Topsoil placement effect on soil carbon stock improvement of exposed subsoil in Iowa

J.B. Grote and M.M. Al-Kaisi

Abstract: Management of exposed subsoil after removing the topsoil for road construction presents a soil management challenge and an opportunity to examine potential techniques for improving soil carbon stocks. It is well documented that the construction of roadbeds leaves behind large areas of unproductive exposed subsoil, which is low in soil organic carbon content. The objective of this study was to determine whether a topsoil addition with a corn (*Zea mays*)–soybean (*Glycine max* L. Merr.) annual rotation could improve soil carbon in areas that have had topsoil removed. The experimental design was a randomized complete block with three replications. Soil organic carbon fractions, potential C inputs from crop residues, soil CO_2 emission, and microbial biomass carbon of topsoil and exposed subsoil treatments managed under a corn-soybean rotation were measured during the growing seasons of 2003 and 2004. Soil temperature and soil moisture at the 5 cm depth were also measured concurrently with soil CO_2 emission readings. The aboveground biomass production and root biomass of corn grown in topsoil was 7.14 Mg ha^{-1} and 0.8 Mg ha^{-1} (3.18 ton ac^{-1} and 0.40 ton ac^{-1}) more than corn grown in the subsoil, respectively. This led to greater potential C inputs from corn grown in topsoil. The improvement in soil organic carbon in the subsoil 0 to 60 cm (0 to 24 in) soil depth with corn and soybean crops over the past 28 years averaged at 0.70 Mg ha^{-1} yr^{-1} (0.31 ton ac^{-1}). In contrast, topsoil replacement treatments had greater SOC contents than exposed subsoil, including the 30 to 45 cm (12 to 18 in) soil depth, which is below any added topsoil but within the tillage zone. These findings suggest that topsoil addition can improve exposed subsoil soil-carbon stocks and its crop productivity. It was also observed that microbial biomass carbon contents were 247 and 157 μg g^{-1} (247 and 157 parts per million) for topsoil and subsoil, respectively. Also, cumulative CO_2 emissions from topsoil were 45% and 47% greater than those from subsoil in 2003 and 2004, respectively.

Key words: carbon dioxide—microbial biomass carbon—particulate organic matter carbon—soil organic carbon—subsoil—topsoil

The exposure of subsoil as a result of roadbed construction presents a challenge and an opportunity to examine potential solutions for improving soil-carbon stocks. The removal of topsoil results in major depletion of the soil organic carbon (SOC) pool (Lal et al. 1998). Carbon sequestration in these greatly disturbed, low SOC content areas could restore soil productivity and other soil quality measurements (Lal 2004). Many investigators have documented carbon sequestration in topsoil, but relatively little work has focused on the potential of exposed subsoil as a carbon sink.

Subsoil is a poor medium for plant growth caused by increased clay content and lack of nutrient availability (Gollany et al. 1992). However, the productivity of subsoil can be increased over time through proper management (Eck 1987). Intensive fertility programs including micronutrients can improve the productivity of subsoil, but fertilizer alone cannot replace the benefits of topsoil (Mielke and Schepers 1986; Olson 1977). Khalaf (1984) found that row crops grown in subsoil of this research site produced less biomass and grain yield than row crops grown in topsoil. In addition to poor fertility, the high bulk density of subsoil is not conducive to plants establishing an extensive root system. Extensive root biomass is a critical component of soil carbon input because of its role in the formation of stable macroaggregates and particulate organic matter carbon (POMC), which is a sensitive indicator of SOC change and soil quality (Cambardella and Elliot 1992; Chan et al. 2002; Gale et al. 2000).

Soil CO_2 emissions from topsoil and subsoil can be used as an indicator for improving soil health and microbial biomass. Lomander et al. (1998) found soil CO_2 emissions were as much as four to five fold greater from topsoil than subsoil in a controlled laboratory soil incubation study. However, Bajracharya et al. (2000a, 2000b) found greater soil CO_2 emission rates from topsoil compared with subsoil only during times of peak air and soil temperatures.

Factors that govern biological activities in the soil such as soil temperature and moisture availability influence CO_2 emission rates (Carlyle and Than 1988). It is generally recognized that soil CO_2 emissions are positively correlated with soil temperature, but a relationship with soil moisture is not well understood. Kowalenko et al. (1978) found increasing soil moisture levels decreased soil CO_2 emissions; whereas Lomander (1998) found increasing CO_2 emission rates with increasing soil moisture content. In contrast, Bajracharya et al. (2000b) concluded that soil moisture had no effect on soil CO_2 emission, and Wilson and Griffin (1975) concluded that soil moisture only affected soil CO_2 emission during periods of extreme dry or extreme wet conditions.

Microbial biomass carbon (MBC) is an important component of the SOC pool and may be an early indicator of SOC improvement or increase (Powlson and Brookes 1987). However, the MBC pool is highly variable and difficult to quantify (Hargreaves et al. 2003). The size of the MBC pool can influence rates of soil CO_2 emission (Franzluebbers et al. 1996), but the amount of available organic substrate will ultimately determine the size of the microbial biomass pool (Wang et al. 2003). Limited substrate availability, poor aeration status, and increased clay content can result in low carbon mineralization rates in subsoil

Jesse B. Grote is a former graduate student and Mahdi M. Al-Kaisi is an associate professor in the Department of Agronomy at Iowa State University in Ames, Iowa.

Reprinted from the *Journal of Soil and Water Conservation*, Volume 62, Number 2.

Table 1
Soil pH, soil organic carbon, and soil bulk density of three topsoil depth treatments in the 0 to 60 cm soil profile in 2003.

	pH				Soil organic carbon (g kg^{-1})				Bulk density (g cm^{-3})			
Soil depth (cm)	0 to 15	15 to 30	30 to 45	45 to 60	0 to 15	15 to 30	30 to 45	45 to 60	0 to 15	15 to 30	30 to 45	45 to 60
0 cm topsoil	7.67	7.57	7.58	7.54	1.97	0.67	0.30	0.67	1.46	1.66	1.70	1.74
15 cm topsoil	7.49	7.38	7.43	7.47	20.15	19.00	9.50	6.78	1.27	1.50	1.71	1.74
30 cm topsoil	7.44	7.18	7.37	7.51	23.66	21.17	11.00	5.11	1.22	1.39	1.59	1.74

(Lomander et al. 1998; Wang et al. 2003).

Topsoil addition is a common reclamation practice used in areas where topsoil has been removed for road construction. The overall objective of this study was to determine whether a topsoil addition can improve corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) productivity and soil carbon stocks of exposed subsoil by evaluating crop residue carbon input, SOC fractions, and soil carbon pool improvement indicators such as, soil CO_2-C emission and soil MBC.

Methods and Materials

Site Description and Management. This study was conducted on a borrow site near Webster City, Iowa, during the growing seasons of 2003 and 2004. In 1978, a research experiment was established on a borrow site where topsoil had been removed and subsoil had been mined for construction purposes in Hamilton County near Webster City, Iowa. The predominant soil on this site was a Nicollet loam (Aquic Hapludolls) with a Clarion loam (Typic Hapludolls) on the hillsides. The topsoil was removed from this 2.43 ha (6 ac) site in 1977 for road construction purposes. The exposed subsoil was a calcareous, un-weathered, and un-oxidized glacial till of Cary age (Khalaf 1984). The soil particle size analysis of the topsoil of this site was 31%, 32%, and 37% of clay, silt, and sand, respectively. The soil particle size analysis of the subsoil of this site was 23%, 35%, and 42%, respectively (Potter 1980). In 1978, a portion of the area was converted to a research site, and three treatments were applied by placing different depths of topsoil over the exposed subsoil. The treatments were (1) exposed subsoil, (2) 15 cm (6 in) topsoil, and (3) 30 cm (12 in) topsoil. The experimental design was a randomized complete block with three replications. Each plot was 9 m wide by 9 m long (30 ft wide and 30 ft long). Corn and soybeans were rotated annually on the site. The 2003 SOC, bulk densities, and soil pH of the three topsoil depth treatments are summarized in table 1. The initial soil properties for subsoil cited in table 1 were collected from a non-cropped area adjacent to the research plots. These data were collected as a baseline.

The site was tilled each fall since 1978 to a depth of 40 cm (16 in) with a two-shank deep ripper. The deep ripper shanks were spaced 45 cm (18 in) apart. In the spring, the field was disked once at a depth of 7 cm (3 in) for seedbed preparation. In 2003, the site was planted with corn using Pioneer 35P17 corn hybrid on May 20, day of year (DOY) 140, at 45,724 seeds ha^{-1} (18,512 seed ac^{-1}) on 76 cm (30 in) row spacing. Weed control consisted of one application of 2,4-D amine at a rate of 2.33 L ha^{-1} (0.25 gal ac^{-1}), followed by cultivation. In 2004, the site was planted with soybean using Pioneer 92B38 soybeans hybrid on July 1 (DOY 182) at 450,000 seeds ha^{-1} (182,186 seed ac^{-1}) on 76 cm (30 in) row spacing.

The fertility use on this research site since 1978 was conducted by applying 112 kg ha^{-1} (100 lb ac^{-1}) of each P and K initially. Soil test for P and K contents was conducted every other year since 1978. The soil P and K test of both top and subsoil showed high levels of P and K of an overall average of 49 and 192 mg kg^{-1} (49 and 192 ppm), respectively (Henning 2006). Therefore, no P or K was applied during either corn or soybean year in 2003 and 2004. In 2003, corn plots on this research site received approximately 170 kg N ha^{-1} (150 lb ac^{-1}). Historically, N was applied to corn since 1978 on an average of 170 kg N ha^{-1} (150 lb ac^{-1}) on all plots (Potter 1980; Khalaf 1984; and (Henning 2006). Weed control consisted of row cultivation and chemical herbicides, one application of Glyphosate at a rate of 2.32 L ha^{-1} (0.25 gal ac^{-1}) in 2003 and 2004.

Soil Organic Carbon and Soil Total Nitrogen Determination. Prior to planting in 2003 and 2004, soil samples were collected from all of the topsoil depth treatments at depth increments of 0 to 15, 15 to 30, 30 to 45, and 45 to 60 cm (0 to 6, 6 to 12, 12 to 18, and 18 to 24 in). A composite soil sample consisting of 10 cores was taken for each depth from each plot using a soil probe with an inner diameter of 1.9 cm (0.75 in). Soil samples were placed in a -4°C (25°F) freezer until analysis was preformed. Soil samples for bulk density determination were taken at the same time and depth increments according to the procedure outlined in Doran and Mielke (1984). Prior to conducting soil C analysis, the soil samples were defrosted, passed through a 2 mm sieve, and allowed to air dry. Two 10 g soil sub-samples were weighed out from each soil sample. The first soil sub-sample was ground with a mortar and pestle and analyzed for SOC and soil total nitrogen (STN) content by dry combustion using a LECO CHN 2000 analyzer (LECO Corporation, St. Joseph, Michigan). The second soil sub-sample was used in the POMC fractionation procedure (Cambardella and Elliot 1992; Kruse 2005). The soil sub-sample was dispersed with sodium metaphosphate and then passed through a 53 μm sieve. The water was evaporated from the slurry that passed through the sieve by placing it in a forced air oven at 50°C (122°F) for 72 hours. The dried soil slurry was ground and analyzed for associated mineral fraction carbon (MFC) organic carbon content using dry combustion with the LECO CHN 2000 analyzer. POMC was calculated by subtracting MFC content from SOC content.

Soil pH was determined using a 1:1 (soil/water) dilution. If soil pH was greater than 7.1, inorganic carbon concentration was determined using a modified pressure calcimeter method (Sherrod et al. 2002) and subtracted from the total carbon content values determined initially by dry combustion with the LECO CHN 2000 analyzer. The C content of each fraction was calculated on an equivalent soil mass by using the bulk density.

Field Soil CO_2 Emission Measurements. The exposed subsoil and 30 cm (12 in) topsoil treatments were selected to measure soil CO_2 emissions from corn and soybean plots in 2003 and 2004, respectively. Carbon dioxide emissions from the soil surface were measured by placing the soil chamber of a LI-6400 infrared gas analyzer (LI-COR Corporation, Lincoln, Nebraska) over polyvinyl chloride (PVC) rings that were pressed

Table 2
Total carbon and total nitrogen inputs from aboveground and root biomasses of corn and soybeans grown in 30 cm topsoil and exposed subsoil.

		Aboveground				Root				Root + aboveground	
			Input				Input			Total inputs	
Crop	Soil	Crop biomass (Mg ha^{-1})	TC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N	Crop biomass (Mg ha^{-1})	TC (Mg ha^{-1})	TN (Mg ha^{-1})	C:N	TC (Mg ha^{-1})	TN (Mg ha^{-1})
Corn	Subsoil	4.37a*	1.83a	0.17a	99.7a	1.33a	0.49a	0.05a	93.1a	2.32a	0.22a
	Topsoil	11.51b	4.93b	0.42b	116.7b	2.13b	0.59b	0.09a	62.1b	5.52b	0.51a
Soybean	Subsoil	3.23a	1.40a	0.62a	22.6a	0.76	0.29	0.13	21.8	1.69	0.75
	Topsoil	3.98a	1.74a	0.76a	23.1a	—	—	—	—	—	—

Notes: Root biomass was measured to 30 cm. Potential TC and TN inputs and carbon to nitrogen ratios were calculated using the C and N concentrations of the respective biomass in 2003 and 2004. TC = total carbon; TN = total nitrogen; C:N = carbon to nitrogen ratio.

*Means with the same letter within each crop are not different at $P \leq 0.05$.

3 cm (1.18 in) into the soil. The PVC rings had an inside diameter of 10 cm (4 in), and 2 cm (0.8 in) of the rings remained above the soil surface. Four PVC rings were placed near the center of each plot. Two rings were placed in the crop row and two were placed between the rows. The mean of the four rings was considered to be the reading for the entire plot. The soil CO_2 measurements were taken approximately every 7 to 14 days from June 5 to October 29 in 2003 (DOY 156 to 302) and from July 6 to November 5 in 2004 (DOY 187 to 309), between the hours of 10:00 am and 2:00 pm. No CO_2 measurements were taken for 48 hours following the row cultivation in 2003. Soil temperature and soil moisture at the 5 cm (2 in) depth were measured concurrently with CO_2 measurements. Soil temperature was measured with a thermometer attached to the LI-6400, and volumetric soil moisture was measured with a TRIME-FM Time Domain Reflectometry device (Mesa Corp., Medfield, Massachusetts). Cumulative CO_2 emissions for the growing season were calculated as follows:

$$\text{Cumulative } CO_2 \text{ (kg ha}^{-1}) = \sum_{i}^{n} \frac{(X_i + X_{i+1})}{2} * (t_{i+1} - t_i) \quad (1)$$

where X_i is the first week CO_2 reading and X_{i+1} is the following week CO_2 reading at times t_i and t_{i+1}, respectively; n is the final week of CO_2 measurement events during the study period.

Cumulative soil CO_2 emissions were then converted to Mg ha^{-1} of CO_2-C.

Soil Microbial Biomass Carbon. Samples for soil MBC determination were taken in 2004 when the soybean crop reached V6 development stage. The same treatments being used for soil CO_2 measurements were used for this experiment. A composite soil sample of ten soil cores was taken from each plot at a depth of 15 cm (6 in). The soil samples were brought back to the laboratory, passed through a 4 mm (0.16 in) sieve, and stored in a 4°C (39°F) cold room overnight. Soil MBC was determined by performing the fumigation extraction method (Horwath and Paul 1994). Fifty-gram moist soil samples were fumigated with ethanol-free $CHCl_3$ for 24 hours in a vacuum desiccator. The soil samples were extracted for 30 minutes with 100 ml of 0.5 M K_2SO_4 and then filtered through Whatman No. 42 filter paper (Whatman International Ltd., Maidstone, UK). Nonfumigated samples were extracted the same way while the others were being set up for fumigation. Extractant alone was also filtered in order to determine the background level of C in the filter paper and extractant. Carbon recovered in the extract was determined with a Shimadzu TOC-5050 carbon analyzer (Rydalmere, New South Wales, Australia). MBC was calculated on an oven-dry soil weight basis.

Laboratory Soil Incubation. The remainder of soil from the samples collected for microbial biomass analysis was used for laboratory soil incubation. A static incubation-titrimetric procedure (Zibliske 1994) was used for this experiment. The soil samples were taken out of the cold room, passed through a 2 mm sieve, and allowed to air dry. Twenty grams of each soil sample was weighed into 20 ml borosilicate vials. Approximately seven grams of water was added to the vials to achieve 60% water-filled pore space. Each vial with soil was placed into a 0.9 L wide-mouth glass jar along with a 10 ml scintillation vial containing 1.0 ml of 2 N NaOH as a base trap. Approximately 3 to 5 ml of water was added in the bottom of the glass jars in order to maintain humidity levels. The lids of the glass jars were completely sealed to isolate

Table 3
Effects of topsoil depth on soil organic carbon, associated mineral fraction carbon, and particulate organic matter carbon content of the 60 cm soil profile in 2004.

	SOC (Mg ha^{-1})				MFC (Mg ha^{-1})				POMC (Mg ha^{-1})			
Soil depth (cm)	0 to 15	15 to 30	30 to 45	45 to 60	0 to 15	15 to 30	30 to 45	45 to 60	0 to 15	15 to 30	30 to 45	45 to 60
Control*	2.85	0.66	1.40	0.70	1.80	2.02	2.90	2.51	1.05	0.00	0.00	0.00
0 cm topsoil	20.56a†	18.76a	20.02a	20.34a	21.08a	19.17a	19.62a	18.87a	0.00a	0.00a	0.40a	1.47a
15 cm topsoil	39.81b	36.73b	28.45b	20.55a	32.24b	30.49b	26.85b	19.68a	7.57b	6.25b	1.60a	0.87a
30 cm topsoil	43.44b	46.10c	30.12b	18.56a	32.32b	39.85c	30.87c	19.97a	11.12b	6.25b	0.00a	0.00a

Note: SOC = soil organic carbon; MFC = mineral fraction carbon; POMC = particulate organic matter carbon.

*Initial SOC fractions prior to establishing crop rotation on subsoil. Soil samples were collected from noncropped area adjacent to the plots in 2003.

†Means with the same letter within each sample depth (column) are not different at $P \leq 0.05$.

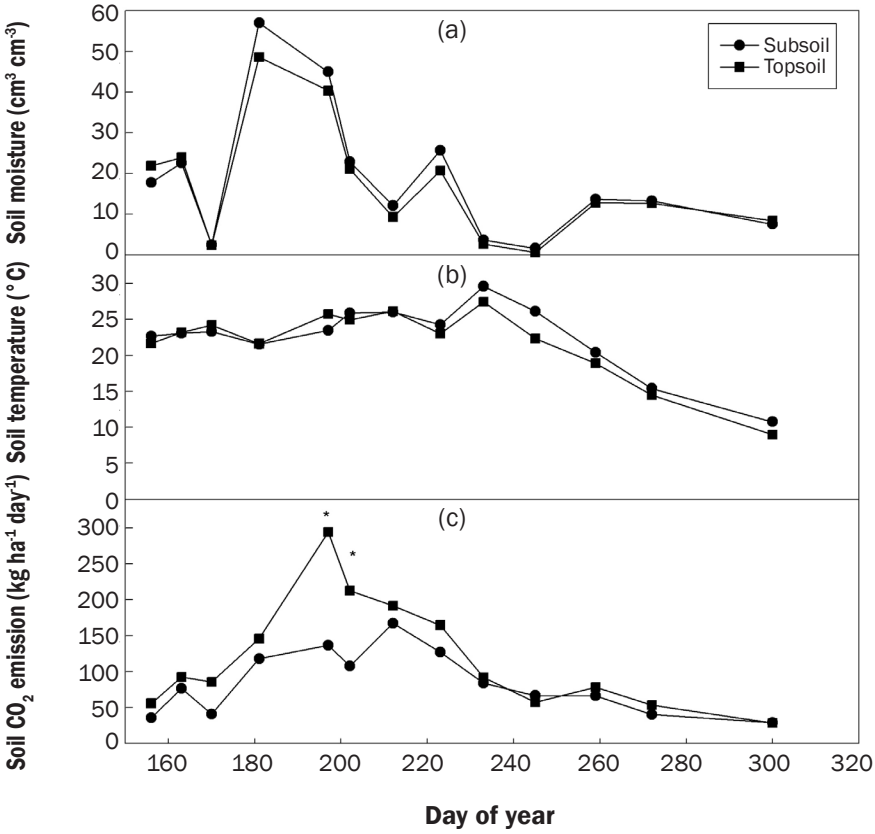
Table 4
Soil organic carbon and soil total nitrogren contents of three topsoil depth treatments in the 0 to 60 cm soil profile in 2004.

	SOC (Mg ha^{-1})				STN (Mg ha^{-1})			
Soil depth (cm)	0 to 15	15 to 30	30 to 45	45 to 60	0 to 15	15 to 30	30 to 45	45 to 60
0 cm topsoil	20.56a*	18.76a	20.02a	20.34a	3.20a	2.33a	2.20a	2.36a
15 cm topsoil	39.81b	36.73b	28.45b	20.55a	3.44a	2.74a	3.02a	2.28a
30 cm topsoil	43.44b	46.10c	30.12b	18.56a	3.95a	4.19a	3.69a	2.59a

Note: SOC = soil organic carbon; STN = soil total nitrogen.

*Means with the same letter within each sample depth (column) are not different at $P \leq 0.05$.

Figure 1
(a) Soil moisture, (b) soil temperature, and (c) CO_2 emission rate measured in topsoil and exposed subsoil planted to corn in 2003.



Note: Soil temperature and soil moisture were measured at the 5 cm depth.

*Dates where subsoil and topsoil CO_2 emission rates were different at $P \leq 0.05$.

the contents from the outside atmosphere. Three controls (blank) jars were also set up by placing a base trap in a jar that contained no soil. All of the glass jars were then placed in a dark incubation room at 30°C (86°F). The amount of CO_2-C evolved was determined by titration. Two ml of 1 M BaCl and 2 to 3 drops of phenolphthalein were added to the base traps. One N HCl was then added with a digital microburette until the indicator showed neutral pH. After titration, a new base trap was added to each jar. Titrations were performed on days 1, 3, 5, 7, 14, 21, 28, 35, 42, 49, 56, 63, and 77. The amount of CO_2-C evolved during the soil incubation was calculated based on air-dry soil weight.

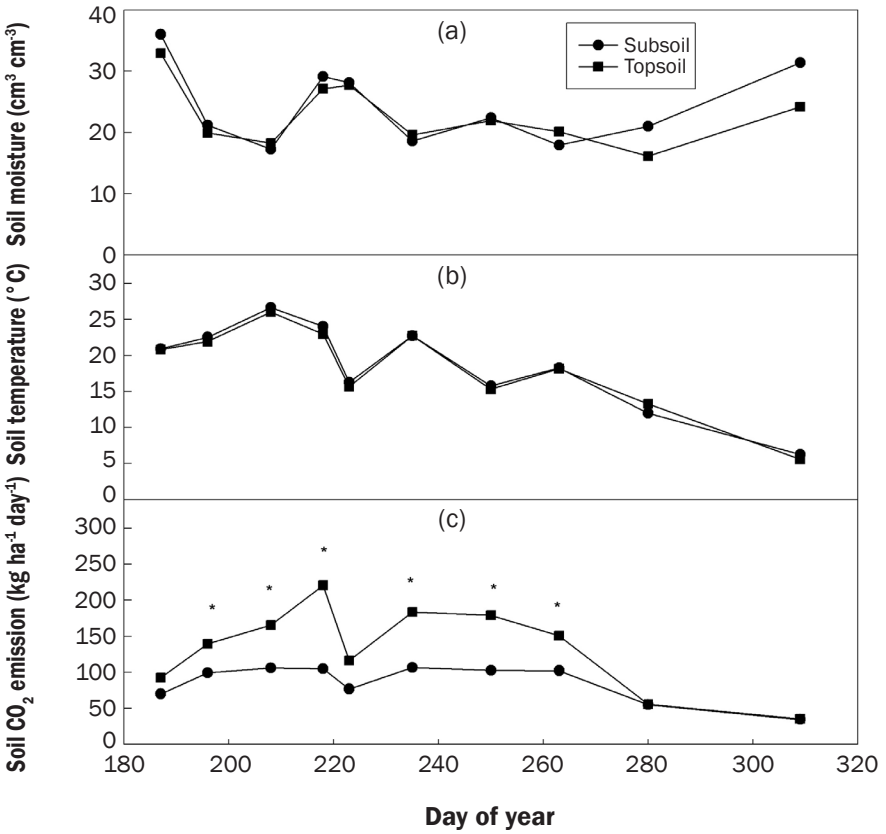
Soil inorganic N (NO_3-N and NH_4-N) concentration was determined prior to and after the incubation period using the KCl extraction method (Mulvaney 1996). Ten grams of soil was extracted with 50 ml of 2 M KCl for 30 min. The supernatant was then filtered through Whatman number 42 filter paper. Inorganic N concentration of the filtrate was measured with a Lachat QuickChem 8000 FIA+ (Lachat Instruments, Milwaukee, Wisconsin).

Potential Total Carbon and Nitrogen Inputs from Crop Residue and Root Biomasses. Crop residue was collected each fall from the subsoil and 30 cm (12 in) topsoil treatments after mechanical harvest of the crop was completed. A one m^2 (10.8 ft^2) frame was randomly placed in the center of each plot, and the entire residue within the frame was collected and placed in mesh bags. Residue was dried at 64°C (147°F) for seven days, weighed, and then ground through a 2 mm (0.08 in) screen using a Wiley Mill Model 2 grinder (Arthur H. Thomas Co., Philadelphia, PA). Crop residue total C and N concentrations were determined by dry combustion with the LECO CHN 2000 analyzer and then multiplied by the biomass to determine potential C and N inputs.

Root biomass samples were collected from the subsoil and 30 cm (12 in) topsoil treatments in 2003 and 2004 when the crops reached R1 growth stage (Ritchie et al. 1986). Root samples from corn in 2003 were obtained by excavating all roots from the top 30 cm (12 in) of soil in a 1 m (3.28 ft) section of the crop row near the center of each plot. Corn roots were taken back to the laboratory and soaked in water for 24 hours. After soaking, they were rinsed of any excess soil. Corn roots were dried in a 64°C (147°F) forced air oven for seven days, weighed, ground with the Wiley Mill, and analyzed for total carbon (TC) and total nitrogen (TN) by dry combustion with the LECO CHN 2000 analyzer.

Corn root weight density in 2003 was calculated as follows:

Figure 2
(a) Soil moisture, (b) soil temperature, and (c) CO_2 emission rate measured in topsoil and exposed subsoil planted to soybeans in 2004.



Note: Soil temperature and soil moisture were measured at the 5 cm depth.
*Dates where subsoil and topsoil CO_2 emission rates were different at $P \leq 0.05$.

$$RWD = RDM / (RL * RW * D) \quad (2)$$

where RWD is root weight density (g cm^{-3}), RDM is root dry matter (g), RL is row length (cm), RW is row width (cm), and D is depth (cm).

Soil samples for soybean root biomass determination in 2004 were obtained by clipping the soybean plants at the soil surface and taking 6.3 cm (2.5 in) diameter soil cores in the row, 30 cm (12 in) deep from each plot. Soybean root samples were taken to the laboratory and stored in a -4°C (25°F) freezer until they were washed using a hydropneumatic elutriation system (Smucker et al. 1982). Soybean roots were dried in a 64°C (147°F) forced air oven for seven days, weighed, ground with the Wiley Mill, and analyzed for TC and TN by dry combustion with the LECO CHN 2000 analyzer. Soybean root weight density in 2004 was calculated as follows:

$$RWD = RDM / (\pi * CR^2 * D) \quad (3)$$

where CR is core radius (cm) and other terms are the same as in equation 2.

Corn and soybean root biomasses were calculated as follows:

$$RB = RWD * D * 100 \quad (4)$$

where RB is root biomass (Mg ha^{-1}), 100 is a conversion factor for area and mass, and other terms are the same as in equation 2.

The total C and total N concentrations determined by dry combustion with the LECO CHN 2000 analyzer were multiplied by the root biomasses to determine potential total C and total N inputs.

Statistical Analysis. All experiments were analyzed as randomized complete block design with three replications. Topsoil depths were treated as fixed factors and replications randomized. A mixed model procedure with repeated measures was used for the daily field soil CO_2 emission rate analysis of variance (SAS Inst. 2005). A compound symmetry covariance structure was used for the repeated measures. Regression analyses were used to test the effects of soil moisture and soil temperature on CO_2 emission rate. All other experiments were analyzed with the general linear models procedure of SAS. An alpha level of 0.05 was used for all comparisons.

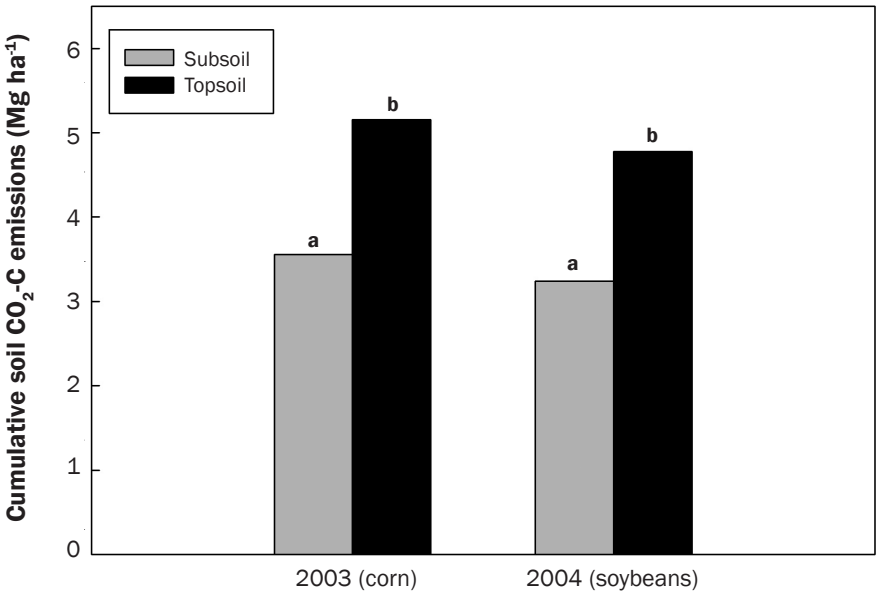
Results and Discussion

Field soil CO_2 emissions, microbial biomass, laboratory incubation, and potential plant TC and TN input experiments involved only the 30 cm (12 in) topsoil and exposed subsoil treatments. The two treatments will be referred to as topsoil and subsoil in presentation and discussion of results. The SOC and STN results will include the 15 cm (6 in) topsoil, 30 cm (12 in) topsoil, and exposed subsoil treatments.

Potential Carbon and Nitrogen Input from Aboveground and Root Biomasses. As expected, corn grown in topsoil produced 7.14 Mg ha^{-1} (3.18 ton ac^{-1}) more aboveground biomass and 0.8 Mg ha^{-1} (0.36 ton ac^{-1}) more root biomass than corn grown in the subsoil (table 2). Gollany et al. (1992) and Olson (1977) also found greater aboveground biomass production from corn grown in topsoil compared with corn grown in subsoil. The combined potential (aboveground + root) crop input of TC was 3.30 Mg ha^{-1} (1.47 ton ac^{-1}) greater from corn grown in topsoil compared with corn grown in subsoil (table 2). In contrast, potential TN inputs were negligible from either treatment. These results suggest that the addition of topsoil to exposed subsoil can contribute significantly to the improvement of SOC by improving crop productivity and potential TC input.

The extremely late planting of soybeans in 2004 prevented the crop from reaching maturity, and statistical analysis showed no difference in aboveground biomass production between the two treatments. However, in research conducted on this site, Khalaf (1984) found soybeans produced less biomass in subsoil compared with topsoil. These findings show that the potential for C and N input for improving SOC and organic N will be much greater with topsoil than from crops alone for improving SOC and TN over the past 28 years. The poor soil conditions of subsoil at the site (i.e., low organic-C con-

Figure 3
Cumulative soil CO_2-C emissions from topsoil and exposed subsoil planted to a corn-soybean rotation during the growing seasons of 2003 and 2004.



Note: Means with the same letter within each year are not different at $P \leq 0.05$.

tent, high pH [Pope 1989], poor soil water infiltration [data not presented], and high bulk density [table 1]) contributed significantly to low productivity.

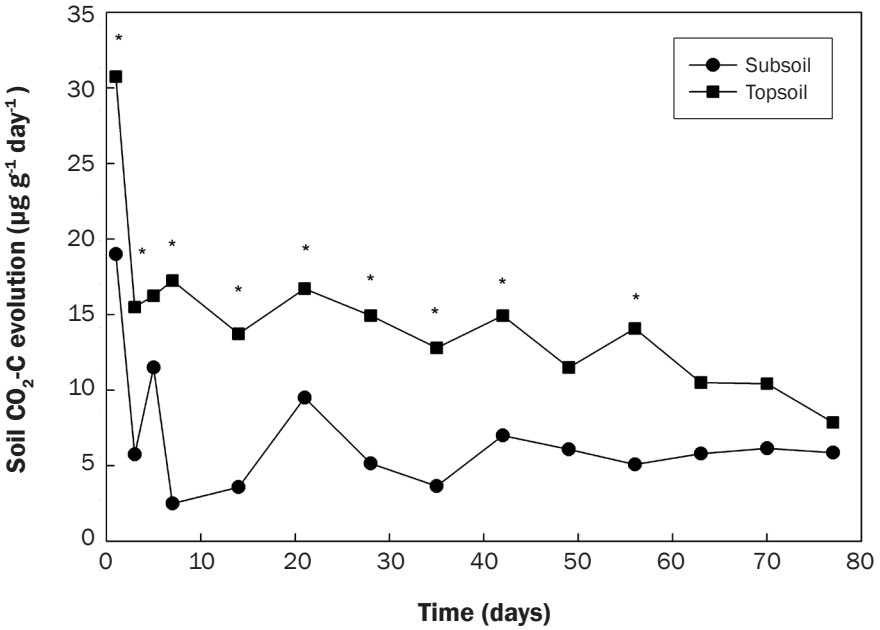
Soil Organic Carbon Fractions and Total Nitrogen. Analysis of variance showed no difference in SOC fractions or STN between sample years; therefore, the main effect of soil placement depth treatment will be presented across years. SOC content was not significantly different between the 15 and 30 cm topsoil placed treatments at all soil depths, except at the 15 to 30 cm (6 to 12 in) soil depth. However, the SOC content of topsoil treatments was greater than that of the exposed subsoil treatment for all soil depths (table 3). The increase in SOC content at all depths was considerable compared to initial SOC content (Pope 1989). The average increase in subsoil SOC content for depths 0 to 60 cm (0 24 in) was 0.70 Mg ha^{-1} yr^{-1} (0.31 ton ac^{-1} yr^{-1}). This increase in SOC content can be attributed to the contribution from the corn and soybean crops grown in rotation over the past 28 years.

The associated MFC content shows a similar trend to SOC content changes for all treatments, except the topsoil treatments of 30 cm, which shows greater MFC content than that of the 15 cm topsoil placed treatments at the 15 to 30 cm (6 to 12 in) and 30 to 45 cm (12 to 18 in) soil depths. However, both topsoil treatments' SOC contents at all depths were greater than those of subsoil treatment for the same soil depths (table 3). The increase in MFC content for the subsoil treatment was 0.61 Mg ha^{-1} yr^{-1} (0.27 ton ac^{-1} yr^{-1}) over the past 28 years. This increase is identical to that of SOC.

Topsoil inherently has more SOC content than subsoil; however, it should be noted that both topsoil addition treatments had greater SOC and associated MFC contents than the exposed subsoil at the 30 to 45 cm (12 to 18 in) soil depth. This depth is below the added topsoil treatment and could indicate an accumulation of SOC in the subsoil below the topsoil additions' interface zone. Also, this increase in SOC faction can be attributed to the deep tillage mixing effect (40 cm deep) (16 in). The greater potential C input (table 2) of crops in the topsoil coupled with the mixing effect of tillage have likely contributed to this increase of subsoil SOC at the 30 to 45 cm (12 to 18 in) soil depth.

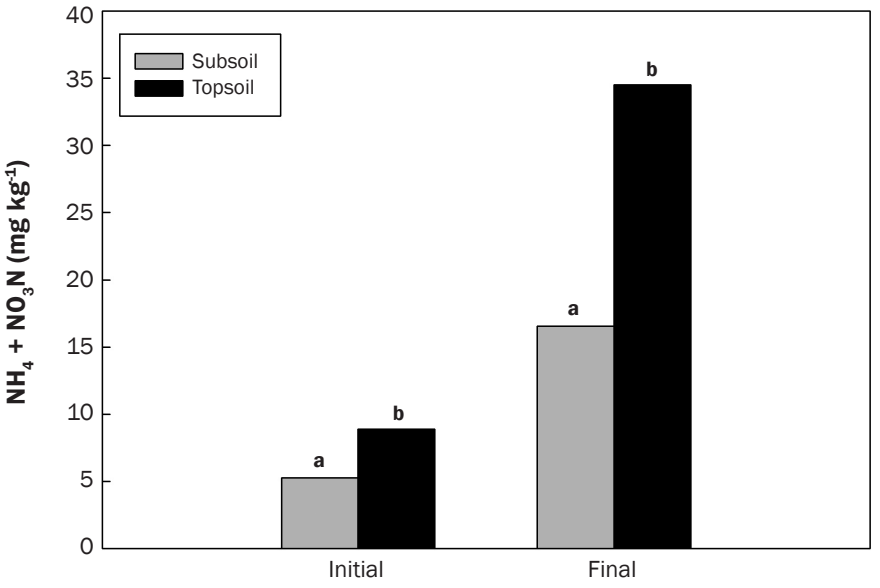
There was not an appreciable increase in POMC pool in any of the subsoil depths over the past 28 years of using corn and soybean crops. In contrast, the 15 and 30 cm (6 and 12 in) topsoil treatments had POMC contents 7.57 and 11.12 Mg ha^{-1} (3.38 and 4.96 ton ac^{-1}) greater than that of the exposed subsoil treatment, respectively for the 0 to 15 cm (0 to 6 in) soil depth (table 3). POMC content of the 15 and 30 cm (6 and 12 in)

Figure 4
Soil CO_2-C evolution rates from topsoil and subsoil during a 77-day laboratory incubation study.



*Days where CO_2-C evolution rates were different at $P \leq 0.05$.

Figure 5
Inorganic nitrogen concentrations of topsoil and exposed subsoil planted to a corn-soybean rotation, before and after a 77-day laboratory incubation study.



Note: Means with the same letter within each sampling time are not different at $P \leq 0.05$.

topsoil treatments was 6.25 Mg ha^{-1} (2.79 ton ac^{-1}) greater than that of the exposed subsoil treatment in the 15 to 30 cm (6 to 12 in) soil depth. Particulate organic matter is an intermediate pool between residue and stable organic matter and is closely related to stable soil macroaggregates (Cambardella and Elliot 1993). The subsoil in this study is very poorly aggregated and inherently does not contain a significant POMC fraction. Additionally, low input of root residues and tillage operations prevent the formation of stable macroaggregates (Cambardella and Elliot 1992; Gale et al. 2000). The improvement in soil POMC fraction of subsoil with corn and soybean and topsoil placement since 1978 was insignificant at all depths. STN contents did not differ between treatments depths (table 4).

Field Soil CO_2 Emissions. During the 2003 corn growing season, the daily rate of soil CO_2 emission was similar for topsoil and subsoil except for DOY 197 and 202 when topsoil CO_2 emissions were greater (figure 1c). In contrast, as expected during the 2004 soybean growing season, soil CO_2 emission rates were greater from topsoil than subsoil every day, except on DOY 187, 223, 280, and 309 (figure 2c). Greater soil CO_2 emissions from topsoil generally occurred when soil temperatures were at their warmest for the year, and no differences were found once soil temperatures began to cool, at approximately DOY 233 in 2003 and DOY 264 in 2004 (figures. 1b and 2b). This also can be attributed to the contribution of active root systems during that period. These findings are consistent with those of Bajracharya et al. (2000b), who found that slightly eroded soils had greater soil CO_2 emission rates than severely eroded soils only when soil temperatures were the warmest.

On no day of either year did subsoil have a greater CO_2 emission rate than topsoil. As a result, cumulative CO_2-C emissions were 45 and 47% greater from topsoil than subsoil in 2003 and 2004, respectively (figure 3). Even though the soybeans were planted extremely late in 2004, cumulative soil CO_2-C emissions were similar from both treatments in both years (figure 3). Similarly, soil MBC concentrations were 247 and 157 μg g^{-1} (247 and 157 ppm) for topsoil and subsoil, respectively. These results agree with Franzluebbers et al. (1999), who found greater soil CO_2 emissions in soils with larger MBC pools. Low substrate availability and the harsh environment of subsoil are likely the reason for low MBC and CO_2 emission in the subsoil. Additionally, the corn growing in topsoil had a larger root biomass than corn growing in subsoil (table 2). This may explain the link between the size of root system and CO_2 emission from both soils. Therefore, soil CO_2 emission along with MBC can be used as indicators to evaluate SOC pool differences.

Laboratory soil incubation results support the field soil CO_2 emission findings, where topsoil had greater rates of CO_2-C evolution during every incubation period except for days 5, 63, 70, and 77 after incubation (figure 4). Cumulative CO_2-C evolutions during incubation were also greater from topsoil than subsoil. Cumulative CO_2-C evolved was 1,043 and 463 μg g^{-1} for topsoil and subsoil, respectively. Topsoil and subsoil had similar inorganic N concentration prior to incubation, but after incubation topsoil had twice the inorganic N concentration of subsoil (figure 5). These results are similar to those of Lomander et al. (1998), who also found greater rates of CO_2-C evolution from topsoil than subsoil in a laboratory incubation study. The greater C and N mineralization in topsoil during the laboratory incubation can be attributed to larger amounts of substrate and greater MBC content.

Soil moisture and soil temperature of the topsoil and subsoil treatments were similar and CO_2 emission rates fluctuated with the changes in both parameters in either year of this study. However, regression analyses showed weak correlation between soil temperature or soil moisture and soil CO_2 emission (data not presented). Variability in soil CO_2 emission rate was greatest during the warmest soil temperatures and more moisture availability (figures 1a–1b and 2a–b). In a laboratory incubation study, Kowalenko et al. (1978) had found a linear relationship between CO_2 emission and soil temperature. In field studies, it is commonly reported that second order polynomial (Bajracharya et al. 2000b), or exponential (Raich and Mora 2005) functions, best explain the effects of soil temperature on soil CO_2 emissions. Our findings about CO_2 emission and soil moisture agree with those by Bajracharya et al. (2000a) and Wilson and Griffin (1975) that soil moisture only affects CO_2 emission rates at extremely low or extremely high soil moisture contents. The soil CO_2 emission and MBC indicators and interaction with soil moisture indicate that topsoil placement is more effective in restoring soil productivity than corn and soybean crops grown on subsoil over the past 28 years.

Summary and Conclusions

Topsoil addition over exposed subsoil increased aboveground and root biomass production of corn. The addition of topsoil

demonstrated significant improvement in soil productivity of exposed subsoil. The findings also showed that the potential C and N input for SOC and organic N improvement of subsoil were much greater when topsoil placement is coupled with corn and soybean over the past 28 years.

Generally, topsoil had greater SOC and MFC contents than exposed subsoil. However, the greater SOC content found in the interface zone between the topsoil addition and subsoil (30 to 45 cm [12 to 18 in]) could indicate carbon accumulation or movement from topsoil influenced by the tillage (40 cm [16 in] deep) mixing effect. It was also observed that SOC content improvement at all depths of subsoil was considerable compared with the initial SOC content. The average increase in subsoil SOC content for depths 0 to 60 cm (0 to 24 in) was 0.70 and 0.61 Mg ha^{-1} yr^{-1} (0.31 and 0.27 ton ac^{-1}) for SOC and MFC, respectively. This increase in SOC content can be attributed to the contributions of the corn and soybean crops in rotation over the past 28 years. However, no noticeable difference in subsoil POMC content was observed at any soil depth. The results of this study show that topsoil addition coupled with corn and soybean can be a viable technique for potentially improving SOC stocks of subsoil and the increase in soil productivity.

Also, it should be noted that cumulative field soil CO_2-C emissions as an indicator of SOC and MBC improvement were 46% greater from corn and soybean in topsoil than corn and soybean in subsoil. It was also observed a greater organic N mineralization occurs in topsoil than subsoil because of greater amounts of substrate and a larger MBC pool. The achievement of long-term improvement of SOC levels of exposed subsoil in row crop production agriculture must include topsoil replacement where corn–soybean rotation is used.

Acknowledgements

We gratefully acknowledge the funding from the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS) for supporting this research. The authors thank Stan Henning for providing the research site and his help in conducting this research.

All trade names and product lines are mentioned solely for the benefit of readers and do not imply endorsement by Iowa State University or the Soil and Water Conservation Society.

References

Akala, V.A., and R. Lal. 2001. Soil organic carbon pools and sequestration rates in reclaimed minesoils in Ohio. Journal of Environment Quality 30:2098–2104.

Bajracharya, R.M., R. Lal, and J.M. Kimble. 2000a. Erosion effects on carbon dioxide concentration and carbon flux from an Ohio alfisol. Soil Science Society of America Journal 63:694–700.

Bajracharya, R.M., R. Lal, and J.M. Kimble. 2000b. Diurnal and seasonal CO_2-C flux from soil as related to erosion phases in central Ohio. Soil Science Society of America Journal 64:286–293.

Cambardella, C.A., and E.T. Elliot. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Science Society of America Journal 56:777–783.

Cambardella, C.A., and E.T. Elliot. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Science Society of America Journal 57:1071–1076.

Carlyle, J.C., and U.B. Than. 1988. Abiotic controls of soil respiration beneath an eighteen-year-old *Pinus radiata* stand in south-eastern Australia. Journal of Ecology 76:654–662.

Chan, K.Y., D.P. Heenan, and A. Oates. 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil and Tillage Research 63:133–139.

Doran, J.W., and L.N. Mielke. 1984. A rapid, low-cost method for determination of soil bulk density. Soil Science Society of America Journal 48:717–719.

Eck, H.V. 1987. Characteristics of exposed subsoil—at exposure and 23 years later. Agronomy Journal 79:1067–1073.

Franzluebbers, A.J., R.L. Haney, and F.M. Hons. 1999. Relationships of chloroform fumigation-incubation to soil organic matter pools. Soil Biology and Biochemistry 31:395–405.

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Science Society of America Journal 60:1133–1139.

Gale, W.J., C.A. Cambardella, and T.B. Bailey. 2000. Root-derived carbon and the formation and stabilization of aggregates. Soil Science Society of America Journal 64:201–207.

Gollany, H.T., T.E. Schumacher, M.J. Lindstrom, P.D. Evenson, and G.D. Lemme. 1992. Topsoil depth and desurfacing effects on properties and productivity of a typic argiustoll. Soil Science Society of America Journal 56:220–225.

Hargreaves, P.R., P.C. Brookes, G.J.S. Ross, and P.R. Poulton. 2003. Evaluating soil microbial biomass carbon as an indicator of long-term environmental change. Soil Biology and Biochemistry 35:401–407.

Henning, Stan. 2006. Personal communication, unpublished report.

Horwath, W.R., and Paul, E.A. 1994. Microbial biomass. Methods of Soil Analysis Part 2. Microbiological and Biochemical Properties. 753–770. Madison, WI: Soil Science Society of America.

Khalaf, J.A. 1984. Soybean growth and yield response to solum depth, substratum characteristics, and selected management practices. Master's thesis. Ames, IA: Iowa State University.

Kowalenko, C.G., K.C. Ivarson, and D.R. Cameron. 1978. Effect of moisture content, temperature, and nitrogen fertilization on carbon dioxide evolution from field soils. Soil Biology and Biochemistry 10:417–423.

Kruse, M.L. 2005. Effects of nitrogen fertilization on soil carbon dynamics in a corn-soybean rotation in Iowa. Master's thesis. Ames, IA: Iowa State University.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

Lal, R., J.M. Kimble, and R.F. Follet. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Chelsea, MI: Ann Arbor Press.

Lomander, A., T. Katterer, and O. Andren. 1998. Carbon dioxide evolution from top- and subsoil as affected by moisture and constant and fluctuating temperature. Soil Biology and Biochemistry 30:2017–2022.

Mielke, L.N., and J.S. Schepers. 1986. Plant response to topsoil thickness on an eroded loess soil. Journal of Soil and Water Conservation 41:59–63.

Mulvaney, R.L. 1996. Nitrogen-inorganic forms, *In* Methods of Soil Analysis Part 3. Chemical Methods. 1129–1131. Madison, WI: Soil Science Society of America.

Olson, T.C. 1977. Restoring the productivity of a glacial till soil after topsoil removal. Journal of Soil and Water Conservation 32:130–132.

Pope, R.O. 1989. Age-hardening behavior of two Iowa soil materials. Master's thesis, Iowa State University, Ames, Iowa.

Potter, K.N. 1980. Effect of corn and soybean yields of selected reclamation techniques applied to highway borrow areas. Master's thesis, Iowa State University, Ames, Iowa.

Powlson, D.S., and P.C. Brookes. 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biology and Biochemistry 19:159–164.

Raich, J.W., and G. Mora. 2005. Estimating root plus rhizosphere contributions to soil respiration in annual croplands. Soil Science Society of America Journal 69:634–639.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1986. How a corn plant develops. Special Report No. 48. Ames, IA: Iowa State University Extension.

Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Science Society of America Journal 66:299–305.

Smucker, A.J.M., S.L. McBurney, and A.K. Srivastave. 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agronomy Journal 74:500–503.

Wang, W.J., R.C. Dalal, P.W. Moody, and C.J. Smith. 2003. Relationships of soil respiration to microbial biomass, substrate availability and clay content. Soil Biology and Biochemistry 35:273–284.

Wilson, J.M., and D.M. Griffin. 1975. Water potential and the respiration of microorganisms in the soil. Soil Biology and Biochemistry 7:199–204.

Zibliske, L.M. 1994. Carbon mineralization, *In* Methods of Soil Analysis Part 2. Microbiological and Biochemical Properties. 836–864. Madison, WI: Soil Science Society of America.