Biol Fertil Soils (1994) 18:175–182

ORIGINAL PAPER

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Decomposition of different organic materials in soils

Received: 10 August 1993

Abstract Laboratory experiments were conducted to evaluate organic C mineralization of various organic materials added to soils. A soil sample was mixed with organic material to approximate a field application of 9 g organic C kg^{-1} soil (0.9% or 50 Mg ha^{-1}). The organic materials used were four crop residues [corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), sorghum (*Sorghum vulgare* Pers.), and alfalfa (*Medicago sativa* L.)], four animal manures [chicken (*Gallus domesticus*), pig (*Sus scrofa*), horse (*Equus caballus*), and cow (*Bos taurus*)] and four sewage sludges [Correctionville (Imhoff tank), Charles City (holding tank), Davenport (secondary digester), and Keokuk (primary digester)]. The soil-organic material mixture was incubated under aerobic conditions at room temperature (20±2 °C) for 30 days. The CO_2 evolved was collected in standard KOH solution by continuously passing CO_2-free air over the soil. Results showed that, in general, the amounts of CO_2-C released increased rapidly initially, but the pattern differed among the organic materials used. More than 50% of the total CO_2 produced in 30 days of incubation was evolved in the first 6 days. Expressed as percentages of organic C added, the amounts of CO_2 evolved ranged from 27% with corn to 58% with alfalfa. The corresponding percentages for animal manures ranged from 21 to 62% with horse and pig manures, respectively, and for sewage sludges they ranged from 10 to 39% for Charles City and Keokuk sludges. All CO_2 evolution data conformed well to a first-order kinetic model. Potentially, readily mineralizable organic C values and first-order rate constants (k) of the organic matter-treated soils ranged from 1.422 g C kg^{-1} soil with a k value of 0.0784 day^{-1} to 6.253 g C kg^{-1} soil with a k value of 0.0300 day^{-1}. The half-lives of the C remaining in soils ranged from 39 to 54 days for plant materials. The corresponding half-lives for the C remaining from animal manures and sewage sludges ranged from 37 to 169 days and from 39 to 330 days, respectively.

Key words Crop residues · Animal manures · Sewage sludges · Carbon mineralization · Rate constant · Global CO_2 · Sustainable agriculture

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Introduction

The C cycle has received considerable attention in recent years because of suggestions that the atmospheric CO_2 concentration is increasing and because of the effect an increase will have on global warming. Changing land use and the application of fertilizer are among the factors that most affect agricultural contributions to atmospheric CO_2. The amount of CO_2 evolved during organic matter decomposition may contribute significantly to the global CO_2 level and, therefore, may further accelerate the greenhouse effect. This feedback mechanism could cause changes in the turnover of organic materials in soils by altering the factors that affect their decomposition (Jenkinson et al. 1991).

In sustainable agriculture, land application of organic materials is extensively practiced. These materials are vital resources for replenishing soil organic matter and for supplying major nutrients. Organic materials added to soils contain a wide range of C compounds that vary in rates of decomposition. The biological breakdown of the added organic material depends on the rate of degradation of each of the C-containing materials present in the sample (Gilmour et al. 1977; Reddy et al. 1980). Variation in environmental factors, however, may cause a change in the decomposition rates of organic materials in soils. Of these factors, O_2, moisture content, temperature, pH, substrate specificity, and available minerals have been reported to be most important (Broadbent et al. 1964; Kowalenko et al. 1978; Clark and Gilmour 1983). Also, the decomposition rates vary among organic materials, depending on their content of N, S, soluble C, lignin, and various carbohydrates (Herman et al. 1977; Parr and Papendick 1978; Reinertsen et al. 1984; Janzen and Kucey 1988). In addition to plant residues, the sources of organic C in soils include animal manures, sewage sludges, and other industrial wastes.

It has been estimated that, under aerobic conditions, about 20–40% of the substrate C is assimilated by microorganisms and that the rest is released as CO_2 (Alexander 1977). For beneficial utilization of organic materials added to soils, quantitative information on the decomposition rates of various sources of organic C is required. In addition, such information is needed for predicting the CO_2 contribution of the organic materials in soils to the global CO_2 pool (Jenkinson et al. 1991). Therefore, the objective of the present study was to assess the amount of CO_2 released during the decomposition of various organic materials (crop residues, animal manures, and sewage sludges) added to soils under given conditions.

Materials and methods

The three surface (0–15 cm) soils used were selected to represent important non-calcareous agricultural soils of Iowa (Table 1). Field-moist samples were brought into the laboratory, mixed, passed through a 2-mm sieve, and stored at 4 °C. A subsample was air-dried for 3 days at room temperature and a portion of this was ground to pass through an 80-mesh (180 µm) sieve.

