Oxidation Potentials of Soil Organic Matter in Histosols under Different Tillage Methods

D. R. Morris,* R. A. Gilbert, D. C. Reicosky, and R. W. Gesch

ABSTRACT

Organic soils in the Everglades Agricultural Area (EAA) of southern Florida, USA, are subsiding due primarily to oxidation by aerobic microorganisms. Since there are large C losses in drained Histosols, it is not certain if minimum tillage will significantly reduce soil C losses below the background levels. The objective of this experiment was to determine if increasing the surface soil disturbance through tillage significantly increases the soil organic matter oxidation potential (OP) in Histosols. Tillage treatments from lowest to highest soil disturbance consisted of (i) no-till; (ii) tine implement cultivation, one pass; (iii) tine implement cultivation, two passes; (iv) heavy harrow disking; and (v) switchplowing. Treatments were conducted on two fields (bare fallow and plant residue covered). Surface soil samples (0–15 cm) and all microbial measurements were taken on 0, 1, 4, 13, 28, and 42 d after tillage. The switchplow treatment had the greatest OP (^{14}C oxidation of benzoate) and soil microbial CO_2 respiration (RESP) averaged across the 42-d period compared with the other treatments. No-till tended to have the lowest OP and RESP. Other tillage treatment effects were intermediate depending on field type. Correlation analyses indicated that greater quantities of extractable N (EXN) were related to increased OP in both fields, while higher quantities of extractable C (EXC) were related to increased RESP in both fields. This research demonstrates that minimum tillage can be used on Histosols to reduce C loss and thereby reduce soil subsidence.

Most of the soils in the EAA are classified as Histosols, many of which have organic matter contents >85% (Snyder et al., 1978). To grow agricultural crops (mostly sugarcane, *Saccharum* spp.), these soils must be drained. Drainage promotes organic matter decomposition by heterotrophic, aerobic microorganisms (Tate, 1980). These microbes efficiently utilize certain fractions of the soil organic matter for their cellular growth (biomass) and respiration (loss of CO_2), resulting in soil subsidence. Recent data from soil marker posts in the EAA have indicated that such oxidation from drainage results in subsidence at an average of 1.4 cm yr^{-1} (Shih et al., 1998). Most of these cultivated soils now have 30 to 150 cm of soil remaining on top of limestone bedrock (Ingebritsen et al., 1999).

One way to increase soil C in mineral soils (<5% organic matter) is through minimum tillage practices, but organic matter decomposition in Histosols due to tillage may not be the same as in mineral soils. At >0.5 MPa water potential, a highly decomposed (saprist) organic soil may have 50% more pore volume compared with a mineral soil (Farnham and Finney, 1965), which provides a high potential for diffusion and storage of O_2 for microbial utilization in the organic soil. Neller (1943) reported that soil O_2 ranges between 15 and 17% at an 81-cm depth in Histosols during January and February. Water table levels were at 91 cm. When soil air contains 0.1% O_2, microbial activity is only 20% less than microbial activity at a soil air concentration of 21% O_2 (Broadbent (1960). Since O_2 concentrations in drained Histosols may not be low enough to inhibit microbial activity, it is not certain if reducing soil tillage will have an impact on reducing soil subsidence.

In mineral soil, short term (within 24 h) gaseous C losses as CO_2 can occur when surface soils are disturbed. Reicosky and Lindstrom (1995) used a large, portable photosynthesis chamber and reported substantial short-term gaseous losses of CO_2 immediately after tillage to partially explain long-term CO_2 losses from tilled mineral soils. The moldboard plow was the most intensive tillage implement and caused more CO_2 loss than less-disruptive tillage methods. No-till or no soil disturbance lost the least amount of CO_2, suggesting minimal environmental impact with these systems. Moldboard plowing was reported to have two major effects: to loosen and invert soil and allow a rapid CO_2 loss and oxygen entry, and to incorporate and mix residues to enhance microbial attack (Reicosky and Lindstrom, 1995). Similar results for less intensive tillage were found by Ellert and Janzen (1999) and Rochette and Angers (1999). This interaction of soil and residue mixing enhances aerobic microbial decomposition of the incorporated residue to cause a net decrease in soil organic C (Reicosky et al., 1995).

Short-term soil C losses in Histosols could be different than in a mineral soil. An organic soil during the winter may contain 4 to 6% CO_2 (Neller, 1943). The impact of tilling Histosols on increasing short-term gaseous C losses (CO_2) compared with undisturbed soil that is already losing gaseous C by diffusion through the large soil pore spaces has not been investigated.

Soil organic matter formation and development is highly dependent on management decisions that influence intensity of tillage and the amount and placement of residue. Minimum tillage methods that leave most of the crop residue on the surface with limited soil contact preserves organic matter (Reicosky, 1997). Methods to maintain soil C levels and aggressive tillage are not compatible. Concern for soil conservation requires new knowledge to minimize agriculture's impact on the envi-

---

D.R. Morris, USDA-ARS, Sugarcane Field Station, 12990 U.S. Hwy. 441, Canal Point, FL 33438; R.A. Gilbert, Everglades Research and Education Center, Univ. of Florida, 3200 East Palm Beach Road, Belle Glade, FL 33430; D.C. Reicosky and R.W. Gesch, USDA-ARS, North Central Soil Conservation Research Laboratory, 803 Iowa Ave., Morris, MN 56267. Received 21 Feb. 2003. *Corresponding author (dmorris@saa.ars.usda.gov).

Published in Soil Sci. Soc. Am. J. 68:817–826 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: EAA, Everglades Agricultural Area; EXC, extractable organic carbon (mg C g^{-1} soil); EXN, extractable total nitrogen (mg N kg^{-1} soil); MBC, microbial biomass carbon (mg C g^{-1} soil); MBN, microbial biomass nitrogen (mg N kg^{-1} soil); OP, organic matter oxidation potential (nmol CO_2 kg^{-1} soil h^{-1}); RESP, microbial respiration (μmol CO_2 m^{-2} s^{-1}).

ronment. With conservation tillage or no-till systems in some mineral soils, organic matter reaches equilibrium levels within 18 yr of constant use (Dick and Durkalski, 1998). To increase the soil organic matter, a delicate balance must be managed between the residue inputs of the previous crops and the tillage intensity associated with establishing the next crop. However, the contribution to C loss from recent (<1 yr) surface soil residue incorporation into a Histosol that already has a high organic matter content relative to C loss in an undisturbed condition is not certain.

Producers in the EAA commonly till soil before planting or subsoiling after a sugarcane harvest to improve water drainage in fields (Matherne et al., 1972). Additionally, frequent tine cultivations (shallow scratchings to a 2- to 4-cm depth) are made after planting to reduce weed competition and increase sugarcane yields (Glaz et al., 1989). Although minimum tillage would not be expected to eliminate C losses in organic soils of the EAA, reduced tillage could decrease the amount of organic matter oxidation (assuming the same tillage principles apply to Histosols as with mineral soils), because tillage aerates the soil and incorporates plant residues, both of which stimulates microbial activity. With high potential rates of C losses in drained organic soil (currently 14 Mg C ha^{-1} yr^{-1}) (Stephens et al., 1984), the magnitude of the impacts of conservation tillage on C dynamics could be large. The objective of this experiment was to determine if increasing the surface soil disturbance through tillage significantly increases the potential for soil organic matter oxidation in Histosols.

