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Relationship Between Mineral Soil Surface Area and Carbon Sequestration Rate for Biosolids Added to Soil

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Additional information is available at the end of the chapter

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Abstract

Biosolid degradation in soil comprises important biological and geochemical processes that operate in the soil matrix and on the soil surface. The microbial ecology is assumed to be associated with mineral soil surface area because of the large surface area of soil. Biological degradation rates for 27 fields (10°C and 10% moisture) ranged from 0.01 to 0.30 yr⁻¹ and were determined by applying a degradation rate model (DRM). A 1-year-long laboratory study was also conducted to determine biosolid microbial degradation rates (21°C and 20% moisture) for soils from eight of the fields. Changes in degradation rates were correlated with changes in mineral soil surface area (1–10 m²/g) with larger degradation rates associated with soils with larger surface areas. The annual soil sequestration rate was calculated to increase from 1 to 6% for field conditions and from 4 to 14% for laboratory conditions when the soil total surface area increased from 1 to 10 m²/g. Therefore, land application of biosolids is an effective way to enhance carbon sequestration in soils and reduce greenhouse gas (GHG) emissions.

Keywords: carbon sequestration, biosolids, biological degradation, mineral soil surface area

1. Introduction

This chapter evaluates the relationship between carbon sequestration rates for biosolids added to soils and soil surface area to provide a better understanding of the variables that control sequestration. Biosolids are nutrient-rich organic materials formed as a result of anaerobic digestion of primary and secondary sludge from wastewater treatment plants. Each year 7.1 Mt of biosolids are generated (dry tons) in the United States [1]. Previous studies have accounted for effects of temperature and moisture on carbon sequestration rate but have

not included adjustments for soil surface area. We hypothesize that due to the large surface area of soils, biological processes that operate on the soil surface are potentially important to the sequestration rate of biosolids in soil. A degradation rate model (DRM) is used to predict the portion of biosolids added to soil that is sequestered (residual microbial biomass). The quantification of the biomass yield is especially important and is a unique feature of the DRM because it provides the ability to separate the soil organic carbon (SOC) into two components: (i) carbon (C) in biosolids that has not been degraded and (ii) C in residual microbial biomass produced during the microbial degradation process (sequestered carbon). Biomass is being developed as biosolids are consumed. One of the most important DRM characteristics is that it can be used to represent the pattern of biomass accumulation from multiple applications of biosolids to soil.

A basic relationship is developed that uniquely predicts changes in the sequestration of organic matter added to soils as a function of mineral surface area that provides a better understanding of the important variables that control sequestration and allows the application of technologies based on their ability to increase the rate of C sequestration. Results demonstrate that soil surface area is much more profound as an indicator of carbon sequestration in soils than previously indicated, and therefore soil surface area is an essential parameter in assessing sequestration rates of organic material added to soils.

The United Nations Framework Convention on Climate Change (UNFCCC) declares that greenhouse gas (GHG) emissions result from anthropogenic activities and recommends C counting as a necessary step toward reduction of such emissions [2]. The land application of biosolids is an effective way to increase SOC. The ability for soils to biologically degrade biosolids and sequester carbon (C) is recognized as one method to mitigate greenhouse gas emissions [2, 3]. Jarecki and Lal [4] also suggested that application of biosolids is an important management practice to increase soil C sequestration in agricultural soils. Net C sequestration rates from biosolids applied to soil have been reported to be between 1 and 3 Mg ha⁻¹ yr⁻¹ with biosolid application rate between 56 and 71 Mg ha⁻¹ yr⁻¹ [5].

The world's degraded soils (1216 Mha) and agricultural soils (4961 Mha) both have high potential for C sequestration. Historical data show that 40 Pg of SOC have been lost in these soils. Considering these soils have capacity to sequester C, it is important to realize that there is a way to reverse the SOC depletion process. The total potential of soil C sequestration is around 0.6–1.2 Pg C yr⁻¹, in which the world cropland could sequester C at the rate of 0.4–0.6 Pg C yr⁻¹ [6] and the desertification control has the C sequestration potential of around 0.2–0.6 Pg C yr⁻¹. Conant et al. [7] pointed out that the grassland also has relative high potential of C sequestration, which can be included in desertification control. These data imply that about 0.9 ± 0.3 Pg C yr⁻¹ additional C could be sequestered in soils [8].

Efforts to improve C sequestration in agricultural soils focus on changes of management practices such as tillage/no tillage, irrigation, farm machinery, and other similar strategies [9]. Yet, C sequestration associated with improved management practices has not been investigated comprehensively because terrestrial C sequestration is a complex function of plant species, type of soil, regional climatic conditions, and topography in addition to management practices [10, 11]. These intricate details are further amplified by the need for long-term

studies required to evaluate dynamic processes involved in the better understanding of a quantitative dynamic process for C sequestration in agricultural soils. The present study overcomes this difficulty by focusing on a specific and clearly defined system: repeated soil application of biosolids under conditions of variable application rates.

Biosolids applied to soil are aerobically transformed into inorganic C, which is released to the atmosphere and into humid substances (biomass) that are available for sequestration. Microbial decomposition of biosolids occurs over a period of years not decades and therefore is susceptible to depletion. Decomposition of accumulated biomass is much slower, and consequently this material has a significant potential as a repository for excess atmospheric C. Through the process described above, biosolid degradation rate plays a key role in governing the SOC dynamics. The rate of biosolid decomposition is one of the key processes governing the dynamic of C sequestration. The DRM is used in this chapter to quantify the degradation rate for biosolids and yield for residual microbial biomass from repeated application of biosolids to soil and provides an easy quantitative method for evaluating C sequestration.

2. Method and materials

2.1. Degradation rate model (DRM)

To assess the dynamic of SOC sequestered process and better understand C sequestration in agriculture soil, Zhai et al. [12] developed a degradation rate model (DRM) to describe the degradation rate process and determine the yield for residual microbial biomass (sequestered carbon) from repeated application of biosolids to soil. The DRM [12] was used in this study to provide the field biological degradation rate for biosolids applied to selected fields from 1972 to 1985 in Fulton County, Illinois [5] (see **Table 1** and **Figure 1**).

This site is located approximately 300 km southwest of Chicago. The climate of the site is continental with an annual average air temperature of 10°C and annual precipitation of 1013 mm. The monthly mean moisture content of soil is near 10%. The pH of surface spoils was neutral to alkaline with variable soil texture [5]. The biosolids applied to 41 fields were in liquid phase with average organic carbon 23.2% [5]. The advantage of using the Tian et al. [5] database is its long duration and the inclusion of repeated measurements of biosolids applied (including the organic constituent) and resulting soil organic carbon (SOC) gain. Forty-one fields were

Type of biosolids	Total solids [‡]	Volatile solids [‡]	Organic carbon [‡]	Organic N*	NH ₄ -N*	C/N*	Total Fe*	Total Al*
			(%)				(%)	
Liquid	2.9–73.0	14.6–47.6	8.5–27.6	2.38	1.54	6.21	3.98	1.13

[‡] Values vary based on biosolids applied from the year 1972 to 1985 in these properties, for detailed information, see Tian et al. database [5].

* Values vary based on biosolids applied from the year 1972 to 1985 in these properties, an average was shown here; for detailed information, see Tian et al. database [5].