Four crop residues, corn (*Zea mays* L.), soybean (*Glycine max* L. Merr.), sorghum (*Sorghum vulgare* Pers.), and alfalfa (*Medicago sativa* L.), were used. The corn and sorghum materials were collected before harvest and included leaves and stems. The soybean material was collected just after harvest. The alfalfa was harvested fresh. All plant materials were dried at 65 °C for 3 days and ground to pass through a 20-mesh (850 µm) sieve. In this paper the term "crop residue" is used to include all plant materials studied.

Four animal manures, chicken (*Gallus domesticus*), pig (*Sus scrofa*), hores (*Equus caballus*), and cow (*Bos taurus*), were used. All animal manure samples were collected fresh and stored at 4 °C. A portion of each manure sample was air-dried at room temperature (23 °C) in a well-ventilated fumehood and ground to pass through a 60-mesh (250 µm) sieve.

The sewage sludges (Table 2) were collected from four wastewater treatment plants in Iowa to represent various sludge treatment processes. The treatments, at cities listed in parentheses, included Imhoff tank (Correctionville), holding tank (Charles City), secondary digester (Davenport), and primary digester (Keokuk). Organic C, total N, and pH of the sewage sludges used are reported in Table 2. Other chemical properties, including heavy metal composition, of the sewage sludges have been reported by Tabatabai and Frankenberger (1979). Before use, all organic materials studied were stored at 4 °C.

In the analyses reported in Tables 1 and 2, the pH values were determined by a combination glass electrode (soil : water ratio, 1 : 2.5; sewage sludge, before drying; and animal manures and plant materials after drying, at waste : water ratio, 1 : 10), organic C by the Mebius method (1960), total N in soils by a semimicro-Kjeldahl procedure (Bremner and Mulvaney 1982), total N in sewage sludges and plant materials by using salicylic acid and a salt catalyst to include NO_3^--N (Nelson and Sommers 1973), NH_4^+-N, and NO_3^--N by steam distillation (Keeney and Nelson 1982), particle-size distribution by the pipette method (Kilmer and Alexander 1949), and cation exchange capacity as described by Chapman (1965).

In the incubation experiment reported, a 20-g sample (on an oven-dry basis) of a field-moist soil and sufficient organic material to contain 0.18 g organic C (9 g organic C kg^{-1} soil, equivalent to a

Table 1 Properties of soils used (classification: Grundy, Aquic Argiudolls; Pershing, Udollic Ochraqualfs; Weller, Aquic Hapludalfs; for pH determination the soil : water or soil : 0.01 *M* $CaCl_2$ ratio was 1 : 2.5)

Soil series	pH		Organic C (%)	Total N (%)	Inorganic N ($mg\ kg^{-1}$)		Cation exchange capacity [cmol(+)kg^{-1}]	Clay (%)	Sand (%)
	H_2O	$CaCl_2$			NH_4^+	NO_3^-			
Weller	6.0	5.6	1.22	0.140	3.7	5.4	18.8	23.5	4.6
Pershing	6.0	5.2	1.57	0.140	3.7	3.0	22.5	29.1	4.5
Grundy	6.1	5.6	2.69	0.190	3.4	0.7	22.2	24.8	4.6

Table 2 Properties of organic materials studied (pH determination: soil : water ratio, 1 : 2.5; sewage sludge, before drying; and animal manures and plant materials at waste : water ratio, 1 : 10; species: corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; alfalfa, *Medicago sativa* L.; sorghum, *Sorghum vulgare* Pers.; chicken, *Gallus domesticus*; pig, *Sus scrofa*; horse, *Equus caballus*; cow, *Bos taurus*; *IT* Imhoff tank, *HT* holding tank, *SD* secondary digester, *PD* primary digester)

Organic material	pH	Organic C (%)	C : N ratio	Total N (%)	Inorganic N ($mg\ kg^{-1}$)	
					NH_4^+	NO_3^-
Plant materials						
Alfalfa	5.9	39.9	14	2.83	476	65
Corn	6.2	40.1	58	0.70	48	23
Sorghum	6.1	41.4	20	2.15	99	1073
Soybean	6.8	43.8	35	1.24	60	18
Animal manures						
Chicken	7.4	30.2	6	5.59	6430	396
Cow	5.2	45.4	23	2.32	2840	230
Pig	6.2	43.6	14	4.07	8700	387
Horse	9.4	25.0	16	1.68	670	511
Sewage sludges						
Correctionville (IT)	6.2	42.4	18	2.52	768	144
Charles City (HT)	5.8	40.5	11	3.94	3659	179
Davenport (SD)	6.9	28.5	8	3.88	720	94
Keokuk (PD)	7.4	52.9	20	2.76	229	157