MATERIALS AND METHODS

The experiment was established in two fields located on the Everglades Research and Extension Center, Univ. of Florida, Belle Glade, FL (26°39′ N, 80°38′ W, 4.5-m elevation). Selected experimental sites were within 1100 m of each other. Sugarcane (interspecific hybrids of *Saccharum* species) was grown in both fields from December 1997 to December 2000, after which no crops were planted in either field before initiation of the experiment. However, weeds were reduced by mowing to a 15-cm height twice per month from December 2000 to November 2001. Soil type was a Lauderhill muck soil (euic, hyperthermic Lithic Haplosaprist), which was formed from sawgrass (*Cladium jamaicense* Crantz) on top of Ft. Thompson limestone bedrock (Snyder, 1994). Depth to limestone bedrock was 48 to 97 cm in both fields. Field 1 was a tillage fallow (no plant residue on the soil surface) area that was prepared by multiple disking operations on 8 Nov., 21 Nov., 6 Dec., and 21 Dec. 2001, and 2 Jan. 2002, followed by spraying with Roundup UltraMAX [1.1 kg a.i. (*N*-phosphonomethylglycine) ha^{-1}; Monsanto Co., St. Louis, MO] on 8 and 16 Jan. 2002. After 16 January, there was no visible plant residue on the soil surface. Field 2 was covered with a plant residue consisting of a mixture of weeds, predominately spreading dayflower (*Commelina diffusa* Burm. f.) and goosegrass [*Eleusine indica* (L.) Gaertn.]. The plants were killed with Roundup on the same dates and application rates as the fallow field. Plant dry matter was determined from the residue field on 24 January by taking eight (0.3- by 0.3-m) randomly selected samples from the soil surface. Plant samples were not washed because they appeared clean such that any soil contamination would be expected to represent <1% of the total dry matter. Residue dry matter averaged 3180 ± 440 kg ha^{-1}.

Both experimental fields consisted of uniform organic soil and relatively flat topography. Tillage treatments consisted of (i) no-till control; (ii) switchplow (Model 3608, LMC Bainbridge Equip. Co., Bainbridge, GA)[1]; (iii) John Deere disk harrow (Model 425 offset disk; Deere and Co., Moline, IL); (iv) tine cultivation (custom built spring tine cultivator) one time, and (v) tine cultivation two times. Treatments were partitioned into four blocks with plot sizes of 4.3 by 7.6 m.

The switchplow is similar in its soil disturbance to a moldboard plow. It consists of eight curved plow blades. Blades were 60 cm wide by 56 cm tall and were spaced 50 cm apart on a tool bar. The average plowing depth for this implement in both fields was 29 cm. The disk harrow contained 16 coulter and 16 round disks (30-cm radius) that were spaced 25 cm apart, and mixed soil to an average depth of 14.5 and 7.8 cm in the fallow field and residue fields, respectively. The spring tine cultivator scratched the soil surface to an average depth of 4 and 2 cm in the fallow and residue fields, respectively, and provided small furrows about 19 cm apart from loosened soil deposited on both sides of the tines. The disk harrow and tine cultivator disturbed less soil in the residue field because dried plant material on the soil surface prevented deeper penetration. Tillage started at 0700 h on 22 and 24 Jan. 2002 in the fallow and residue fields, respectively. Both fields could not be tilled and sampled on the same day because of limitations of laboratory equipment that was available to process samples for analysis. However, general climate data from the weather station showed the 2 d of tillage had no rainfall and air temperature differences were <5°C (Fig. 1).

To obtain representative data from each plot, six soil samples were randomly selected and composited. Samples (0–15 cm) were taken using a 2-cm-diam. probe. For tilled plots, the samples were taken on the furrow ridges. This depth was sampled because most of the microbial biomass changes occur in the upper soil surface with tillage (Granatstein et al., 1987). One soil temperature (7-cm depth) in each plot was taken with a 15-cm length alcohol thermometer at each soil sampling by randomly pressing the thermometers into the plots. In cultivated plots, probes were inserted on the furrow ridges. Soil samples and temperature were taken between 0700 and 0800 h on 0, 1, 4, 13, 28, and 42 d after tillage with 0 d representing the day of tillage. Samples could not be taken during a longer period of time because the land was not available after 42 d. On Day 0, samples were taken immediately after tillage.

All samples were thoroughly mixed inside plastic bags and analyzed for OP by the ^{14}C substrate induced respiration method (Tate, 1979). Analyses were performed by adding 0.5 mL of deionized water containing 12 nmol ^{14}C (carboxyl)-benzoate (specific activity of 344 MBq mmol^{-1}) to 10 g fresh soil inside a glass culture tube (20 × 150 mm). Benzoate was used because it is a major intermediate in the decomposition of aromatic compounds that are prevalent in organic soil, and it worked well in evaluating potential degradation of organic soil in Canada (Williams and Crawford, 1983). The culture tube was stoppered, and the contents were mixed end-over-end 20 times. The samples were then incubated for 2 h while a stream of air was passed over the soil surface and into 10 mL of 1 *M* NaOH trap solution. The apparatus was similar to that described by Zibilske (1994). At the conclusion of the incubations, the NaOH trap solution was analyzed for $^{14}CO_2$

---

[1] Names of the products are included for the benefit of the reader and do not imply endorsement or preferential treatment by USDA or the University of Florida.

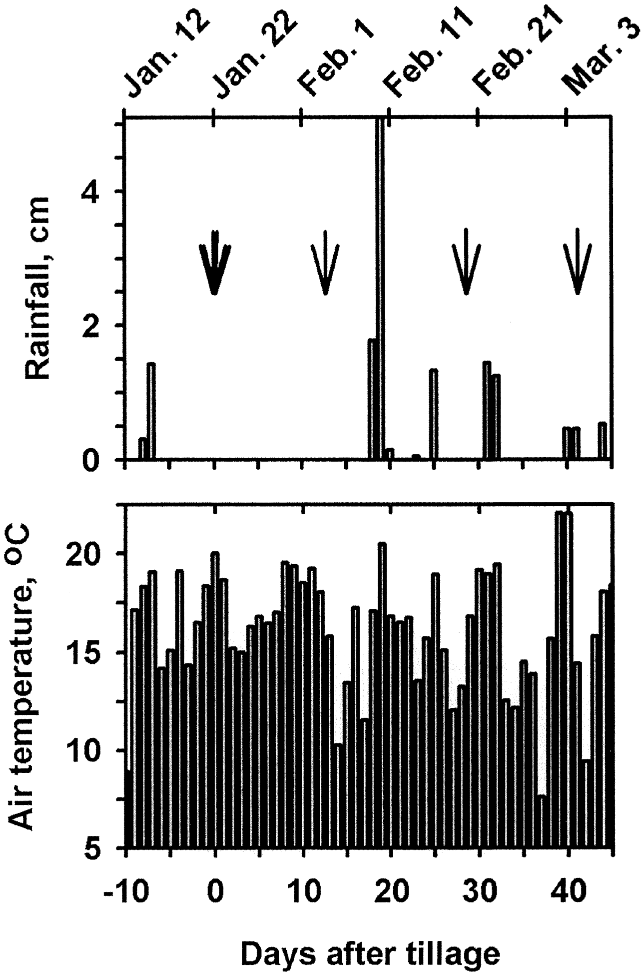

Fig. 1. Rainfall and air temperature (0800 h) after tillage of bare fallow field. The arrows indicate days of soil sampling.