Table 1. Properties of biosolids applied in this study (values are from Tian et al. database) [5].



Figure 1. Biosolids applied on selected field in Fulton County, IL [13].

divided into three groups based on soil type. Group I consisted of 20 fields of “coarse” mine spoil soils, primarily Lenzburg (fine-loamy, mixed, active, calcareous, mesic Haplic Udarents) and Lenzwheel soil series [14]. Group II is primarily Rapatee (fine-silty, mixed, superactive, nonacid, mesic Mollic Udarents) soil series and contains nine fields of “fine” mine spoil soils, [14, 15]. Group III contains 12 fields of various non-mined soils that were degraded by intensive cultivation or overgrazing [14, 15] (**Figure 2**).

The DRM was developed by employing pertinent information from Tian et al. [5] on the long-term application of biosolids to soil in 41 fields with variable application periods ranging from 8 to 34 years (1972 to 2006). The model is based on a mass balance between the amount



Figure 2. Typical soil samples from group I, II, and III applied in this study.

of biosolid carbon applied to soil and the amount of SOC present in the soil plus the carbon evolved as CO₂. The mass balance could be written as follows:

$$\begin{aligned} & \text{Applied biosolids carbon} - \text{first-order kinetic biosolids remaining} \\ & + \text{Carbon sequestered} + \text{CO}_2 \text{ emissions} \end{aligned} \quad (1)$$

The biosolid decomposition rate in the DRM is described by first-order kinetics:

$$\frac{dC}{dt} = -kt \quad (2)$$

where:

C = the carbon concentration present in the biosolids (Mg/Ha);

k = the first-order degradation rate (yr⁻¹);

t = biosolid decomposition time (yr).

Based on the first-order kinetics, the accumulated residue could be calculated by the following equation:

$$\text{residue} = (1 + f^1 + f^2 + f^3 + \dots + f^n) (\text{SEQequation_num} * \text{MERGEFORMAT3}) \quad (3)$$

where

f is the fraction left after 1-year decay or $f = \frac{C_t}{C_0} = e^{-kt}$, with $t = 1$.

To develop the DRM model, a curve fitting approach was applied that compared field measurements of SOC to calculations of SOC. Curve fitting, the measured values of SOC for each year with model-generated values of SOC using trial and error, produced a best-fit average degradation rate for biosolid degradation and biomass yield. The DRM is based on quantification of both the degradation rate for the biosolids and the yield for residual microbial biomass and provides an easy quantitative method for evaluating residual microbial biomass. One of the most important DRM characteristics is that it uses one degradation rate constant to adequately represent the pattern of accumulation from multiple applications of biosolids to soil. The DRM can be applied to estimate (1) the biosolid degradation as a function of time, (2) the SOC portion due to biosolids remaining, and (3) the residual microbial biomass (C sequestered). To apply the DRM, the appropriate biomass yields and degradation rate that are estimated from curve fitting are needed [15]. It should be noticed that the microbial biomass yield is considered as constant (35–40%) determined by curve fitting results. It is an important assumption when computing biomass (C sequestered) during the biosolid degradation process in each field.

Figure 3 shows the C flow simulated in the DRM model. A wide range of factors control the rate of sequestration of carbon from biosolids and their residence time in soil.

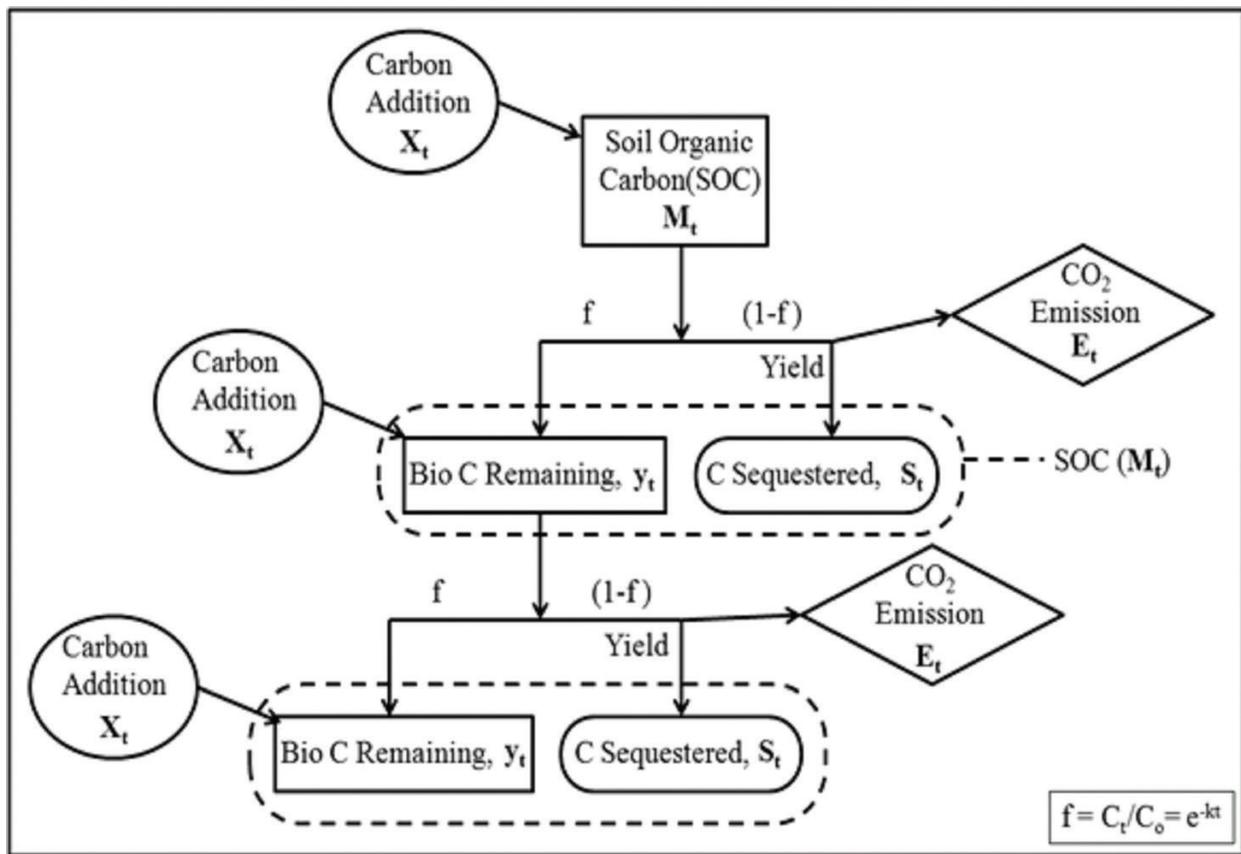


Figure 3. Flow diagram of the DRM as a function of C addition [12].

The DRM is presented as follows:

$$y_t = (y_{t-1} + X_{t-1}) \times f \tag{4}$$

$$S_t = \left(\frac{(1-f)}{f} \right) \times \text{Yield} \times \sum_1^t y_t \tag{5}$$

$$M_t = y_t + S_t = y_t + \left(\frac{(1-f)}{f} \right) \times \text{Yield} \times \sum_1^t y_t \tag{6}$$

$$E_t = \frac{(1-f)}{(f)} \times (1 - \text{Yield}) \times y_t \tag{7}$$

where $f = e^{-k}$;

X_t is the biosolid carbon application amount (mg) at time t (day);

y_t is the biosolid carbon remaining at time t (mg);

S_t is the biomass carbon mass or sequestered carbon accumulation at time t (mg);

M_t is mass of SOC at time t (mg);

E_t is the annual C-CO₂ emission at time t (mg).