field application of organic C in cornstalk residue, 40% organic C, at 50 Mg ha^{-1}) were mixed thoroughly and transferred into a 250-ml French square bottle. The moisture content of the soil-organic material mixture was adjusted to about 0.03 MPa tension. The incubation bottle was connected to an aerobic incubation apparatus similar to that described by Cheng and Coleman (1989) and Stotzky (1965). This apparatus consisted of a flow meter connected to a manometer to regulate air flow; a scrubber consisting of 2 l 4 M NaOH to absorb CO_2 from the air supply; 2 l concentrated H_2SO_4 to remove any NH_3 from the air supply; a manifold of Tygon tubes (8 mm) to distribute the CO_2-free air to the incubation bottles; and test-tubes containing 0.2 M KOH solution as CO_2 traps. The outlet of the trapping tube containing 25 ml KOH was connected to a short capillary tube to restrict the outflow. The air flow to each incubation bottle was controlled by a pinch clamp to give a flow rate of about 10 ml min^{-1}. The incubation bottle was connected to the incubation apparatus, and the soil-organic material mixture was incubated for 30 days at room temperature (20±2 °C). The trapping solution was replaced with fresh solution every day for 11 days, every other day for 6 days, every third day for 12 days, and once at the end of the incubation. The CO_2 trapped in the KOH solution was determined potentiometrically by titrating a 10-ml aliquot of the KOH solution against a standard of 200 mM HCl after precipitating the carbonate with 3 ml 375 mM $BaCl_2$. Controls were included to estimate the CO_2 evolved from untreated soils. Blanks were included to account for any trace amount of CO_2 that might be present in the airstream. This titration procedure can detect as little as 0.1 mg CO_2. All incubations were carried out in duplicate, and the results are expressed on a moisture-free basis, moisture being determined from the loss in weight after drying at 105 °C for 48 h (soils) and 65 °C for 48 h (organic materials).

The non-linear regression approach described by Smith et al. (1980) for N mineralization was used to solve the following equation for estimating the readily mineralizable organic C pools (C_o) and the first-order rate constant (k):

$$C_m = C_o\,[1 - \exp(-kt)]$$

where C_m is organic C mineralized (mg kg^{-1}) at specific time (t). The Statistical Analysis System (SAS) computer language was used to calculate C_o and k (Barr et al. 1976).

To estimate the decomposition rates (k_i) of the various organic C pools in each organic material, k_i values were calculated from slopes of the linear segments of curves obtained from plotting the natural log of organic C remaining against time as described by Gilmour et al. (1977). The segment with the steepest slope (highest k_i value) was considered to represent the most readily decomposable organic C fraction. The segment with the flattest slope (smallest k_i value) was considered to represent the least decomposable (resistant) fraction of organic C. The k_i value of the resistant fraction was used in calculating the half-life ($t_{1/2}$) of the most resistant C fraction in the organic material:

$$t_{1/2} = 0.693/k_i$$

Results and discussion

The total amounts of CO_2-C released in 30 days from untreated soils (controls) were 424, 429, and 480 mg C kg^{-1} soil for Pershing, Weller, and Grundy soils, respectively. The cumulative amounts of organic C mineralized in the control soils were linear over time. The patterns and total amounts of organic C mineralized in the organic material-treated soils varied considerably, depending on the type of organic material used. In general, the amount of CO_2-C released from organic material-treated soils increased at a decreasing rate. This was seen as a rapid increase during the initial stages of incubation, followed by a slower, relatively linear release. In this study, the decomposition rate of the native soil organic C in the presence of organic material (priming effect) is assumed to be the same for each type of organic material. This assumption is based on early findings that suggested a similar priming effect in soils whether different crop residues or residues from various parts of the same plant were applied (Pinck et al. 1950; Hallam and Bartholomew 1953; Broadbent and Nakashima 1974). Bingeman et al. (1953) found that the priming effect caused by adding plant materials high in solubles was as effective as adding insoluble materials if they were added to soils at the same rate. Results obtained by Terry et al. (1979) showed a similar priming effect among different sewage sludges. For convenience, the results obtained are discussed under subheadings according to the type of organic material studied.

Plant materials

The total amount of CO_2-C released from plant material-treated soils ranged from 2.875 to 3.105 g C kg^{-1} soil for corn, from 3.295 to 3.825 g C kg^{-1} soil for soybeans, from 5.397 to 5.644 g C kg^{-1} soil for alfalfa, and from 5.072 to 5.314 g C kg^{-1} soil for sorghum-treated soils. Expressed as a percentage of organic C in plant residues, the cumulative amounts of C mineralized as CO_2 in 30 days with the three soils ranged from 27% for Pershing soil treated with corn residue to 58% for Weller soil treated with alfalfa (Table 3). Cumulative CO_2-C evolution values from plant residue-treated Grundy soil during 30 days of incubation are shown in Fig. 1. The results obtained for the other two soils used showed similar decom-

Table 3 Percentage of organic C evolved as CO_2-C from organic material-treated soils in 30 days (percentages were calculated by subtracting the total organic C mineralized in untreated soil from that mineralized in organic material-treated soil and dividing the results by the amount of organic C added in waste material)

Organic material	Organic C evolved (%)		
	Weller soil	Pershing soil	Grundy soil
Plant materials			
Alfalfa	58	56	55
Corn	30	27	29
Sorghum	54	52	53
Soybean	38	32	33
Animal manures			
Chicken	45	53	52
Cow	46	46	48
Pig	62	58	58
Horse	22	21	25
Sewage sludges			
Correctionville	39	34	38
Charles City	39	39	38
Davenport	32	30	31
Keokuk	11	10	11

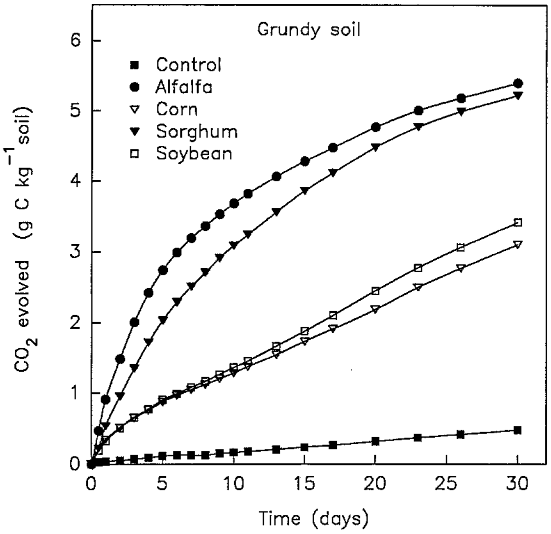

Fig. 1 Cumulative amounts of organic C released as CO_2 from Grundy soil treated with crop residues. At all *data points,* the differences between duplicate values were smaller than the point size

position patterns. The differences in soil properties did not markedly affect the amounts of CO_2 evolved.

The rate of CO_2 evolution was initially very rapid in the alfalfa residue- and sorghum residue-treated soils; 50 and 40%, respectively, of the total CO_2 evolved in 30 days of incubation was measured during the first 5 days. The rate of CO_2 evolution from corn residue- and soybean residue-treated soils was relatively constant after the second day of incubation. The amounts of organic C mineralized during the initial stages of incubation of soils treated with these crop residues, however, were small compared with the amounts mineralized in soils treated with alfalfa and sorghum residues. This suggests that the readily decomposable organic C fractions in alfalfa and sorghum residues are greater than those in corn and soybean residues. Studies on wheat (*Triticum aestivum* L.) straw decomposition have shown that the microbial populations were primarily limited by available C rather than by available N, especially during the early stages of incubation (Knapp et al. 1983a; Reinertsen et al. 1984). In the present study, total organic C mineralization did not reflect the C:N ratio (Table 2) of the crop residues used, but rather, the mineralization increased with the higher total N content of the residue. Janzen and Kucey (1988) evaluated the decomposition of wheat, lentil, and rape crop residues under three N application rates. They found that CO_2 evolution increased substantially from low-N to high-N treatments, but the amount of CO_2 released from the lentil residue was not significantly affected by N treatments. They further reported that the amount of C mineralized was positively correlated with the N concentration in the crop residue and the size of the water-soluble fraction. Conflicting results, however, have been reported on the relationship between organic C mineralization and N status of the substrate (Ladd et al. 1981; Knapp et al. 1983 a, b; Fraser et al. 1988; Janzen and Kucey 1988). Herman et al. (1977) showed that decomposition rates of a range of plant residues could not be predicted from properties of the original materials studied such as C:N ratio, lignin, or carbohydrate content when evaluated individually. When combined, however, these properties could accurately estimate the decomposition rates.