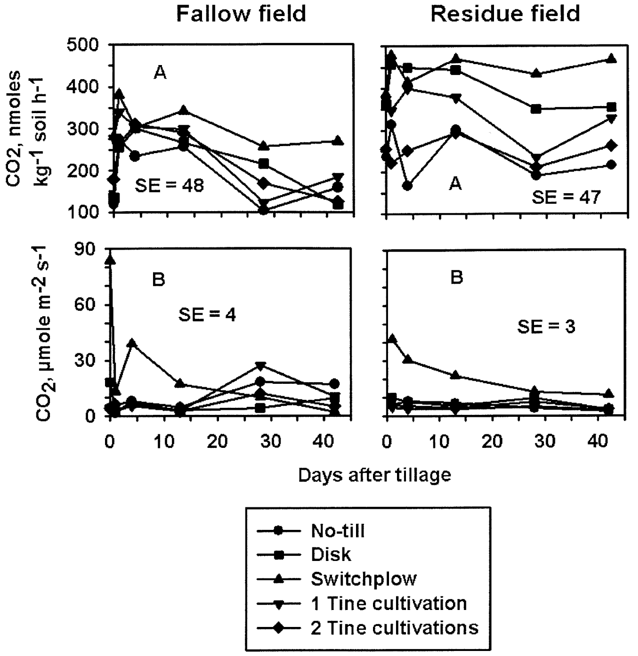

Fig. 2. Soil organic matter oxidation potential (A) and respiration (B) due to tillage treatment across time in fallow and residue fields.

content with a scintillation counter. The quantity of CO_2 evolved was calculated on the basis of ^{14}C content in benzoate.

After ^{14}C evolution analysis for microbial activities, all data were adjusted to the same substrate concentration (1.9 μM) because soil samples had different water contents and enzyme activity is related to substrate concentration. Adjustments could be made because substrate was applied at less than saturating concentrations, and at the levels applied in this study for all treatments there was a linear relationship between microbial activity and substrate concentration with origin at 0 (Morris and Snyder, 2002).

Water content was calculated after drying samples for 24 h at 105°C (Sanchez, 1990). Soil samples from each plot on Days 0 and 42 were air dried, sieved through a 2-mm screen, and analyzed for pH (2:1, soil to water), water-extractable P, and 0.5 *M* acetic-acid-extractable K by the standard tests used for organic soils in Florida (Sanchez, 1990). Extractable P and K levels at the beginning and ending of the experiment was determined so that nutrient release from organic matter oxidation or immobilization could be assessed.

In addition, microbial biomass carbon (MBC) and nitrogen (MBN) were determined by the fumigation/extraction method of Voroney and Winter (1993), except soil samples were filtered through a Whatman (Clifton, NJ) no. 42 filter paper, and the extractant (0.5 *M* K_2SO_4) before and after chloroform fumigation was analyzed for organic C and total N by high temperature combustion (USEPA, 1987) on a Shimadzu (Columbia, MD) CN Analyzer (Model TOC-V_{CSH}). Sparling et al. (1990) suggested the extraction efficiency for MBC in high organic matter soils should be 0.35, but they did not suggest an extraction efficiency for MBN. To be consistent between relative extraction efficiencies between C and N, the extraction efficiencies of 0.25 and 0.15 for C and N, respectively, as reported by Voroney and Winter (1993), were used. In addition, the relative differences among tillage treatments were of greater interest than precise values for MBC and MBN. Extractable organic C and EXN were represented by the organic C and total N in the extraction before fumigation.

Soil RESP was measured on the same days and similar times as the soils were sampled using a soil respiration chamber (9.8-cm diam. by 10.2-cm-high chamber) attached to a photosynthesis meter (CID Inc., Vancouver, WA, Model CI 301PS). The system was closed (air outside the chamber was not allowed to enter during RESP measurements), air was circulated inside the chamber and photosynthesis meter by two circulating fans and one small pump, respectively, and CO_2 fluxes were automatically calculated and recorded to a data logger after a 30-s stabilization period. To seal the chamber from outside air before each CO_2 flux sampling, the chamber cylinder was gently pressed about 1 cm into the soil surface. Three RESP measurements were taken in each plot. In the residue field, the photosynthesis instrument malfunctioned on Day 0, so RESP data were not collected for that sampling. Air temperature (2-m height) at 0800 h and daily rainfall were obtained from a weather station located within 850 m of both fields.

For each field, data were analyzed as a randomized complete block design, assuming all treatments were random with sampling day as a repeated measure with the PROC MIXED statistical program (SAS Institute, 1999). The covariance structure was determined by the procedure of Tao et al. (2002). An LSMEAN test ($P \leq 0.05$) was used to determine differences in treatment means (SAS Institute, 1999). The average standard error for each parameter shown in Fig. 2 through 6 was obtained from the LSMEAN test (SAS Institute, 1999) of the tillage treatment by sampling day interaction. Correlations coefficients (r) among the parameter means as shown in Fig. 2

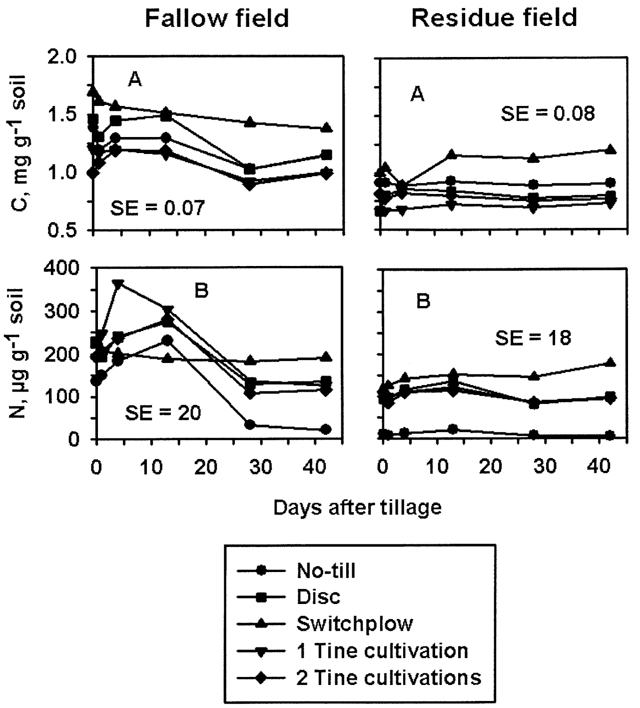

Fig. 3. Soil extractable C (A) and N (B) due to tillage treatment across time in fallow and residue fields.

through 6 ($n = 30$) within each field type were calculated (SAS Institute, 1999).

RESULTS

Oxidation Potential

Analysis of variance for OP in the fallow field indicated there were significant main effects for sampling time and tillage treatment and their interaction. The first day after tillage, OP increased for all treatments in the fallow field (Fig. 2). Dew at 0700 was very heavy on 0 and 1 d after tillage. Dew was observed dripping from sugarcane leaves in surrounding plots and on the soil surface. The high humidity in the soil surface may have caused part of the increase in OP, as indicated by the increase in the control (no-till) treatment. However, the switchplow tended to have higher OP rates throughout the 42 d after tillage and was significantly higher than the other treatments at 42 d. Even though the tillage by sampling day interaction was significant, the net effect of potential organic matter loss as indicated by average OP across 42 d is also important in evaluating tillage treatments. Averaged across the 42-d period, the switchplow and one-transit cultivation had the highest OPs (305 and 254 nmol CO_2 kg^{-1} soil h^{-1}, respectively) compared with the other tillage treatments, which averaged 230 nmol CO_2 kg^{-1} h^{-1} (Table 1).