2.2. Soil particulate surface area

Tian et al. [5] classified the 41 fields evaluated in this study as coarse (group I), fine (group II), and mixed (group III) but provided no additional information concerning physical differences in the type of soils in each group. Therefore, a sieve analysis based on the mass fraction of soil that passes through a specified screen size was used to determine the mass distribution of the coarser, larger-sized particles, and a hydrometer was used to determine the size distribution of the finer particles [16]. Twenty-seven fields were strategically selected from the 41 fields to have a wide range of mineral surface areas (see **Table 2**). Of the 27 fields selected, nine were from group I, seven from group II, and 11 from group III.

A soil texture analysis was used to determine the physical characteristics of the soils. [16]. Quantitatively, soil texture denotes the proportion of sand (0.05–2 mm diameter), silt (0.002–0.05 mm diameter), and clay (less than 0.002 mm diameter) that occur in a given soil.

Particulate surface area size distributions were estimated from the mass size distributions to determine the effect of surface area on biosolid degradation. It was assumed that the soil particles are spherical with a smooth surface and the number of soil particles was estimated by Eq. (8) [15]:

$$N = M / (\rho \cdot 4 / 3 \cdot \pi \cdot r^3) \quad (8)$$

where:

N = the number of soil particles;

r = soil particle radius (cm);

M = the mass of the soil particle (g);

ρ = soil density [17] (g/cm^3).

The soil particulate surface area (S) was estimated by Eq. (9):

$$S = 4\pi r^2 \cdot N \quad (9)$$

where:

N = the number of soil particles;

r = soil particle radius (m);

S = particle surface area (m^2).

Eqs. (8) and (9) were applied to calculate mineral soil surface based on known mass distribution and average particle size for sand, silt, and clay [18].

2.3. Laboratory experiment using soil respirator

A yearlong laboratory study using a soil respirator was conducted to determine the degradation rate constants for eight of the 27 fields under laboratory conditions (21°C and 20% moisture). The fields were selected strategically from the 41 fields to represent different mineral

Soils	Organic materials	G	Field no.	Environment conditions		C*	K1 ^s	K2 ^t	D	SFC	Soil texture
				Fields	Lab						
The soil samples from this study (eight soil samples)	Biosolids	I	F32	10°C and 10%	21°C and 20%	8.93	0.02	0.11	2.6	1.29	Sandy loam
	Biosolids	I	F39	10°C and 10%	21°C and 20%	11.95	0.05	0.12	2.6	1.73	Sandy loam
	Biosolids	III	F10	10°C and 10%	21°C and 20%	12.85	0.06	0.14	2.6	2.29	Sandy loam
	Biosolids	I	F15	10°C and 10%	21°C and 20%	15.44	0.11	0.24	2.6	2.42	Sandy loam
	Biosolids	III	F37	10°C and 10%	21°C and 20%	11.75	0.14	0.35	2.6	6.55	Clay loam
	Biosolids	II	F47	10°C and 10%	21°C and 20%	18.02	0.15	0.42	2.6	8.54	Clay loam
	Biosolids	II	F45	10°C and 10%	21°C and 20%	12.95	0.15	0.38	2.6	7.63	Clay loam
The soil samples from this study (19 soil samples)	Biosolids	II	F43	10°C and 10%	21°C and 20%	15.63	0.20	0.47	2.6	7.65	Clay loam
	Biosolids	I	F8	10°C and 10%	N/A	11.59	0.01	N/A	2.6	1.12	Loamy sand
	Biosolids	III	F16	10°C and 10%	N/A	12.30	0.01	N/A	2.6	1.27	Loamy sand
	Biosolids	III	F22	10°C and 10%	N/A	14.74	0.02	N/A	2.6	1.14	Sandy loam
	Biosolids	III	F23	10°C and 10%	N/A	8.64	0.03	N/A	2.6	1.27	Loamy sand
	Biosolids	I	F4	10°C and 10%	N/A	9.01	0.03	N/A	2.6	2.29	Loamy sand
	Biosolids	III	F35	10°C and 10%	N/A	15.39	0.06	N/A	2.6	1.66	Sandy loam
	Biosolids	I	F2	10°C and 10%	N/A	10.46	0.06	N/A	2.6	2.34	Sandy loam
	Biosolids	III	F34	10°C and 10%	N/A	10.80	0.07	N/A	2.6	2.41	Sandy loam
	Biosolids	I	F30	10°C and 10%	N/A	18.00	0.10	N/A	2.6	2.66	Sandy loam
	Biosolids	I	F28	10°C and 10%	N/A	17.97	0.12	N/A	2.6	4.04	Loam
	Biosolids	I	F7	10°C and 10%	N/A	11.64	0.13	N/A	2.6	4.80	Loam
Biosolids	II	F9	10°C and 10%	N/A	9.71	0.01	N/A	2.6	4.58	Silt loam	
Biosolids	III	F36	10°C and 10%	N/A	11.98	0.10	N/A	2.6	5.15	Loam	

Soils	Organic materials	G	Field no.	Environment conditions		C* Mg ha ⁻¹	K1 [§] Yr ⁻¹	K2 [¶] Yr ⁻¹	D g cm ⁻³	SFC m ² g ⁻¹	Soil texture
				Fields	Lab						
	Biosolids	III	F21	10°C and 10%	N/A	11.32	0.13	N/A	2.6	7.83	Clay loam
	Biosolids	III	F31	10°C and 10%	N/A	16.55	0.17	N/A	2.6	7.64	Clay loam
	Biosolids	II	F41	10°C and 10%	N/A	11.50	0.19	N/A	2.6	7.89	Clay loam
	Biosolids	II	F42	10°C and 10%	N/A	13.90	0.20	N/A	2.6	8.45	Clay loam
	Biosolids	II	F40	10°C and 10%	N/A	15.48	0.25	N/A	2.6	10.09	Silt clay loam
	Biosolids	III	F20	10°C and 10%	N/A	10.93	0.30	N/A	2.6	10.02	Silt clay loam
Terry et al. [21] soils	Sludge	N/A	Fincastle	N/A	21°C and 20%	5.15	N/A	0.35	2.6	4.81	Silt loam
	Sludge	N/A	Chalmers	N/A	21°C and 20%	5.15	N/A	0.29	2.6	4.66	Silt loam
	Sludge	N/A	Tracy	N/A	21°C and 20%	5.15	N/A	0.12	2.6	2.13	Sandy loam

G, group no.;

C*, annual carbon application rate;

K1[§], degradation rate under field conditions;

K2[¶], degradation rate under lab conditions;

D, soil density; SFC, mineral soil surface area.

Table 2. Variation in the environmental conditions (temperature and moisture content), annual application rate (C), degradation rate under both field (K1) and laboratory (K2) conditions, soil density(D), mineral soil surface area (SFC), and soil texture for soils evaluated.

surface areas. This approach facilitates the objective of establishing an association between total mineral surface area and degradation rate.

For the laboratory experiment, 10 g of air-dried soil from each field was added to 500 ml Erlenmeyer flasks plus additional water to provide the desired moisture content (0.2 g of water per gram of soil). The flasks were connected to a scrubber system consisting of a series of flasks containing concentrations of sulfuric acid, sodium hydroxide, and water to provide humidified, CO₂-free air to pass over the surface of each soil sample. The flow rate of humidified, CO₂-free air was controlled at 9 ml/min for each soil sample, which was incubated in the dark at 21°C for 360 days. The evolved CO₂ was absorbed in 200 ml of a 0.5 NaOH solution. Periodic replacement of NaOH solutions guaranteed the accuracy of CO₂ production rate measurements for each sample. Duplication experiments were conducted. The CO₂ amount was measured by back-titration with 1.0M HCl after the CO₂ was stabilized by precipitation with 1.5M BaCl₂ solutions [19]. At the beginning and the end of the 1-year incubation period, samples of soil taken from the flasks were analyzed to determine SOC concentrations using the Walkley-Black method [20]. This method used excess dichromate ion to oxidize the SOC and titrate the dichromate residual after oxidization with ferrous ion.

Terry et al. [21] also conducted a yearlong laboratory experiment to evaluate the biological degradation of synthetic biosolids (with the decomposition and degradation rate similar to real biosolids) using three different soil types under controlled conditions (**Table 2**). Terry's paper reports on the emissions from biosolids added to soil with little analysis of the results. Terry's CO₂ emission database was reanalyzed in this study to provide the laboratory degradation rate of biosolids, based on first-order kinetics. Results from Terry's experiment were compared with results from this study.

3. Results

3.1. Sequesterate rates determined from DRM application

DRM provides C sequestration rates based on first-order kinetics and estimates the SOC concentration for each field in Tian et al. [5] database. After annual biosolid application for 15–22 years to each field, the modeled SOC concentrations and amount of C sequestered were estimated by applying DRM. **Figure 4** provides example plots for two of the selected fields [15]. The SOC measured and estimated with the DRM matched very good base on the coefficient of determinations between them (average coefficient of determination is 0.94), indicating that the curve fitting technique was able to provide biomass yield and degradation rate. Therefore, DRM model is allowed to provide acceptable estimates of the measured SOC values and sequestration amounts [15].

The slow rates of biosolid degradation resulted in large increases in SOC; this is because of the presence of biosolids that have not reacted [15]. The peak of the SOC concentration occurred in the mid-1980s after 12 years of annual biosolid application. After the year 1985, the accumulation of biosolids stopped in increasing and the biosolid application declined. An increased SOC was caused by the accumulation of stored biosolids when the biosolid

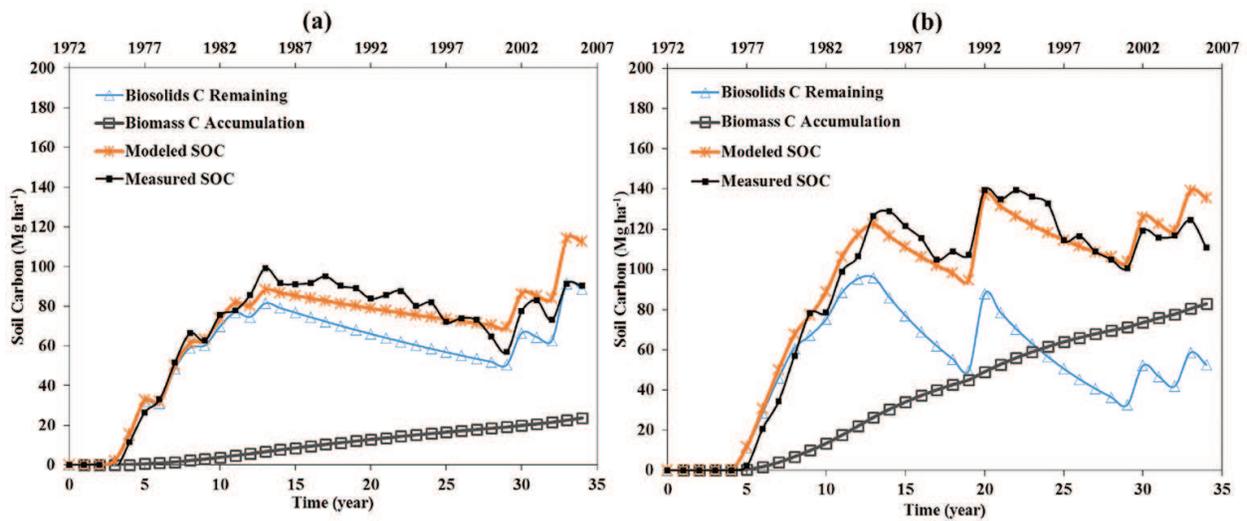


Figure 4. Example of the variation in biosolids remaining, measured and modeled soil organic carbon (SOC), and accumulated biomass. (a) Field 32 and (b) field 47.

accumulation exceeded degradation during the early stage of biosolid application. A steady state was approached when of decomposition converged on the amount of biosolid application [15]. This result is supported by Hamaker’s study [22], which developed a mathematical model to predict the cumulative levels of pesticides in soil. The study indicated that when pesticides application rate equals to its decomposition rate, a steady state was approached. Also, Jastrow et al. [23] suggested carbon sequestration occurs when a positive disequilibrium sustained between C input and C degraded over some period of time. A new steady-state system would eventually be achieved when the amount of degradation converged on the amount of application. Jastrow’s [23] result explains the increasing of SOC during the early stages of biosolid addition in this study, and Hamaker’s [22] finding corresponds to achieving a steady state between biosolid degradation and biosolid application.

Analyses of DRM simulation results (**Figure 5**) for the group I and II in the Tian et al. [5] database indicate that higher biosolid degradation rates occur with finer soils. Several long-term agroecosystem studies also indicate that SOC accumulation increases with increase in C input [23, 24]. To assess the relationship between soil type, biosolid degradation rate, and biosolid C application rate, the fields were divided into coarse and fine soils [5]. It can be observed that the microbial degradation rate was larger for fine than for coarse soil type based on the separation of the regression lines. The error bars in **Figure 5** represent one standard deviation for each average biosolid application rate for related fields in Tian’s database [15]. The average difference in the degradation rate between the linear regression lines was near 0.10 yr^{-1} (**Figure 5**). This represents the difference in the average degradation rate of biosolids when applied on coarse and fine soils. It can be observed in **Figure 5** that there is a linear relationship between biosolid degradation rate and biosolid carbon application rate for both coarse and fine soils.

Figure 5 and **Table 2** also identify eight of the 41 soils that were selected for a laboratory experiment using a soil respirator (21°C and 20% moisture content). The fields were selected strategically from the 41 fields to represent different mineral surface areas.

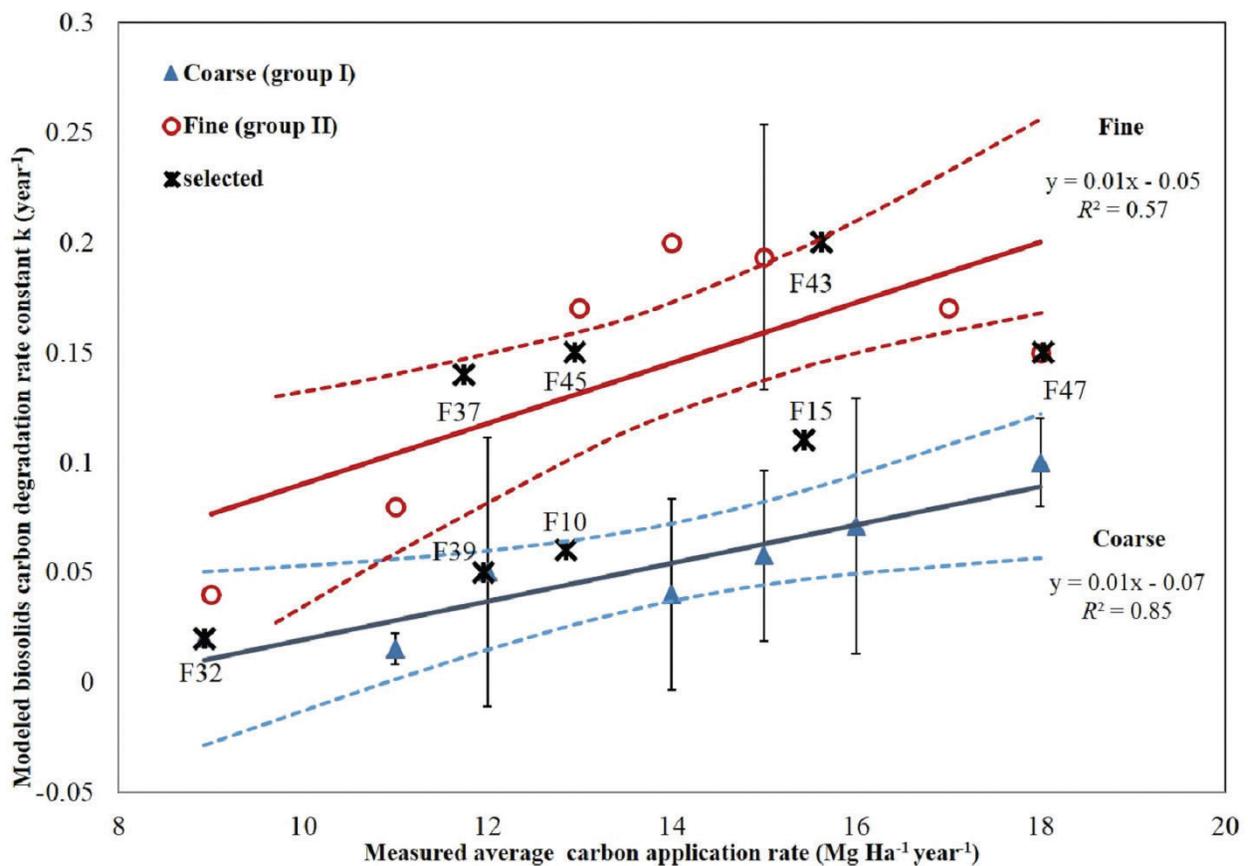


Figure 5. Biosolids degradation rate as a function of average annual carbon application rate separated into coarse and fine soil types (group I and II). Also, identified are the eight soil samples used in this study with 95% confidence interval shown for each soil group.

The DRM was used to determine rates of C sequestration for the eight soils based on Eqs. (2)–(7) (see **Figure 6**). There was a marked increase in the ratio of C sequestered to C application rate up to the year 1985 due to accumulation of the C from the conversion of biosolids to new biomass [15]. Beyond 2025, the ratio of C sequestration to C application rate shows the almost same trend as indicated in **Figure 6**. In the short term, lower biosolid degradation rates result in less microbial production and produce a smaller increase in C sequestration [15], i.e., F32. In the long term, the total amount of biosolid application determined the amount of sequestered C since all of the applied biosolids may undergo degradation. Under aerobic conditions, it may take a long time, i.e., 20–100 years, to sequester 35–40% biosolid C based on known degradation rate k (0.20 and 0.02 yr^{-1}) with 95% biosolid conversion (see **Table 2** and **Figure 6**) [15].

3.2. Relationship between measured soil surface area and DRM-simulated degradation rate

Table 2 provides a summary of the information used in this study. The table identified the 27 soils evaluated in this study (field numbers) that were selected from the 41 field samples

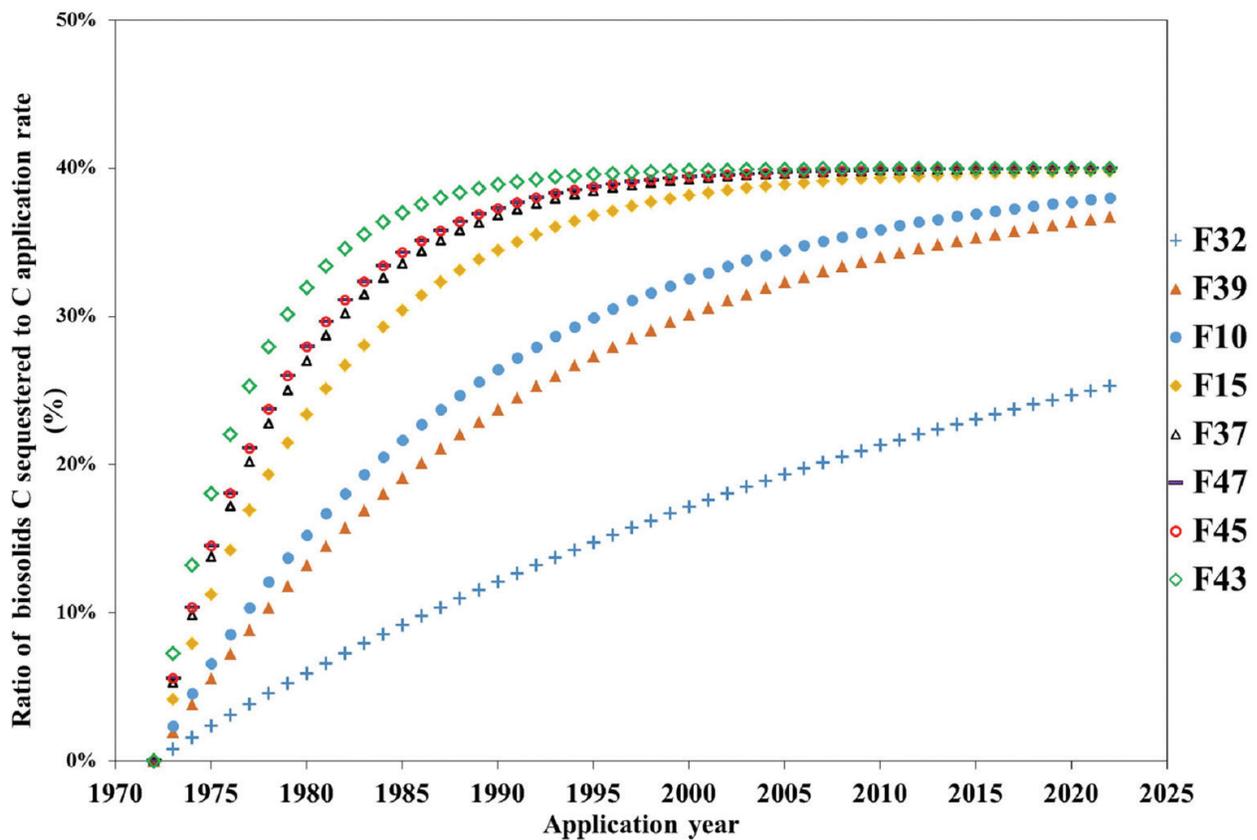


Figure 6. Percent of biosolids converted to biomass (carbon sequestration) between 1972 and 2025 for the eight fields. The variation between fields is due to difference in the degradation rate (see **Table 1**).

in the [5] database. The table also identifies the eight soils evaluated in the laboratory soil respirator experiment and three soils from Terry’s laboratory study [21]. The table provides (1) the experiment conditions (temperature, moisture content, annual carbon application rate), (2) the degradation rate calculated with the DRM model for field samples and measured for the laboratory studies, and (3) the surface area and soil texture for each soil.

Figure 7 provides the relationship between the total mineral soil surface area and the DRM-simulated degradation rate for the 27 fields in **Table 2**. The figure indicates that the degradation rate increased when there was an increase in the total surface area. The degradation rate varied from 0.01 to 0.30 yr⁻¹ when the soil total surface area varied from 1.1 to 10.1 m²/g of soil. A multiple linear regression analysis was conducted between the degradation rate for the 27 soils and the variables of total mineral soil surface area and the annual biosolid application rate. The analysis performed by SPSS (version 22.0, 2015) indicates that the total mineral soil surface area is a significant indicator of degradation rate with a high coefficient of determination ($R^2 = 0.87$), but annual application rate is not statistically significant ($p = 0.34 > 0.05$). The equation for the relationship between soil surface area and degradation rate (average-field environmental conditions of 10°C and 10% moisture) is:

$$y = 0.02x + 0.01 \tag{10}$$

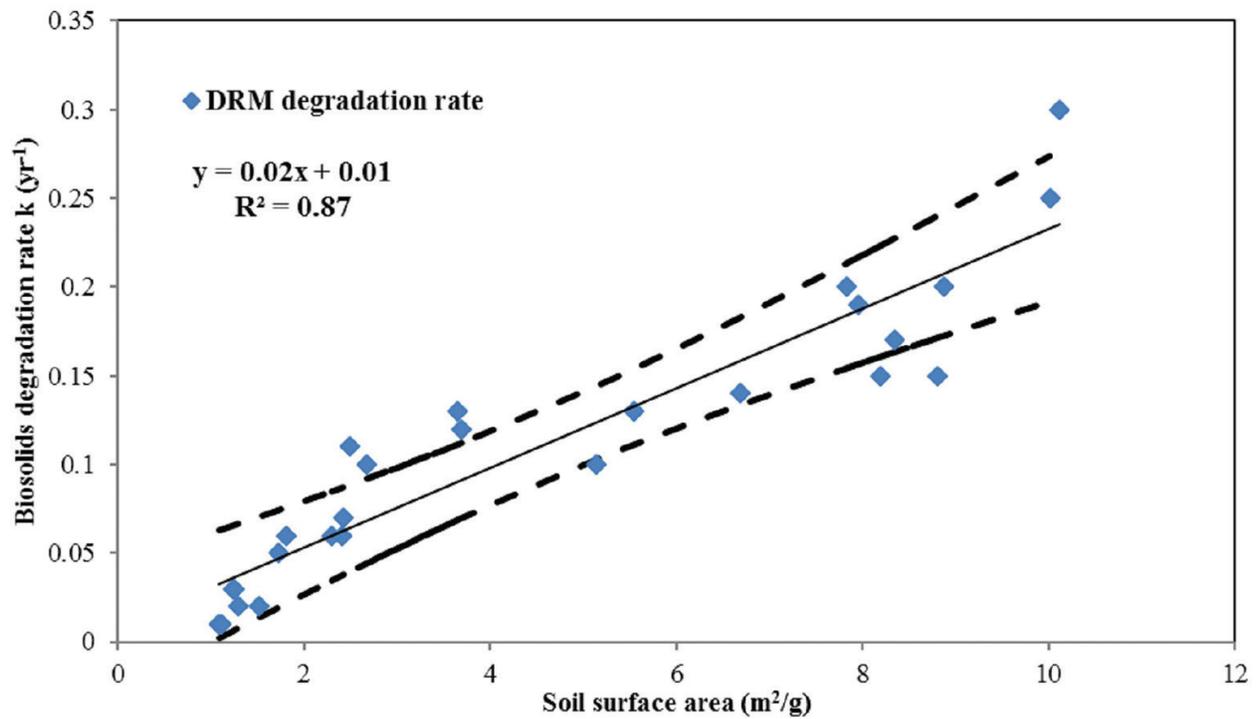


Figure 7. Biosolids degradation rate as a function of surface area for total of 27 soils from different fields with 95% confidence interval.

where:

y = the degradation rate (yr^{-1});

x = the total mineral soil surface area (m^2/g).

Soil texture and mineral surface area (**Table 2**) are closely related with higher mineral soil surface area associated with finer soil texture. Additionally, many studies have demonstrated that decomposition rates are related to soil texture [25, 26]. However, soil texture represents a range of soil surface areas, and therefore surface area provides a more definitive parameter to relate to organic degradation rates in soil.

Historically soils with a finer texture have been associated with a higher retention of applied biomass (carbon sequestration) [27]. Application of the DRM model demonstrates that higher degradation rates are associated with higher long-term sequestration rates and also with larger soil surface areas. [15]. And that soil surface area represents a more definitive parameter to relate to organic degradation rates in soil than soil texture.

3.3. Laboratory biosolid degradation rates

Figure 8 and **Table 2** provide the laboratory biosolid C degradation rates (incubated at 21°C and 20% moisture) determined from the yearlong soil respirator experiment for the eight soil samples based on first-order kinetics. The slopes of the regression lines in **Figure 8** represent the average first-order degradation rate for the biosolids in the soil (from Eq. (1) where

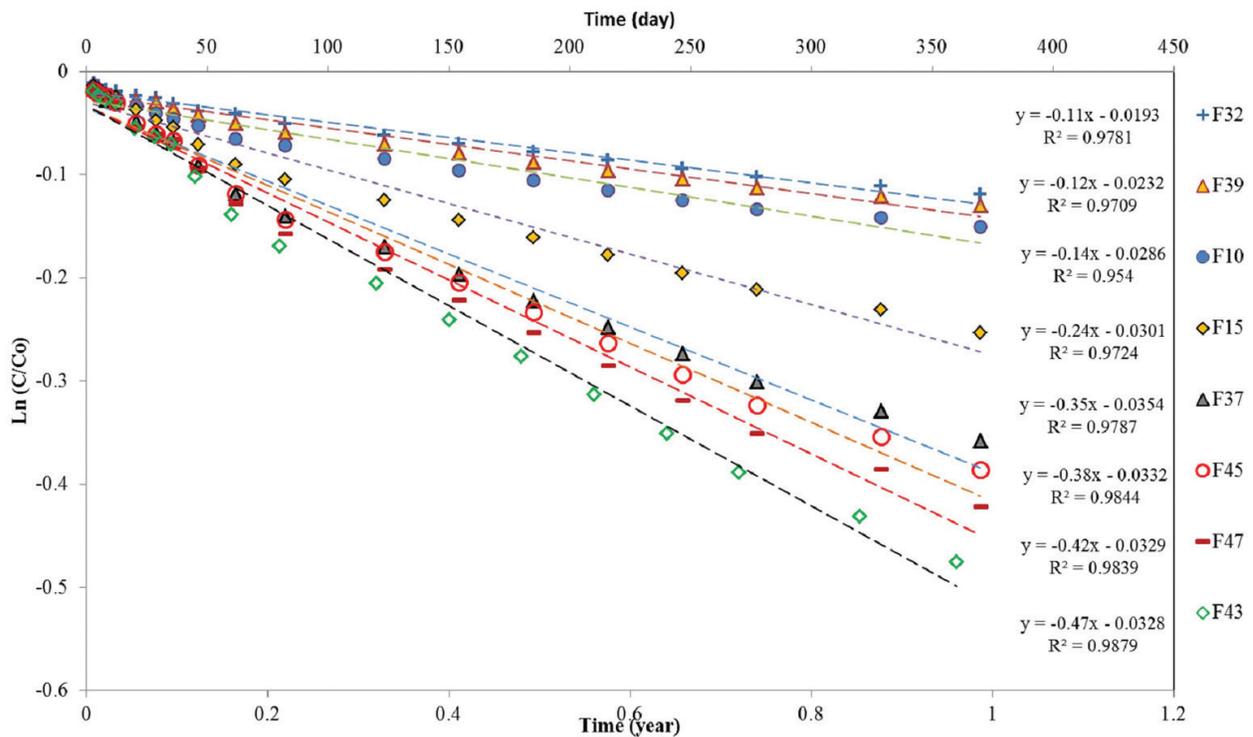


Figure 8. Variation in laboratory degradation rate (yr^{-1} , slope of trend line) for eight soil samples based on first-order kinetics ($\ln(C/C_0) = -kt$).

$\ln(C/C_0) = -Kt$. The difference between biosolid carbon remaining and the original biosolid organic carbon (C/C_0) was determined by measuring evolved CO_2 concentration once per week during the incubation period. CO_2 evolution is an indication of biological decomposition and is used as an index of biosolid C degradation [28, 29]. At the end of 360 days of incubation, between 11 and 40% of the original biosolid organic carbon was evolved as CO_2 from the eight soil samples. The variation in the slopes for the eight soils is due to differences in the soil surface area as shown in **Table 2**. Soils with more surface area had higher degradation rates and therefore larger slopes.

Analyses of DRM simulation results for the eight fields indicate that the field degradation rates for the eight fields varied between 0.02 and 0.20 yr^{-1} and were much lower than the laboratory degradation rates that varied between 0.11 and 0.47 yr^{-1} (**Table 2**).

Figure 9 and **Table 2** provide the laboratory degradation rates determined for the biosolids added to the three soils from Terry et al. [21]. The biosolid degradation rate varied from 0.19 to 0.35 yr^{-1} . The data are for synthetic biosolids incubated from 28 to 336 days at 21°C and 20% moisture. The synthetic sludge applied to Terry's experiment was in the liquid phase with volatile solids similar to biosolids applied to 41 fields in Illinois. The synthetic biosolids had an organic carbon percent (22.3%) similar to biosolids used in this study (23.2%) [5]. Decomposition of the biosolids was initially very rapid with 54–63% of the total C in the biosolids removed during the first 28 days followed by a slow decomposition for the period from 28 to 336 days. This is because fresh biosolids were applied that had

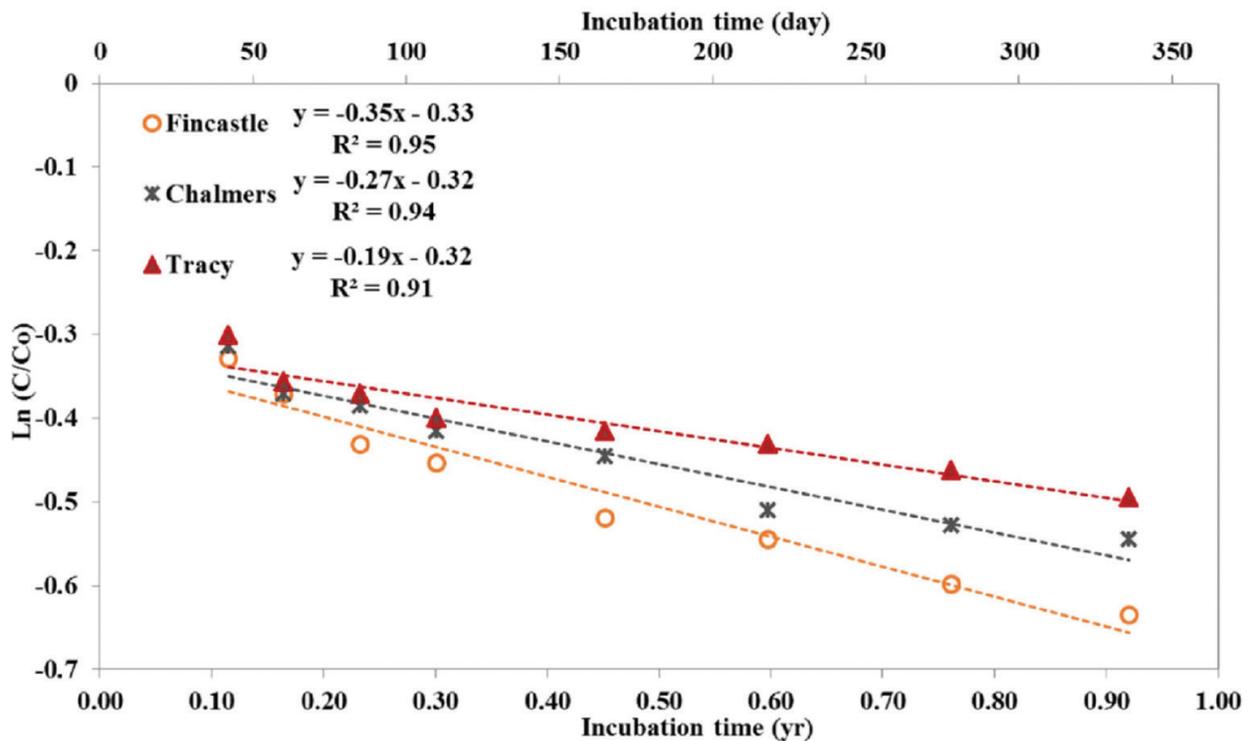


Figure 9. Variation in degradation rate (yr^{-1} , slope of trend line) for three soils based on first-order kinetics ($\ln(C/C_0) = -kt$) and Terry et.al [21] laboratory decomposition data (incubated for 28–336 days at a temperature of 21°C and moisture content of 20%).

not undergone short-term volatile losses. For the eight soil samples used in our laboratory study, it is assumed that the rapid fraction was consumed before 1985 and there was no rapid degradation phase [30].

Figure 10 compares the soil surface area and degradation rates for the field and laboratory studies. The annual average-field environmental conditions were estimated to be 10°C and 10% moisture content [5], and the laboratory conditions were 21°C and 20% moisture content. **Figure 10** indicates that degradation rates for the 27 fields varied between 0.02 and 0.30 yr^{-1} and were much lower than the laboratory degradation rates that varied between 0.11 and 0.47 yr^{-1} . The decomposition of biosolids at the field site with environmental conditions of 10°C and 10% moisture content is calculated to be only 37% of that under laboratory conditions of 20°C and 20% moisture content.

3.4. C sequestration

Figure 11 shows the relationship between increased annual percentage of applied biosolids that can be sequestered and total mineral soil surface area. The DRM was applied to estimate biomass C sequestered in the soil and gases C emitted to the atmosphere based on mass balance described in Eq. (1). The annual percentage of biosolids converted to biomass is determined then. Eqs. (4)–(6) were used to determine the C sequestration values with assumed 40% biomass yield. Eq. (9) was applied to estimate the total mineral soil surface area for different

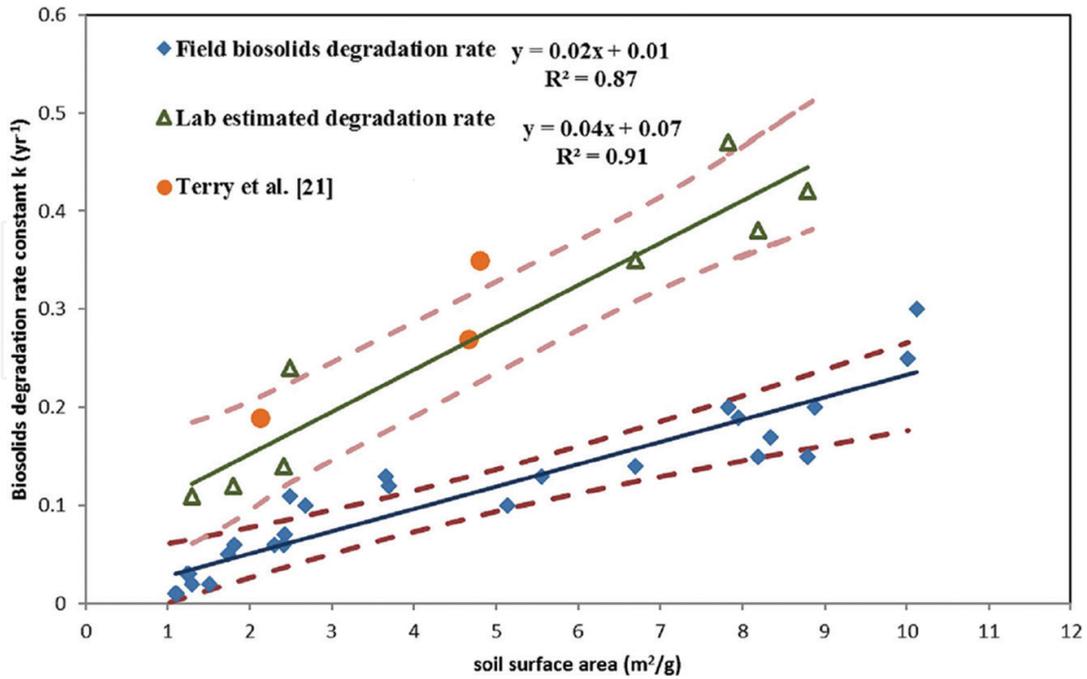


Figure 10. A comparison of field modeled (10°C and 10% moisture content) and laboratory measured biosolids (21°C and 20% moisture content) degradation rates for different fields with 95% confidence interval as a function of soil surface area.

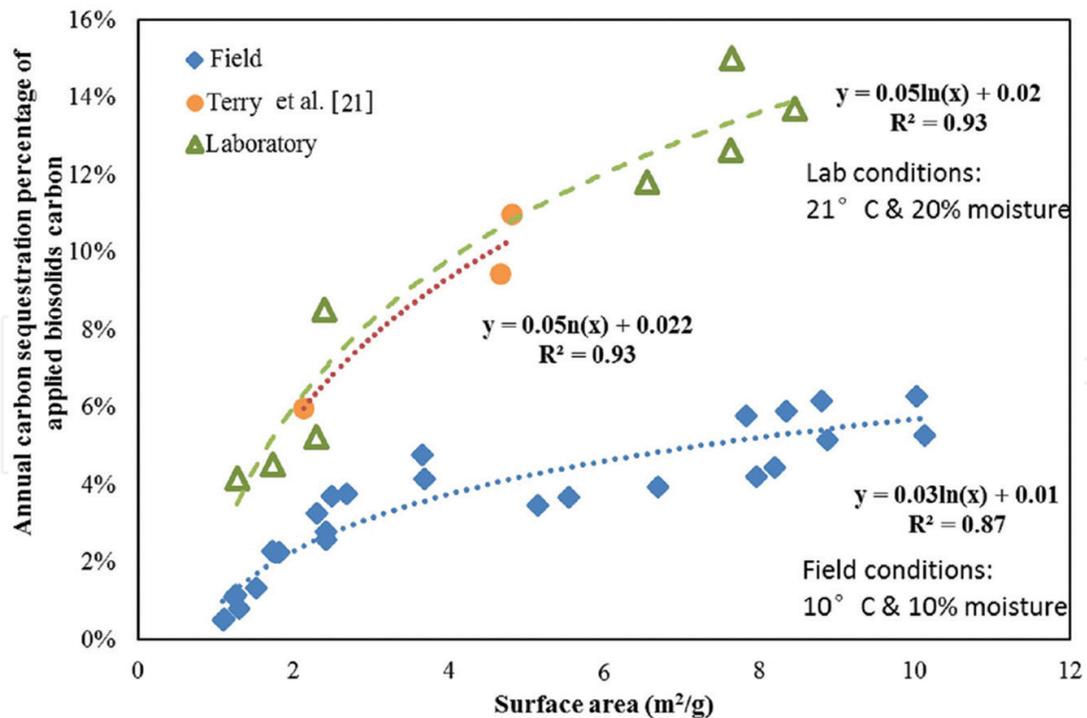


Figure 11. Annual percentages of applied biosolids converted to sequestered carbon as a function of mineral soil surface area of 27 soil samples for field (10°C and 10% moisture) and 11 laboratory soil sample (21°C and 20% moisture) conditions. Sequestered % is based on first-order kinetics and a biomass yield of 40%.

degradation rates [15]. The sequestration rates for Terry et al. [21] soils were computed by using degradation rates determined from **Figure 8** and for the eight fields from **Figure 9**. For Terry's [21] soils the increase in total surface area was 2.7 m²/g and produced an increase in the annual sequestration rate from 6 to 11%. For the eight soil samples, the increase in total surface area was 7.2 m²/g and produced an annual increase sequestration rate between 4 and 14%. For the soils from the 27 fields, the increase in total surface area was 9.9 m²/g and this produced an increase in the annual sequestration rate from 1 to 6%. Applying biosolids is much more effective in enhancing C sequestration than other agriculture methods such as applying animal manure or plant materials [31, 32].

4. Conclusion

Applying biosolids to soils with fine texture contributes to the reduction of GHG more effectively than applying to coarser soils. Importantly, the present study indicated that land application of biosolids is an appropriate way to enhance C sequestration in soils and contribute to the reduction of greenhouse gas emissions and that soil total surface area as well as temperature and moisture affect the rate of biosolid degradation and the rate of C sequestration.

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