Animal manures

The total amount of CO_2-C released from animal manure-treated soils ranged from 5.176 to 5.283 g C kg^{-1} soil for chicken manure-, from 4.515 to 4.797 g C kg^{-1} soil for horse manure-, from 5.672 to 6.046 g C kg^{-1} soil for pig manure-, and from 2.349 to 2.704 g C kg^{-1} soil for horse manure-treated soils. Expressed as percentages of the organic C added, the cumulative amounts of organic C mineralized as CO_2 in 30 days for the three soils ranged from 21% for Pershing soil treated with horse manure to 62% for Weller soil treated with pig manure (Table 3). The results obtained from the four types of animal manures added to Grundy soil are shown in Fig. 2. The results obtained with the other two soils showed similar patterns to those obtained for Grundy soil. As for alfalfa residue- and sorghum residue-treated soils, the rates of CO_2 evolution from chicken manure-treated soils and pig manure-treated soils were initially very rapid; more than 50% of the total CO_2 evolved in 30 days of incubation was measured during the initial stages of decomposition (first 5 days). With cow manure-treated soils, the rate of CO_2 evolution was initially rapid, but the rate was relatively lower than the rates for soils treated with chicken or pig manures. The rates of CO_2 evolution from soils treated with horse manure were constant for the first 20 days of incubation.

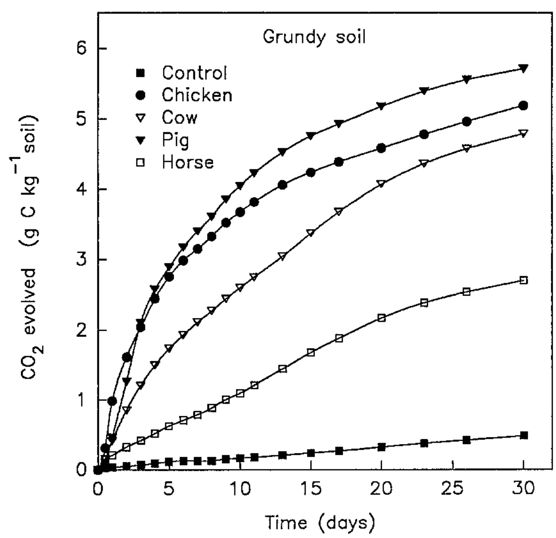

Fig. 2 Cumulative amounts of organic C released as CO_2 from Grundy soil treated with animal manures. At all *data points,* the differences between duplicate values were smaller than the point size

The cumulative CO_2 evolution from all manure-treated soils showed a second inflection in the exponential curve after 5–7 days of incubation. Hsieh et al. (1981) reported a similar trend after the first maximum was reached. Their explanation for the second CO_2 rate inflection was that, after the readily digestable materials are exhausted, the population has to use more resistant materials. Therefore, the microbial activity increases for a short time until the new steady state of the system is established. In comparison with plant residues, the CO_2 evolution from only soybean and corn residues showed a second inflection that occurred after 7 days of incubation.

In a short-term incubation study with various animal manures, Castellanos and Pratt (1981) showed that most of the CO_2 evolved occurred during the first 2 weeks of incubation. Their data showed that about 45 and 47% of the organic C in chicken and pig manures, respectively, was released as CO_2 during 4 weeks of incubation. These values are within the ranges obtained in the present study. The decomposition rates of animal manures, however, depend largely on the type of ration fed to these animals.

Sewage sludges

The total amount of CO_2-C released from sewage sludge-treated soils ranged from 3.568 to 3.922 g C kg^{-1} soil for Correctionville sludge, from 3.509 to 3.954 g C kg^{-1} soil for Charles City sludge, from 3.130 to 3.294 g C kg^{-1} soil for Davenport sludge, and from 1.322 to 1.462 g C kg^{-1} soil for Keokuk sewage sludge-treated soils. Expressed as percentages of organic C added, the cumulative amounts of organic C mineralized as CO_2 in 30 days with the three soils ranged from 10% with Pershing soil treated with Keokuk sludge to 39% with Weller and Pershing soils treated with sludge from Charles City and Weller soil treated with sludge from Correctionville (Table 3). The cumulative amounts of CO_2-C evolved from Grundy soil treated with the four sewage sludges are shown in Fig. 3. The results for Pershing and Weller soils showed patterns of decomposition similar to those for Grundy soil.

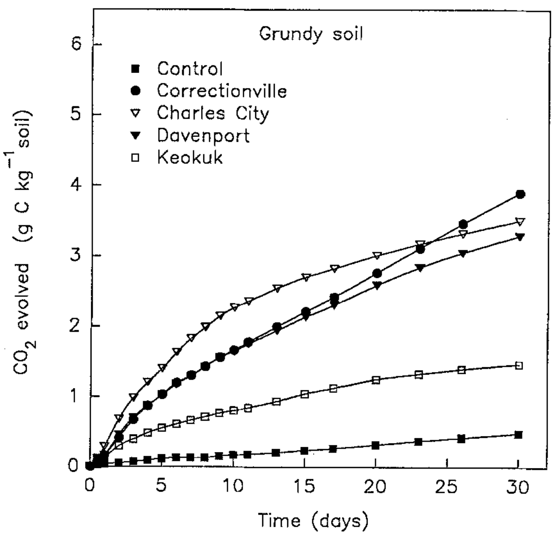

Fig. 3 Cumulative amounts of organic C released as CO_2 from Grundy soil treated with sewage sludges. At all *data points*, the differences between duplicate values were smaller than the point size

Organic C mineralization in soils amended with sewage sludges varies widely depending on the source and heavy metal contents of the sludge (Tabatabai and Frankenberger, 1979). At high concentrations, heavy metals may have deleterious effects on microbial activities in soils. Terry et al. (1979) found that 26–42% of the added organic C was evolved as CO_2 from soils treated with four anaerobically digested sewage sludges incubated for 130 days. They suggested that a fraction of anaerobically digested sludge was readily decomposable when added to aerobic soil under standardized laboratory conditions. Their data showed that most of the CO_2 evolution occurred during the first 30 days of incubation and that the major portion (55–80%) of sludge organic C was resistant to decomposition in soil. Tester et al. (1977) found that only 16% of the added organic C was evolved as CO_2 in 54 days of incubation. Hsieh et al. (1981) evaluated the decomposition patterns of two types of sewage sludge in soil. They found that activated sludge showed a much greater mineralization rate than the digested sludge because of a larger portion of active organic C. About 26% of organic C in the activated sludge treatment was mineralized in 6 weeks, but only 8% of the organic C was mineralized in the digested sludge. Gilmour et al. (1985) found that the decomposition rate of sewage sludge was not related to the N content of the substrate but that the net N mineralized was related to the net C mineralized.

Decomposition models

A variety of models has been proposed for calculating plant residue decomposition rates and soil organic matter levels. These include models with decomposition rates that are constant in time, models with decomposition constants that are variable in time, and models with different fractions of soil organic matter, each having a different decomposition rate (Bouwman 1990). All these models involve equations with exponential functions. Because the composition and the rate of decomposition of the constituents of the organic pools in plant materials, animal manures, and sewage sludges are markedly different and unpredictable, we used an exponential equation developed for describing N mineralization in soils to calculate the decomposition rate constants and the readily decomposable organic C pool in each of the organic materials studied. All results of CO_2 evolution from organic material-treated soils conformed well to the exponential model developed for N mineralization (Smith et al. 1980). Convergence of the estimates occurred within 10 iterations. The first-order rate constants (k) and potentially mineralizable organic C values (C_o) for plant residue-treated soils are presented in Table 4. The C_o values ranged from 4.027 g C kg^{-1} soil with a k value of 0.0375 day^{-1} for corn residue-treated Pershing soil to

Table 4 First-order rate constants for decomposition of organic C in soils treated with plant materials (k was calculated from cumulative CO_2-C evolved during 30 days of incubation by using the exponential, equation, $C_m = C_o[1-\exp(-kt)]$ where C_m is organic C mineralized at time t; k_1, k_2, and k_3 were estimated graphically; – indicates that no phase was present; C_o mineralizable organic C pool

Soil or plant material	Rate constant (day^{-1})				C_o ($g\,kg^{-1}$)	Percentage of C evolved at each phase			Half-life of C remaining (days)
	k	k_1	k_2	k_3		D_1	D_2	D_3	
Weller soil									
None		0.0017				4.8			
Alfalfa	0.1560	0.0972	0.0238	0.0143	5.308	34.2	21.8	6.7	49
Corn	0.0378	0.0298	–	0.0138	4.338	7.5	–	7.0	50
Sorghum	0.0937	0.0645	0.0259	0.0150	5.446	27.5	26.4	5.1	46
Soybean	0.0300	0.0334	–	0.0180	6.253	8.3	–	34.2	39
Pershing soil									
None		0.0016				4.7			
Alfalfa	0.1481	0.0893	0.0231	0.0141	5.133	31.8	24.2	4.2	49
Corn	0.0375	0.0226	–	0.0128	4.027	6.7	–	25.2	54
Sorghum	0.0949	0.0623	0.0231	0.0166	5.130	26.4	24.4	5.6	41
Soybean	0.0314	0.0263	–	0.0164	5.143	7.2	–	29.4	42
Grundy soil									
None		0.0017				5.3			
Alfalfa	0.1389	0.0791	0.0234	0.0149	5.135	33.2	19.8	7.0	47
Corn	0.0341	0.0198	–	0.0142	4.628	7.2	–	27.3	49
Sorghum	0.0839	0.0536	0.0281	0.0160	5.548	27.9	21.9	8.2	43
Soybean	0.0265	0.0218	–	0.0156	6.071	7.3	–	30.7	44

5.308 g C kg^{-1} soil with a k value of 0.1560 day^{-1} for alfalfa-treated Weller soil.

To identify the various phases involved in decomposition of the organic materials added to soils and to estimate the decomposition rate (k_i) of the various organic pools in each organic material, we constructed graphs by plotting the natural log of the C remaining versus time (days) for each set of the data collected. For illustration, the results obtained with the Grundy soil treated with corn residue or pig manure are shown in Fig. 4.

Transformation of the CO_2 evolution data revealed that decomposition of organic C in alfalfa and sorghum residues occurred in three phases. Decomposition of organic C in corn and soybean residues occurred in two phases. The amount of organic C evolved in phases I and II (presented as the percentage of C mineralized, D_1 and D_2) are the easily decomposable fractions of organic C. Phase III (presented as D_3) of decomposition represents the slowly decomposing and resistant fractions. During phase I, a large fraction of organic C was evolved as CO_2 from alfalfa and sorghum, with values ranging from 31.8 to 34.2% for alfalfa, and from 26.4 to 27.9% for sorghum residue. A relatively small fraction of organic C was evolved from corn and soybean residues, with values ranging from 6.7 to 8.3%. About 5% of the native soil organic C was evolved as CO_2 in 30 days (Table 4).

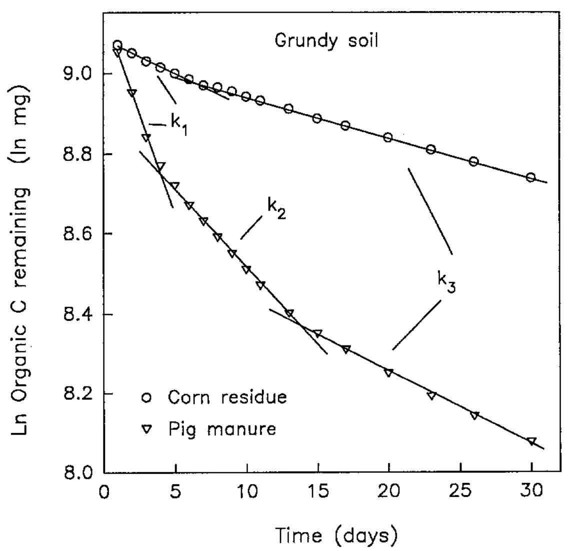

Fig. 4 Natural log of organic C remaining in Grundy soil treated with corn residue or pig manure as a function of time. At all *data points,* the differences between duplicate values were smaller than the point size

Decomposition of only alfalfa and sorghum residues occurred as phase II (D_2 fraction), within the first 20–23 days of incubation. A relatively small fraction of organic C was decomposed during phase III. Reddy et al. (1980) summarized first-order rate constants for decomposition of C in soils treated with plant residues and animal manures from different sources. They found that plant residue decomposition occurs in two phases. Their review, however, did not include alfalfa or sorghum residues.

The C_o values ranged from 4.175 g C kg^{-1} soil with a k value of 0.0279 day^{-1} for horse manure-treated Pershing soil to 6.118 g C kg^{-1} soil with a k value of 0.1124 day^{-1} for pig manure-treated Weller soil. Organic C decomposition in soils treated with chicken, cow, and pig manures occurred in three phases, and in soils treated with horse manure in two phases (Table 5). Rapidly decomposable organic C fractions were highest in pig manure, with values ranging from 28.6 to 35.2%. The fractions of organic C decomposed in both phase I and phase II were similar. Chicken manure, however, contained a larger fraction decomposing in phase I than in phase II. Cow manure followed an opposite order to that of chick-

Table 5 First-order rate constants for decomposition of organic C in soils treated with animal manures (for other explanations, see Table 4)

Soil or animal manure	Rate constant (day^{-1})				C_0 ($g\ kg^{-1}$)	Percentage of C evolved at each phase			Half-life of C remaining (days)
	k	k_1	k_2	k_3		D_1	D_2	D_3	
Weller soil									
Chicken	0.1520	0.0997	0.0321	0.0187	4.941	27.6	17.8	13.3	37
Cow	0.0685	0.0529	0.0177	0.0129	5.137	16.2	29.6	4.9	54
Pig	0.1124	0.0841	0.0313	0.0155	6.118	35.2	27.7	4.3	45
Horse	0.0265	0.0113	–	0.0041	4.485	21.0	–	6.1	169
Pershing soil									
Chicken	0.1689	0.1279	0.0271	0.0113	4.870	29.1	21.0	7.4	61
Cow	0.0683	0.0515	0.0226	0.0137	5.053	15.8	29.0	5.4	51
Pig	0.1215	0.0938	0.0367	0.0133	5.690	31.1	26.3	5.6	52
Horse	0.0279	0.0111	–	0.0073	4.175	22.2	–	3.9	94
Grundy soil									
Chicken	0.1538	0.1090	0.0182	0.0147	4.883	27.2	17.9	12.6	47
Cow	0.0688	0.0503	0.0258	0.0125	5.423	16.7	28.5	8.1	55
Pig	0.1319	0.0931	0.0413	0.0114	5.644	28.6	26.2	8.7	61
Horse	0.0235	0.0129	–	0.0063	5.547	26.5	–	3.5	110

en manure. Horse manure had the smallest fraction of easily decomposable organic C compared with the other types of manures studied. Gilmour et al. (1977) reported three phases of decomposition of feedlot manure over a 42-day incubation period. Their data showed that a steady state was reached after 20 days of incubation. Our results showed that a steady state was reached after 20–23 days for cow manure, after 13–17 days for chicken manure, after 17–23 days for pig manure, and after 20–23 days for horse manure. Decomposability of organic C in animal manures reflects the type of ration fed to these animals. The pig manure was low in fibrous materials and high in N content. The horse manure contained large amounts of fibrous materials and a small amount of N.

The first-order rate constants and potentially mineralizable organic C (C_0) for the decomposition of organic C in soils treated with sewage sludges are shown in Table 6. The C_0 values ranged from 1.422 g C kg^{-1} with a k value of 0.0784 day^{-1} for Keokuk sewage sludge-treated Pershing soil to 6.061 g C kg^{-1} soil with a k value of 0.0330 day^{-1} for Correctionville sewage sludge-treated Weller soil. Decomposition of organic C in sewage sludges, except for that from Correctionville, occurred in three phases. The rate constants and percentages of C evolved at each phase of decomposition varied widely among the sludges studied. Keokuk (primary digester) and Correctionville (Imhoff tank) contained the smallest amounts of readily decomposable organic C. In these treatments, however, microbial activities could have been influenced by the metals present in the sludge. A wide range of microbial sensitivity to metals in sewage sludges has been reported (Babich and Stotzky 1977; Zibilske and Wagner 1982; Wiseman and Zibilske 1988). At high concentrations, metals may have deleterious effects on microbial activities and growth. Microbial activities, therefore, may

Table 6 First-order rate constants for decomposition of organic C in soils treated with sewage sludges (for other explanations, see Table 4)

Soil or sewage sludge	Rate constant (day^{-1})				C_0 ($g\ kg^{-1}$)	Percentage of C evolved at each phase			Half-life of C remaining (days)
	k	k_1	k_2	k_3		D_1	D_2	D_3	
Weller soil									
Correctionville	0.0330	0.0262	–	0.0179	6.061	13.3	–	30.3	56
Charles City	0.0877	0.0422	0.0139	0.0121	4.089	22.0	8.0	13.9	57
Davenport	0.0511	0.0239	0.0146	0.0096	4.116	12.6	16.6	7.1	72
Keokuk	0.0802	0.0197	0.0052	0.0025	1.484	3.3	9.8	23.2	277
Pershing soil									
Correctionville	0.0439	0.0267	–	0.0150	4.714	12.9	–	26.7	46
Charles City	0.0990	0.0466	0.0152	0.0087	3.992	23.2	14.5	5.6	80
Davenport	0.0597	0.0250	0.0130	0.0087	3.675	13.0	17.4	4.4	80
Keokuk	0.0784	0.0183	0.0051	0.0023	1.422	4.9	8.4	1.4	301
Grundy soil									
Correctionville	0.0322	0.0266	–	0.0178	6.050	13.2	–	30.1	39
Charles City	0.0993	0.0370	0.0207	0.0086	3.569	18.1	10.1	10.8	81
Davenport	0.0537	0.0244	0.0136	0.0086	4.005	13.0	15.7	7.9	81
Keokuk	0.0747	0.0141	0.0057	0.0021	1.599	5.4	8.4	2.4	330

not reflect the actual available C substrate in sewage sludges, especially during the early stages of incubation.

The half-lives of the C remaining in soils ranged from 39 to 54 days for plant materials. The corresponding half-lives for the C remaining from animal manures and sewage sludges ranged from 37 to 169 days and from 39 to 330 days, respectively.

Acknowledgements Journal Paper No. J-15461 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Projects No. 2710, 3022, and 3047. This work was supported in part by the Biotechnology Byproducts Consortium of Iowa.

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