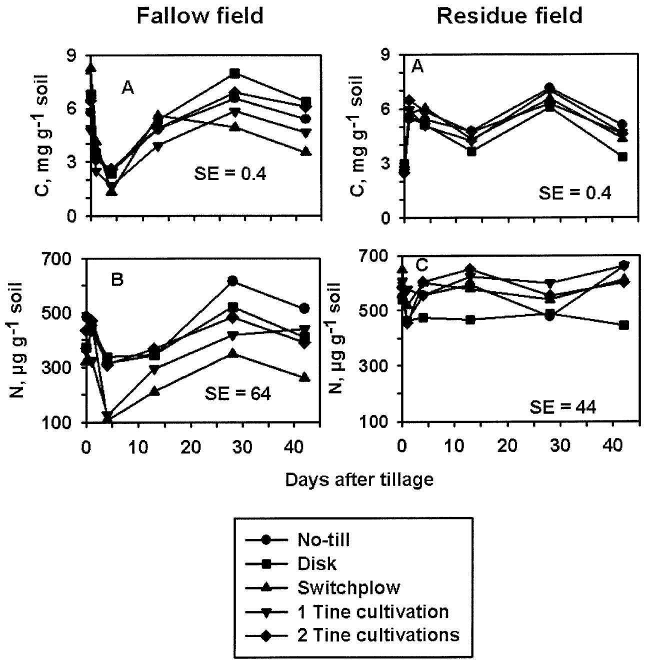

Fig. 4. Soil microbial biomass C (A) and N (B) due to tillage treatment across time in fallow and residue fields.

Analysis of variance in the plant residue field showed a similar response for main effects and interaction as the fallow field. However, the responses for tillage treatments in the residue field did not correspond the same as in the fallow field. Part of the difference likely resulted from the residue on the soil surface, which may have absorbed some of the dew, preventing water from reaching the soil surface for some treatments. Thus, all treatments did not show a significant increase in OP on Day 1 (Fig. 2). The OP response fluctuated during the 42 d after tillage, but OP for the switchplow treatment remained significantly higher than the other treatments on the final two sampling dates. When all sampling times are averaged, the switchplow and disk had the highest OP (441 and 403 nmol CO_2 kg^{-1} h^{-1}, respectively), followed by one-transit cultivation (344 nmol CO_2 kg^{-1} h^{-1}) (Table 1). The two-transit cultivations and no-till control had the lowest OP (249 and 238 nmol CO_2 kg^{-1} h^{-1}, respectively).

Soil Respiration

Sample time, tillage treatment, and their interaction were significant for RESP in the fallow field. Immediately after tillage there was a very large increase in RESP in the switchplow treatment that remained higher than the other treatments up to 18 d after tillage (Fig. 2). At 42 d after tillage, less CO_2 evolved from the switchplow treatment compared with the no-till treatment. However, when averaged across the 42 d after tillage, switchplow had RESP of 27 μmol CO_2 m^{-2} s^{-1}, while the other treatments averaged only 8 μmol CO_2 m^{-2} s^{-1} (Table 1).

Similar to the fallow field, tillage and sampling date main effects and interaction were significant in the residue field. The increase in RESP of the switchplow was not as great as in the fallow field, probably because a sample was not taken on Day 0 in the residue field because of instrument malfunction. The RESP tended to decline from 3 to 42 d after tillage, but remained significantly higher than the other treatments after 42 d from tillage (Fig. 2). Averaged across the 42 d, switchplow RESP was 24 μmol CO_2 m^{-2} s^{-1}, while the other

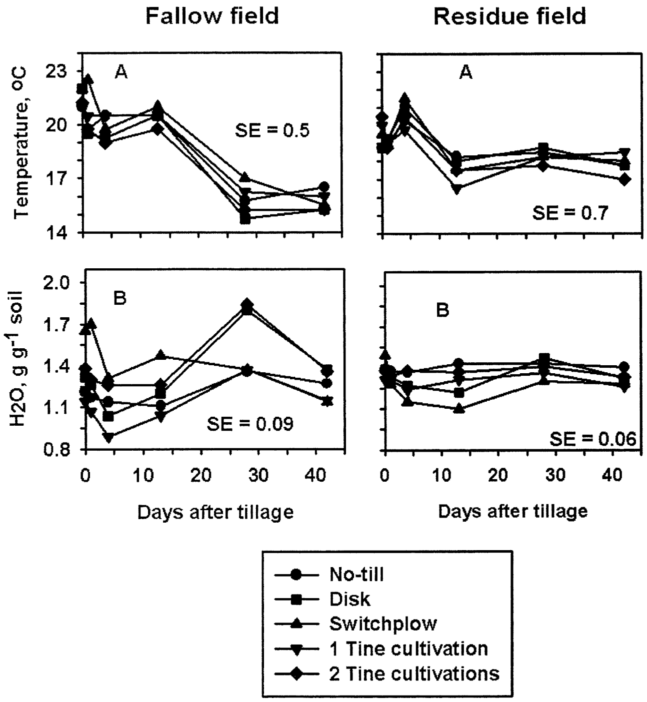

Fig. 5. Soil temperature (A) and water content (B) due to tillage treatment across time in fallow and residue fields.

treatments were <25% of the switchplow, averaging 6 μmol CO_2 m^{-2} s^{-1} (Table 1).

Extractable Carbon and Nitrogen

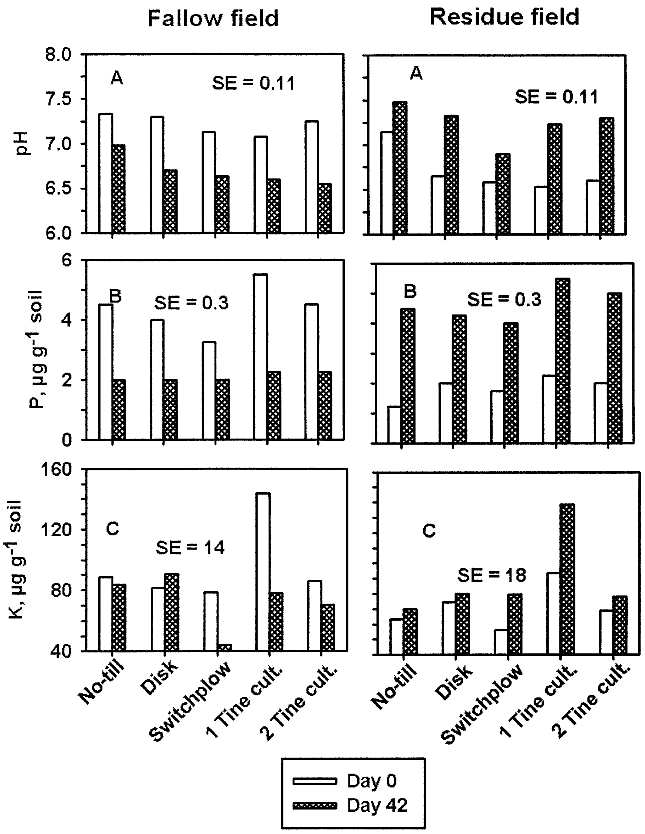

Fig. 6. Soil pH (A), extractable P (B), and extractable K (C) due to tillage treatment across time in fallow and residue fields.

Extractable organic C and EXN represent readily available C and N for microbial utilization. Extractable C and N were significantly affected by main effects of sample time and tillage treatment and their interaction in the fallow field. The switchplow treatment tended to have more EXC throughout the 42 d after tillage, while the one-transit cultivation treatment tended to have more EXN up to 15 d after tillage compared with the other tillage treatments (Fig. 3). This pattern was maintained when averaged across the 42 d after tillage. The switchplow had the highest EXC (average 1.5 mg C g^{-1} soil), and the one-transit cultivation had the highest EXN (average 235 mg N kg^{-1} soil) of all treatments (Table 1). But, at 42 d after tillage, switchplow had significantly higher EXC and EXN than the other tillage treatments, possibly because of the switchplow bringing up undecomposed organic matter to the soil surface (Fig. 3). Evidence was indicated by small chunks (1 to 3 cm) of light brown peaty material being observed on the soil surface of the switchplow plots after tillage that were not seen on the other plots.

For the residue field, ANOVA was similar to the fallow field except the interaction was not significant for EXC. The switchplow tended to have higher EXC and EXN than the other treatments throughout the 42-d sampling period (Fig. 3). Averaged across the 42 d, the switchplow had EXC and EXN of 1.1 mg C g^{-1} soil and 144 mg N kg^{-1} soil, respectively, in contrast to no-till of 0.9 mg C g^{-1} soil and 11 mg N kg^{-1} soil, respectively (Table 1).

Microbial Biomass Carbon and Nitrogen

In the tillage fallow field (disk harrowed five times in the preceding 2 mo), MBC was significantly affected by tillage and sampling date treatments and their interaction, while MBN was only affected by the main effects.

Table 1. Tillage treatment means averaged across sampling times for oxidation potential (OP), microbial respiration (RESP), extractable organic carbon (EXC), and extractable nitrogen (EXN) in fallow fields (FF) and residue fields (RF).

	OP		RESP		EXC		EXN	
Treatment	FF	RF	FF	RF	FF	RF	FF	RF
	– nmol CO_2 kg^{-1} soil h^{-1} –		– μmol CO_2 m^{-2} s^{-1} –		— mg C g^{-1} soil —		— mg N kg^{-1} soil —	
No-till	**191b†**	**238c**	**8.92b**	**5.50b**	**1.22c**	**0.90b**	**126c**	**11.0c**
Disk	**215b**	**403ab**	**7.42b**	**7.27b**	**1.31b**	**0.79cd**	**200b**	**104.4b**
Switchplow	**305a**	**441a**	**26.99a**	**23.66a**	**1.53a**	**1.07a**	**200b**	**144.4a**
1-transit cultivation	**254ab**	**344b**	**8.89b**	**4.05b**	**1.11d**	**0.69d**	**235a**	**102.3b**
2-transit cultivation	**222b**	**249c**	**6.34b**	**5.28b**	**1.06d**	**0.79cd**	**190b**	**100.5b**

† Numbers followed by the same letter within each column are not significantly different according to an LSMEAN test (SAS Institute, 1999) at $P = 0.05$.

Table 2. Tillage treatment means averaged across sampling times for microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), soil temperature, and soil water content in fallow fields (FF) and residue fields (RF).

	MBC		MBN		Soil temperature		Soil water	
Treatment	**FF**	**RF**	**FF**	**RF**	**FF**	**RF**	**FF**	**RF**
	mg C g^{-1} soil		mg N kg^{-1} soil		°C		g H_2O g^{-1} soil	
No-till	4.70b†	5.05a	450a	550b	19.0b	18.8a	1.21cd	1.40a
Disk	5.39a	4.44b	404a	479c	18.5c	18.9a	1.33bc	1.33abc
Switchplow	4.62b	4.98a	285b	583ab	19.6a	19.0a	1.44a	1.27c
1-transit cultivation	3.90c	4.90a	327b	604a	19.1b	18.7a	1.11d	1.30c
2-transit cultivation	5.00b	5.06a	409a	575ab	18.4c	18.7a	1.40ab	1.37ab

† Numbers followed by the same letter within each column are not significantly different according to an LSMEAN test (SAS Institute, 1999) at $P = 0.05$.

The most visible interaction was with the switchplow treatment, which showed a decline in MBC to levels lower than the other treatments by 42 d after tillage (Fig. 4). Averaged across the 42 d, the switchplow treatments had intermediate MBC and MBN (4.6 mg C g^{-1} soil and 285 mg N kg^{-1} soil, respectively), while the disk treatment was among the highest in MBC and MBN (5.4 mg C g^{-1} soil and 404 mg N kg^{-1} soil, respectively) (Table 2).

The plots in the residue field were not tilled the previous 2 mo, and MBC and MBN in the residue field were affected by tillage and sample day main effects and their interaction. The interaction can be seen for MBC and MBN, with all treatments showing varying degrees of increases and decreases across time with no consistent response pattern (Fig. 4). Averaged across the 42 d after tillage, the disk treatment had among the lowest MBC and MBN (4.4 mg C g^{-1} soil and 479 mg N kg^{-1} soil, respectively), while switchplow had MBC and MBN (5.0 mg C g^{-1} soil and 583 mg N kg^{-1} soil, respectively) similar to the no-till control (5.1 mg C g^{-1} soil and 550 mg N kg^{-1} soil, respectively) (Table 2).

Soil Temperature

Tillage and sample date main effects and their interaction were significant for soil temperature in the fallow field. The switchplow tended to have the warmest soil temperatures in three out of the six sample times (Fig. 5), averaging 19.6°C across the 42 d after tillage (Table 2). The lowest average temperature of all tillage treatments averaged 18.5°C in the two-transit cultivations and disk treatments (Table 2). For the residue field, soil temperature was only affected by sampling date (Fig. 5). Average temperature during the 42 d was 19°C (Table 2).

Soil Water Content

Similar to soil temperature in the fallow field, all main effects and their interaction were significant for soil water content. Even though switchplow tended to have less water 13 d after tillage (Fig. 5), probably because of greater evaporation, averaged across 42 d, it was among the highest with 1.4 g H_2O g^{-1} soil (Table 2).

Likewise, in the residue field, all effects were statistically significant. The no-till treatment tended to have the highest and switchplow treatment the lowest quantity of soil water (Fig. 5) because of the mulching effect of preventing water loss and higher water-holding capacity of the plant residue on the soil surface of the no-till treatments and better drainage in the switchplow treatment. Differences in soil water content in no-till and switchplow averaged across the 42 d after tillage was also statistically significant (1.4 and 1.3 g H_2O g^{-1} soil, respectively), but differences were small ($<10\%$) among treatments (Table 2).

Rainfall and Air Temperature

Although the dew was very heavy the first few days after tillage, there was no rainfall from 7 d before to 18 d after tillage (Fig. 1). From 20 d after tillage there was standing water (1- to 2-cm depth) in both fields that declined during a 3-d period. Rainfall occurred almost weekly from Day 20 to the completion of the experiment.

Air temperatures varied from 8 to 22°C, with an average temperature of 16°C. The lowest temperatures were 8 and 9°C at 37 and 42 d after tillage, respectively.

In the residue field, there were fewer significant correlations than in the fallow field. Oxidation potential was positively correlated with RESP ($r = 0.52$, $P = 0.01$) and EXN ($r = 0.73$, $P = 0.01$) and negatively correlated with soil water content ($r = -0.59$, $P = 0.01$) (Table 3).

Table 3. Correlation coefficients (*r*) for fallow and residue fields.

	Fallow field†				Residue field			
	OP	**RESP**	**MBC**	**MBN**	**OP**	**RESP**	**MBC**	**MBN**
RESP	−0.01ns‡	–	–	–	0.52**	–	–	–
MBC	−0.58**	0.33ns	–	–	−0.19ns	0.14ns	–	–
MBN	−0.58**	−0.15ns	0.55**	–	−0.13ns	−0.05ns	−0.21ns	–
Soil temp.	0.55**	0.14ns	−0.27ns	−0.37*	0.06ns	0.29ns	0.02ns	−0.11ns
Soil water	−0.17ns	0.40*	0.66**	0.41*	−0.59**	−0.47*	0.02ns	0.01ns
EXC	0.52**	0.41*	−0.17ns	−0.47**	0.34ns	0.54**	0.02ns	0.01ns
EXN	0.68**	−0.08ns	−0.45*	−0.69**	0.73**	0.39*	−0.12ns	0.14ns

* Significant at $P = 0.05$.

** Significant at $P = 0.01$.

† OP = oxidation potential, RESP = microbial respiration, EXC = extractable organic carbon, EXN = extractable total nitrogen, MBC = microbial biomass carbon, MBN = microbial biomass nitrogen.

‡ ns, nonsignificant at $P = 0.05$.

Soil RESP was positively correlated with EXC ($r = 0.54$, $P = 0.01$) and EXN ($r = 0.39$, $P = 0.05$) and negatively correlated with soil water content ($r = -0.47$, $P = 0.05$). Microbial biomass C and N were not correlated with any of the parameters measured.

Soil Chemical Properties

Microbial activity can also be detected by changes in nutrient mineralization. The ANOVA of soil pH, extractable P, and extractable K showed the main effects in the fallow field to be significant. The interaction was not significant for pH. No consistent response pattern relating nutrient change to depth of tillage could be discerned from the data (Fig. 6). Even though there were greater decreases in P across time compared with K, P at 42 d after tillage in the no-till treatment was similar to the other treatments. The data show a tendency for a decline in pH and nutrient contents from Days 0 to 42 with the exception of extractable K in the disk treatment. The average decline from Days 0 to 42 was pH 7.2 to 6.7, 4.4 to 2.1 mg P kg^{-1} soil, and 96 to 73 mg K kg^{-1} soil. The high pH is typical for soils in the EAA that are overlying limestone bedrock (Snyder, 1994), and the high P loss is expected based on previous reports (Diaz et al., 1993).

Main effects of sampling time and tillage treatment were significant in the residue field for all soil chemical properties, but the interaction was only significant for soil pH and K. As in the fallow field, no consistent response of nutrient increase could be related to depth of tillage, and P showed greater changes during the 42 d compared with K (Fig. 6). In contrast to the fallow field, the trend was always for an increase in pH and nutrients across time due to mineralization of crop residues (Fig. 6). Average increase from Days 0 to 42 was pH 6.7 to 7.2, 1.9 to 4.7 mg P kg^{-1} soil, and 71 to 89 mg K kg^{-1} soil.

Correlation Analyses

The OP in the fallow field was negatively correlated with MBC ($r = -0.58$, $P = 0.01$) and MBN ($r = -0.58$, $P = 0.01$) and positively correlated with soil temperature ($r = 0.55$, $P = 0.01$), EXC ($r = 0.52$, $P = 0.01$), and EXN ($r = 0.68$, $P = 0.01$) (Table 3). Soil RESP was positively correlated with soil water content ($r = 0.40$, $P = 0.05$) and EXC ($r = 0.41$, $P = 0.05$). Microbial biomass C was positively correlated with soil MBN ($r = 0.55^{**}$) and soil water content ($r = 0.66$; $P = 0.01$) and negatively correlated with EXN ($r = -0.45$, $P = 0.05$). Microbial biomass N was correlated with more parameters than MBC, having positive correlation with soil water content ($r = 0.41$, $P = 0.05$) and negative correlations with soil temperature ($r = -0.37$, $P = 0.05$), EXC ($r = -0.47$, $P = 0.01$), and EXN ($r = -0.69$, $P = 0.01$).

DISCUSSION

Microbial activity was influenced by environmental factors such as dew, rainfall, and temperature interacting with tillage treatments during the course of the experiment. This can be seen in the no-till treatment OP in both fields (Fig. 2). The no-till treatment should have been constant during the 42 d after tillage if influenced by tillage alone, but OP in the no-till treatment of the fallow field increased at Day 1, then declined steadily to Day 28, and then increased again at Day 42 (Fig. 2). The reason for the increase in activity between Days 0 and 1 is not certain because there was little difference in soil water content and temperature among those sampling days (Fig. 5). In the residue field, OP in no-till increased at Day 1 then fluctuated during the remaining 42 d (Fig. 2). Even though environmental factors appeared to be significant, they were expected, because they are encountered in all field experiments. Small differences in microenvironments may be affected by tillage method, but these were not measured. However, since it is of interest to know long-term (42-d) net effects of tillage treatment on potential C loss and microbial biomass rather than short-term (daily) effects, this discussion will focus on the average tillage treatment effects during the 42-d period. The interpretation is reasonable because tillage was a significant source of variation in all parameters measured except soil temperature. Also, the no-till control likely reflects the longer-term variations independent of tillage.

Our data demonstrate that deep tillage of muck soils can produce OP responses with ^{14}C-labeled substrate (OP) that corresponds to responses in mineral soils (Fig. 2). There is no published information on use of OP in mineral soil, but Reicosky et al. (1997) showed that greater soil disturbance in mineral soils increased soil aeration and microbial activity, which in turn increased organic matter oxidation as measured by increased CO_2 flux. In both fields of the present study, the switchplow had the highest OP, which persisted more than 42 d because of the greatest soil disturbance (Table 1). The switchplow promoted greater aeration for microbial activity and tended to bring more soil water content and EXC to the soil surface before 13 d after tillage (Fig. 3). Thus, greater EXC content in the soil surface, combined with increased oxygen and water allowed for higher OP.

Differences between the two field types occurred for EXN. In the residue field, there were greater amounts of EXN in the soil surface of the switchplow plots compared with the other tillage treatments (Table 1), which further contributed to increased OP (Table 1), since available N is essential for microbial growth. The switchplow treatment in the fallow field did not show greater amounts of EXN, but obviously N was sufficient for greater microbial activity (OP and RESP).

In both fields, no-till had the lowest EXN and EXC compared with the tilled treatments (Table 1) because there was less organic matter decomposition from not incorporating surface organic matter in the no-till treatment. These results correspond to those of Reicosky and Lindstrom (1995), with use of CO_2 flux to measure organic matter decomposition in tilled and nontilled mineral soils. Our data show that even in high organic matter soils, leaving organic residue on the soil surface is a desirable management practice to conserve organic N and C.

However, OP responses due to tillage treatments that disturbed soil intermediate to no-till and switchplow treatments was not the same in both field types (Table 1). In the fallow field, OP for the disk treatment was similar to both tine cultivation treatments, while in the residue field, OP for the disk treatment was similar to the one-transit cultivation treatment and greater than the two-transit cultivation treatment. Differences between OP due to tillage treatment in both fields could not be explained by available C and N levels for microbial activity as expressed by EXC and EXN (Table 1). In the fallow field, the disk treatment had greater EXC and similar EXN compared with both tine cultivation treatments, while in the residue field, the disk treatment had less EXC compared with one-transit cultivation treatment and similar EXN compared with both tine cultivation treatments. Since OP did not correspond to EXC or EXN, the differences in OP among tillage treatments could also be related to changes in soil physical properties (not measured in our study) resulting from incorporation of fresh plant material, such as reduced bulk density or increased water percolation rate (Livingston et al., 1990), but are beyond the scope for interpretation in our study.

The switchplow treatments in both fallow and residue fields showed a larger CO_2 flux than the other tillages on Days 0 and 1 (Fig. 2). Similarly, Reicosky and Lindstrom (1995) reported large fluxes within 24 h after tillage in mineral soils from the release of CO_2 trapped in the soil pores and enhanced microbial activity. Furthermore, Reicosky (2002) indicated the CO_2 flux in a moldboard treatment continued to be higher than the no-till treatment for up to 87 d after tillage. Unlike mineral soil, the large flux in our study persisted for approximately 20 d in the fallow field (Fig. 2). In the residue field, the flux persisted for a longer period (up to 42 d after tillage) (Fig. 2). Greater EXC and sufficient EXN in the switchplow compared with the other tillage treatments could have contributed to the persistence in the residue field, suggesting that the incorporated residue controlled the increased flux (Table 1).

Averaged across the 42 d, CO_2 flux was 3.4 and 4.3 times greater from the switchplow treatment in the fallow and residue fields, respectively, compared with the average from the other tillage treatments (Table 1). The greater CO_2 flux in the switchplow could not be attributed to greater MBC or MBN in the surface soil that immobilize both C and essential nutrients in the microbial cells, because the switchplow treatment had similar or lower microbial biomass than the no-till treatment in both fields. The reason for the lack of correspondence between RESP and either MBC or MBN may be because of large diffusion losses of trapped CO_2 from the soil pores immediately after tillage (Fig. 2) (Reicosky and Lindstrom, 1995).

Reicosky et al. (1997) conducted a tillage experiment in a mineral soil and reported that CO_2 flux immediately after moldboard tillage (25-cm depth) was about 17 μmol m^{-2} s^{-1}, which is 4.7 times less than the switchplow treatment immediately after tillage in the fallow field of our experiment. Pioneering research of Broadbent (1960) and Waksman and Stevens (1929) indicated that C is the most limiting factor for microbial activity in organic soils. Even though C may be a limiting factor for microorganisms in Histosols, there are sufficient amounts of available C to result in greater microbial activities compared with some mineral soils.

The microbial biomass data in the fallow field conform to that of Follett and Schimel (1989) who compared no-till, mulch, and moldboard plow tillage in mineral soils and reported that greater soil disturbance decreased average microbial biomass. However, in our study, unlike the fallow field, the switchplow and no-till treatments had similar average MBC and MBN in the residue field (Table 2). There probably was sufficient available C and nutrients for microorganisms in the surface and subsurface soil of the residue field to minimize the influence of tillage practices on MBC and MBN.

The flux of CO_2 in the switchplow treatment was reduced by an average of 80 and 50%, 20 d after tillage in the fallow and residue fields, respectively (Fig. 2). Part of the reduction in RESP across time is expected because of soil settling from dew, wind, and rain disturbance of the soil surface, which reduces O_2 diffusion into the soil for RESP. Since cultipacking (compressing the soil with heavy steel rollers) accelerates the settling or soil particle consolidation process, future experiments should investigate cultipacking or other secondary tillage of Histosols to reconsolidate the soil particles soon after tillage as another option for reducing C losses.

Higher OP and RESP in the switchplow treatment compared with other treatments in both fields could not be explained by more favorable soil temperatures and soil water content contents. The fallow field had higher average soil water content and warmer temperatures in the switchplow treatment compared with the other treatments (Table 1), but the residue field's switchplow treatment had similar soil temperature and was among the lowest in soil water content compared with the other treatments (Table 1). Depth of soil mixing, presence of fresh plant residue, soil temperature, and soil water content had an interacting affect on organic matter decomposition.

Heavy rainfall on Days 18 and 19 that flooded the fields and very low air temperatures on Days 37 and 42 (Fig. 1) did not cause drastic and consistent shifts in periodic measurements of OP, RESP, MBC, and MBN (Fig. 2, 4) probably because flooding and low temperatures did not persist for a long enough period of time. Also, high rainfall did not pack the soil (according to visual observation in both fields of no ponding of water on the soil surface and loose soil structure) in the switchplow plots enough to reduce the OP compared with the other tillage treatments (Fig. 2). Strongly anaerobic conditions likely did not occur in the present study. Snyder et al. (2002), also working on Histosols in the same general area, did not detect significant amounts of CH_4 evolution from flooded rice fields.

Nutrients are released as a result of microbial mineralization from soil organic matter. Annual nutrient release in Florida Histosols has been reported to be as high as 72 and 1200 kg ha^{-1} of P and N, respectively (Diaz et al., 1993; Terry, 1980). Nutrient release was not detected in the fallow field, as there was either a decrease or no change in nutrient content from Days 0 to 42 (Fig. 6). Also, these data were collected during the coolest season of the year. Low levels of mineralization and leaching losses could have minimized differences or reduced nutrient levels across time. The response was different in the residue field, which generally showed nutrient releases (Fig. 6). Even with the high rates of nutrient mineralization in Histosols and potential for leaching during the 42-d period, the fresh organic matter from the plants in the residue field decomposed faster than the native soil organic matter, resulting in detectable amounts of nutrient release in the surface soil. The reason for the pH decline in the fallow field and increase in the residue field may be related to addition of fresh residue, but will require further investigation.

Both radioactive C and soil RESP methods were effective in detecting differences in C loss due to tillage practice in Histosols, even though each method was measuring a different C substrate for microbial utilization; OP measures the potential decomposition of recalcitrant organic C compounds, and RESP measures potential decomposition of all available C sources. But in the fallow field OP and RESP were not correlated, while in the residue field there was a correlation between OP and RESP (Table 3). The reason for the lack of correlation in the fallow field is probably because of nutrient limitations for OP microorganisms, as indicated by a decline in soil P and K across 42 d and available C limitations for RESP microorganisms as indicated by a lack of a readily available C source (residue cover). In the residue field, there were adequate nutrients and C availability for all microbes as indicated by an increase in soil P and K across 42 d and the presence of a readily available C source.

Correlation analyses for the fallow field also showed a negative relationship between OP and MBC and MBN and no relationship between OP and MBC and MBN in the residue field (Table 2). We surmise that the microorganisms in the fallow field responsible for OP had to compete with other microbes for nutrients in the soil so that greater microbial biomass from soil populations resulted in fewer populations of microbes that degraded recalcitrant compounds. This is indicated in the fallow field by OP showing positive correlation between EXC and EXN, while MBC and MBN showed negative correlations with EXN. In contrast, the residue field had adequate amounts of nutrients for the microbial populations such that a relationship between OP, MBC, and MBN was not obtained. Consequently, there was no correlation between MBC or MBN and EXC or EXN; EXC and EXN were in adequate supply for microbial growth, so there was little competition for soil nutrients. However, higher EXN levels promoted greater OP, suggesting a N limitation for degradation of organic matter by microorganisms.

Higher soil temperatures resulted in greater OP in the fallow field as indicated by correlation analysis (Table 3), which is consistent with the finding that oxidation of organic matter in soil is increased with increasing temperatures (Volk, 1973). Since soil temperatures in the residue field were not correlated with OP (Table 3), and there were no significant differences among treatments in the residue field (Table 2), it appears that the unincorporated plant material on the soil surface may have helped maintain lower temperatures, thus leading to lower OP than the nonresidue field under various tillage practices.

Soil water content was not related to OP in the fallow field (Table 3) because the field drained within a short enough time period after rain to maintain favorable soil conditions for microbial growth. Microbial biomass C and N were increased with increased soil water content in the fallow field (Table 3). However, in the residue field, higher water contents resulted in lower OP levels (Table 3).

Soil RESP was increased with increasing soil water content in the fallow field and decreased with increasing water content in the residue field. In the fallow field, the soil drained sufficiently so that O_2 diffused into the soil and CO_2 diffused out of the soil into the atmosphere. In the residue field, the plant organic matter absorbed and retained some water, which reduced gaseous diffusion in the soil to a greater extent than in the fallow field. The differences in CO_2 flux between the two fields was probably more of a physical effect (soil water content or other soil property) rather than a biological phenomenon due to microbial activity, because RESP was not related to MBC or MBN (Table 3).

CONCLUSIONS

Some of the principles involved in minimum tillage to conserve soil C in mineral soils also apply to organic soils. Namely, greater potential for C loss occurred from implements that created the greatest soil disturbance, which was shown by both OP and RESP methods. Unlike mineral soils using CO_2 flux measurements (RESP), C losses due to tillage could only be detected for up to 20 d after tillage in the fallow soil, suggesting that most of soil C was unavailable for microbial utilization. But, similar to mineral soils using CO_2 flux measurements, RESP in the residue field and OP measurements in both fields showed long-term (up to 42 d) effects of tillage resulting in C losses. Potential for C loss (RESP) as in a mineral soil was greatest within 24 h of tillage. Since RESP was not related to MBC or MBN in either field, the data would suggest the CO_2 release even with the high soil C content was more a physical than a biological phenomena. In mineral soils, increasing the readily available C supply (EXC) increases RESP, which occurred in our study regardless of residue cover. However, in a Histosol it appears that available N (EXN) was more important for microorganisms responsible for degradation of recalcitrant organic compounds. Short flooding periods or a few days of low temperatures in a Histosol does not result in a drastic change in microbial activity (OP and RESP) from tillage practices compared with no-till. As in mineral soils, fresh organic material on the surface of a Histosol is readily decomposed, but unlike mineral soils, nutrient mineralization may be high, especially P, regardless of tillage depth. Nutrient mineralization can be detected in the soil surface within 42 d after tillage. Even though Histosols in the EAA are losing large amounts of C mostly because of aerobic microbial oxidation of organic matter, minimum tillage practices provides a means to reduce those losses and should be a major component in the overall management strategy for soil conservation.

ACKNOWLEDGMENTS

The authors thank Dr. Clair Erickson of Monsanto Corp. for financial support to conduct this research, and Brian Maxwell for his technical assistance in data collection and sample analysis.

REFERENCES

Broadbent, F.E. 1960. Factors influencing the decomposition of organic soil of the California delta. Hilgardia 29:587–612.

Diaz, O.A., D.L. Anderson, and E.A. Hanlon. 1993. Phosphorus mineralization from Histosols of the Everglades Agricultural Area. Soil Sci. 156:178–185.

Dick, W.A., and J.T. Durkalski. 1998. No-tillage production agriculture and carbon sequestration in a Typic Fragiudalf of northeastern Ohio. p. 59–71. *In* R. Lal et al. (ed.) Management of carbon sequestration in soil. CRC Press, New York.

Ellert, B.H., and H.H. Janzen. 1999. Short-term influence of tillage on CO_2 fluxes from a semi- arid soil on the Canadian prairies. Soil Tillage Res. 50:21–32.

Farnham, R.S., and H.R. Finney. 1965. Classification and properties of organic soils. Adv. Agron. 17:115–162.

Follett, R.F., and D.S. Schimel. 1989. Effect of tillage practices on microbial biomass dynamics. Soil Sci. Soc. Am. J. 53:1091–1096.

Glaz, B., M.F. Ulloa, and R. Parrado. 1989. Cultivation, cultivar, and crop age effects on sugarcane. Agron. J. 81:163–167.

Granatstein, D.M., D.F. Bezdicek, V.L. Cochran, L.F. Elliott, and J. Hammel. 1987. Long-term tillage and rotation effects on soil microbial biomass carbon and nitrogen. Biol. Fertil. Soils 5:265–270.

Ingebritsen, S.E., C. McVoy, B. Glaz, and W. Park. 1999. Florida Everglades. p. 95–120. *In* D. Galloway et al. (ed.) Land subsidence in the United States. Circ. 1182. U.S. Geological Survey, Denver, CO.

Livingston, S.J., L.D. Norton, and L.T. West. 1990. Effect of long-term cultivation on aggregate stability, organic carbon distribution, and porosity of two soil series. p. 89–95. *In* L.A. Douglas (ed.) Soil micromorphology. Elsevier Science Publ., Amsterdam, the Netherlands.

Matherne, R.J., R.D. Breaux, and R.D. Jackson. 1972. Culture of sugarcane for sugar production in the Mississippi delta. USDA, ARS Handbook 417. U.S. Gov. Print. Office, Washington, DC.

Morris, D.R., and G.H. Snyder. 2002. Substrate induced respiration in soils using ^{14}C (carboxyl)-benzoate. Paper 784. *In* Trans. 17th World Congr. Soil Sci., Bangkok, Thailand [CD-ROM]. 14–21 Aug. 2002. Int. Union of Soil Sci., Bangkok, Thailand.

Neller, J.R. 1943. Significance of the composition of soil air in Everglades peat land. Soil Sci. Soc. Am. Proc. 8:341–344.

Reicosky, D.C. 1997. Tillage-induced CO_2 emissions from soil. Nutr. Cycling Agroecosyst. 49:273–285.

Reicosky, D.C. 2002. Long-term effect of moldboard plowing on tillage-induced CO_2 loss. p. 87–97. *In* J.M. Kimble et al. (ed.) Agricultural practices and policies for carbon sequestration in soil. Lewis Publ., Boca Raton, FL.

Reicosky, D.C., W.A. Dugas, and H.A. Torbert. 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Tillage Res. 41:105–118.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50(3): 253–261.

Reicosky, D.C., and M.J. Lindstrom. 1995. Impact of fall tillage and short-term carbon dioxide flux. p. 177–187. *In* R. Lal et al. (ed.) Soils and global change. Lewis Publ., Boca Raton, FL.

Rochette, P., and D.A. Angers. 1999. Soil surface carbon dioxide fluxes induced by spring, summer, and fall moldboard plowing in a sandy loam. Soil Sci. Soc. Am. J. 63:621–628.

Sanchez, C.A. 1990. Soil-testing and fertilization recommendations for crop production on organic soils in Florida. Bull. 87. Univ. of Florida, Gainesville.

SAS Institute. 1999. SAS system for Windows. v. 8.01. SAS Inst., