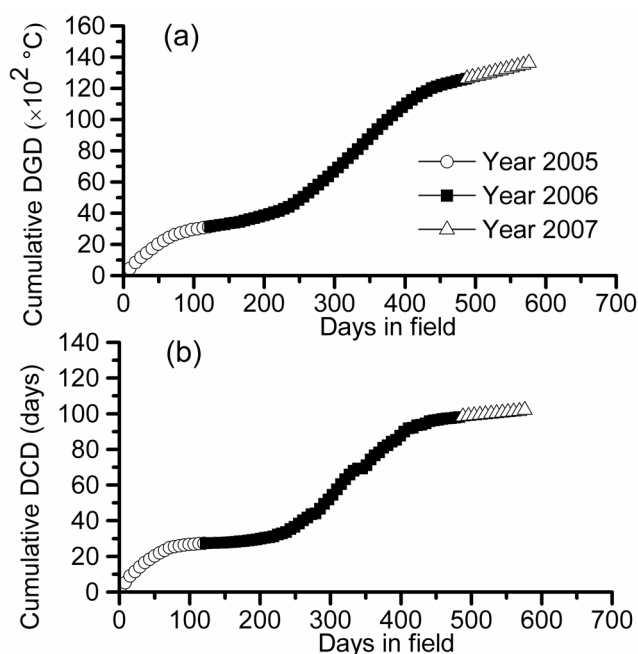


Figure 2. (a) Cumulative degree-days (DGD), and (b) decomposition-days (DCD) for the experimental site during the incubation period from 01 September 2005 to 22 February 2007 at the experimental site

3.2 Decomposition Rate Constant (k)

Single-pool exponential decomposition model parameters estimated from nonlinear regression equations are presented in Table 2, which were used to characterize residue decomposition in actual days, DGD and DCD time scales.

Table 2. The single-pool exponential decomposition model parameters (Equation 1) for rice straw, sawdust, and composted residues estimated from the mass loss data during 540 days field incubation. Time scales are in actual days, degree-days (DGD) and decomposition-days (DCD)

Residue type	k^*	X_0 (%)	R^{2**}	$RMSE^{***}$
	(day ⁻¹):			
Rice straw	0.00557	97.66	0.95	6.90
Sawdust	0.00309	100.4	0.96	1.65
Composted residue	0.01889	99.95	0.99	2.84
	(DGD ⁻¹):			
Rice straw	0.00019	98.2	0.96	1.94
Sawdust	0.00015	102.1	0.88	4.35
Composted residue	0.00056	99.9	0.99	2.58
	(DCD ⁻¹):			
Rice straw	0.02264	100.4	0.97	3.77
Sawdust	0.01693	102.1	0.84	3.04
Composted residue	0.0600	99.9	0.99	1.52

* Decomposition rate constant; values are means of four samples.

** Coefficient of determination, *** Root mean square error.

Of all the residues, the values of k at any time scales followed the sequence: compost > straw > sawdust. The k for compost was 29.5 and 16.4% higher than those of straw and sawdust, respectively; when the k was estimated on actual days time scale. When time scale was expressed as DGD the k values of compost were 34.7 and 27.3 % higher as compared to the k values of straw and sawdust residues, respectively. The largest increment in the k values among all residues was observed when time scale was expressed as DCD; for which the k values of compost were 37.7 and 28.2% higher than the k values of straw and sawdust, respectively. Regardless of residue types, the k value estimated by DCD time scale was substantially higher than that estimated by actual days and DGD. For example, for straw, sawdust, and compost the k values estimated using DGD were 97.0, 96.5 and 95.0% lower than the k values estimated by actual days. On the other hand, compared to the k values estimated by actual days, the k values estimated using DCD were 217, 306, and 447% higher for straw, sawdust, and compost, respectively.

3.3 Mass loss, and C and N Release

The % mass remaining of straw, sawdust, and compost varied significantly ($P < 0.0001$) with respect to time (expressed as actual days, DGD and DCD) and residue type (Figures 3a-3c). The interaction of time and residue type was also significantly different ($P < 0.0001$). On average, compared to straw and sawdust, the rate of decomposition of compost was significantly higher ($P < 0.0001$). After 540 days of incubation, the % mass remained for straw, sawdust, and compost was 19.4, 79.0, and 15.4%, respectively. Mass loss in residues exhibited three distinct transitional phases of decomposition (expressed as actual days, DGD, and DCD), i.e., a rapid loss in the initial incubation period (0-90 days), relatively slow at the intermediate phase (90-360 days), and finally tended to be ceased at the end of incubation period (360-540 days). These transitional phases were much obvious when the % of original mass remaining was expressed in DGD and DCD time scales (Figures 3b and 3c, respectively).

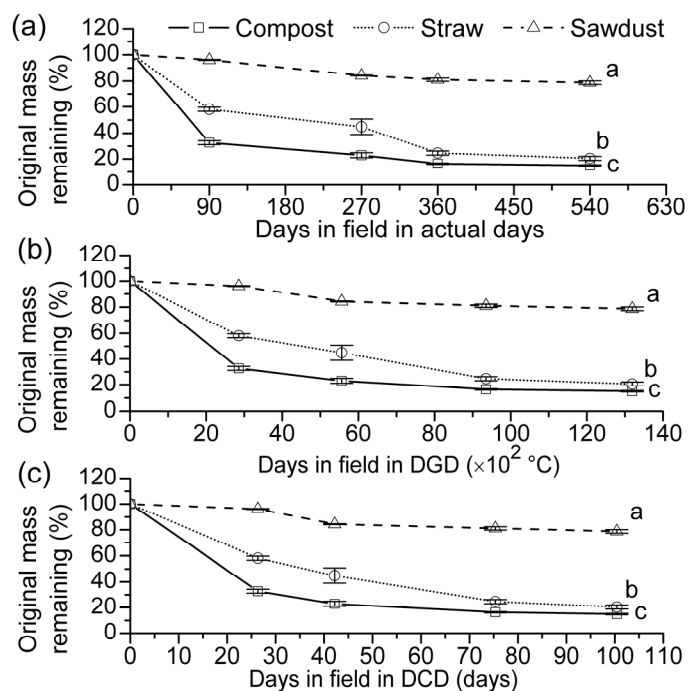


Figure 3. Original mass remaining (%) expressed as (a) actual days, (b) DGD, and (c) DCD time scales for compost, rice straw, and sawdust. Values are means of four samples. Vertical bars are the standard deviation of the sample mean. Means followed by different letters are significantly different ($P<0.05$)

The amount of C released from residues varied significantly ($P<0.0001$) with time and residue types during the entire incubation period (Figures 4a-4c).

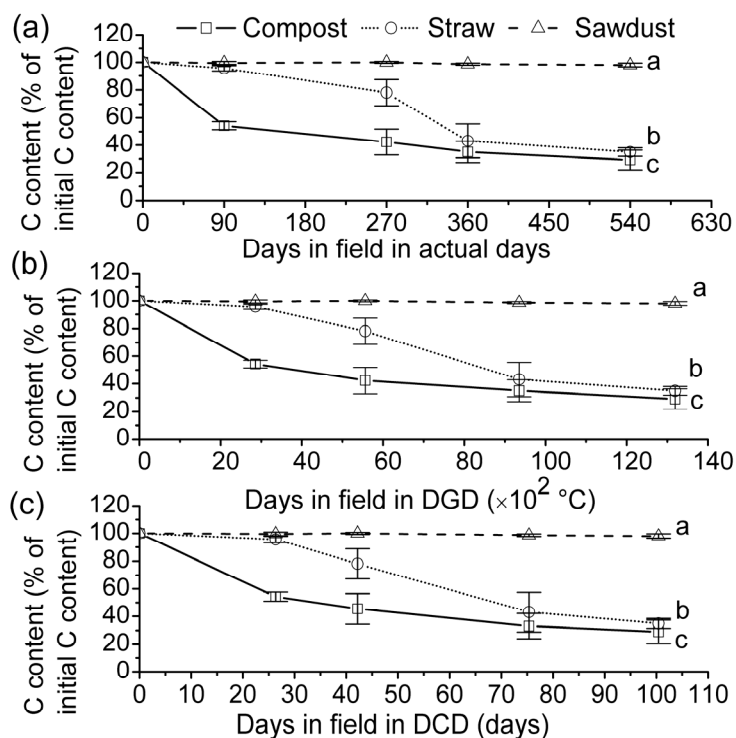


Figure 4. Carbon (C) release rates (as the % of initial C content) from compost, rice straw and sawdust as (a) actual days, (b) DGD, and (c) DCD time scales. Values are means of four samples $\pm$ 1 standard deviation. Means followed by different letters are significantly different ($P<0.05$)

A comparison among residue types with respect to actual days, DCD and DGD showed a significant difference ($P < 0.0001$) for C release from the residues, except for sawdust ($P > 0.05$). The N release from residues also varied significantly ($P < 0.05$) with time and residue types (Figures 5a-5c), and there was a time interaction ($P < 0.05$) among all residue types.

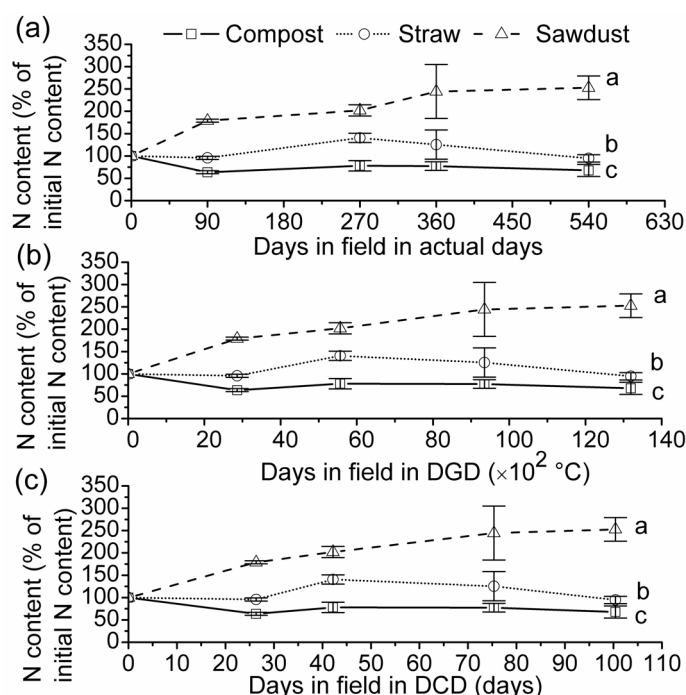


Figure 5. Nitrogen (N) release rates (as the % of initial N content) from compost, rice straw, and sawdust expressed as (a) actual days, (b) DGD, and (c) DCD time scales. Values are means of four samples 1 standard deviation. Means followed by different letters are significantly different ($P < 0.05$)

The % of C released from compost was higher at the early phase of incubation, while that was lower for straw (Figures 4a-4c). On the other hand, the amount of C in sawdust did not change throughout the incubation period. Almost half of the initial N content of compost decreased rapidly at the first quarter of the incubation (90 days) period and thereafter remained relatively constant (Figures 5a-5c). The N content in straw showed a constant phase at the initial period (90 days), then a short immobilization (270 days), and thereafter started to mineralize at the third sampling period, i.e., from 360 actual days, 93 DGD and 75 DCD, respectively (Figures 5a-5c). For the same time scale, the N content in sawdust was almost double at the initial phase, which continued to increase during the intermediate phase, and after 540 days of incubation the N content in sawdust was almost 250% of its initial N content. The correlation coefficients among the % of mass loss, C and N contents, and C: N ratio after the 540 days of incubation were strong in compost as compared to straw and sawdust (Table 3).

Table 3. Pearson correlation coefficient ($n = 16$) between mass loss and initial chemical characteristics of rice straw, sawdust, and composted residue biomass

Characteristics	Rice straw	Sawdust	Compost
C	0.87**	-0.42 ^{ns}	0.96**
N	-0.23 ^{ns}	-0.85**	0.67*
C:N	0.87**	0.86**	0.83**

^{ns} $P > 0.05$, ^{ns}: not significant; * $P < 0.01$; ** $P < 0.001$.

Except for sawdust, the % of mass loss was positively correlated with the C content as well as with the C: N ratio. On the contrary, the % of mass loss was negatively correlated with the N content for straw and sawdust. The N

content in compost, however, was positively correlated with mass loss and was significant ($P < 0.01$).

4. Discussion

Regardless of incubation period, the accumulation of DGD consistently increased. The cumulative DCD curve, however, showed both slow and rapid accumulation, suggesting both favorable and limiting conditions for decomposition (Figure 2). The relative difference between DGD and DCD is the M_c , and it can be inferred that moisture (in the form of precipitation) was the reason of temporal variability in accumulated DCD, particularly during the dry period. Ma et al. (1999) compared different decomposition models and concluded that M_c is the most limiting factor for DCD accumulation. Compared to DCD we observed a large difference of DGD between sampling intervals, which may be attributed to the seasonal air temperature differences during summer and winter periods. On the other hand, the DCD, a function of precipitation, remained unchanged during the dry period and increased sharply during the wet period. Hence the net difference of DCD for the sampling period is minimal as compared to DGD. The contrasting dynamics of DCD and DGD accumulation suggest that DCD could better predict the effect of climate on residue decomposition as it accounts for both temperature and precipitation. The remarkable difference in the k values estimated using the actual days, DGD and DCD (Table 2) may be attributed to the accumulation of cumulative days. The accumulation of cumulative days was the highest for DGD and the lowest for DCD (Figure 2). Considering the effect of air temperature and moisture the significant differences in the k values estimated by these three time scales are consistent. In actual days time scale, the k was estimated only based on the mass loss. The effect of air temperature and precipitation was not taken into account, which might be subject to a possible under- or overestimation of the k values. On the other hand, the effect of air temperature and moisture was integrated in DCD time scale, while assuming a linear relationship of the k with temperature the DGD estimation considered only temperature effect. It is likely that the effect of precipitation is large enough to cause differences in the k values estimated by DCD and DGD time scales. The range of mean air temperatures measured in this study was large enough (from -10°C to 32°C) to generate differences in the k values estimated by DCD and DGD.

Of significant note, despite the fact that many studies considered 0°C as the limiting air temperature value for microbial decomposition (Ruffo & Bollero, 2003; Liski, Nissinen, Erhard, & Taskinen, 2003), we observed a slow decomposition of straw, sawdust and compost residues even such a minimum air temperature threshold of -10°C . Although soil temperature was not measured, the experimental field was covered with thick snowpack and soils were frozen at -10°C air temperature. A possible explanation of this slow decomposition in such a low temperature might be due to the existence of unfrozen water even at -10°C (Elberling & Brandt, 2003). The microscopic films of unfrozen water on the surface of soil particles might contribute to activate psychrophilic and psychrotrophic soil microbes (Anderson, 1970). The soil temperature under snowpack can remain around 0°C for many months, allowing the proliferation of a large and diverse cold-adapted microbial community (Ley, Williams, & Schmidt, 2004).

Since information pertinent to the in-situ decomposition experiment of residue biomass in cold climatic regions is very limited, we could not directly compare our results with other reported studies. However, in a laboratory incubation study, Kaboneka et al. (1997) found that the relative decomposition rate constant varied between 0.013 and 0.03 day^{-1} for wheat, corn and soybean residues. In our in-situ decomposition study, the k for compost (Table 2) was within the same range as reported by Kaboneka et al. However, straw and sawdust had lower k than values reported by Kaboneka et al. The k estimated by single-pool exponential decay model (Equation 1) in DGD time scale for compost, straw and sawdust ranged from 0.556×10^{-4} to $0.152 \times 10^{-4} \text{ DGD}^{-1}$. These k values for crop residues are also within the values reported by other studies (e.g., Ma et al., 1999). The k estimated by DCD time scale for all the residues ranged from 0.017 to 0.060 DCD^{-1} (Table 2). These values are within the range of k for wheat, barley and oat residues estimated by Steiner et al. (1999). The wide variation in k values estimated by actual days, DGD and DCD time scales allowed us to postulate that the moisture effect (either from rainfall or snowfall) should be taken into account for the accurate estimation of in-situ residue decomposition. Notably, a substantial proportion of precipitation occurs through snowfall in the study area.

The C release in compost and straw showed low potential for immobilization compared to sawdust, which was associated with the initial C content (Table 1). Decomposition rate (k) was lower for low initial C-enriched residue biomass. Except for sawdust, this postulation seems to be supported by the positive relationship between the k and C content for residues (Table 3). The C release after a 540-day incubation period was around 70% for compost, 65% for straw, and only 2% for sawdust. The rate at which all the residues decomposed, as reflected in the C release pattern, was also related with initial N content. The decomposition rate (k) for all the residues was directly related to C: N ratio or N content. Owing to the low C: N ratio, relatively large amount of N released during the initial 90 days of compost decomposition and then tended to increase. Although at higher initial N

content, a substantial amount of N was immobilized in straw after 270 days of incubation period. As expected, due to high C: N ratio and low N content, the decomposition rate for sawdust was very low and at the end of the decomposition period N content in litterbags increased by almost 250% of its initial N. Studies reported that N content, expressed as initial N, increased as materials decomposed for various residue types (Bocock & Gilbert, 1957). Bocock and Gilbert (1957) reported a 100% increase of initial N content for wheat residue decomposition over 20 days of incubation period. Some studies concluded that fungal hyphae led to the increased N in decomposing organic materials (Holland & Coleman, 1987; Frey, Elliott, Paustian, & Peterson, 2000). Presence of the fungal hyphae was visible in the retrieved litterbags in our experiment, which might also lead to N immobilization in straw and sawdust decomposition. Generally, the C: N increases with the ease of residue decomposition, because the labile fraction of organic residues is readily utilized by microbes, leaving behind more recalcitrant materials that contain lignin, phenol with high C: N. However, in our experiment, C: N for all residue types decreased with the ease of decomposition. This was most likely due to the decrease in the %C with minimal or no change of the %N, which might cause a decrease in the C: N of decomposing organic residues.

5. Conclusions

In general, composted residues decomposed rapidly and showed a potential source of N, while a considerable amount of N were immobilized in straw and sawdust decomposition. The effect of temperature and precipitation on residue decomposition was fairly estimated by using DGD and DCD time scales. Of all the residues, decomposition rates on the basis of actual days, DGD, and DCD time scales followed the sequence: compost > rice straw > sawdust. Comparatively, DCD time scale, which accounted for both air temperature and moisture effects on residue decomposition, appeared to be a potential indicator of residue decomposability in the study area. For all the residues studied, decomposition exhibited at a slow rate even at minimum threshold mean air temperature value of -10 °C during the soil freezing conditions, suggesting that under cold climatic conditions decomposition of residue biomass may be more governed by moisture than temperature. However, since litterbags were not retrieved during periods when the experimental field was covered with a thick snow layer (approximately 50 cm) further study may place more emphasis on evaluating the decomposition rates of these residues under such soil freezing conditions.

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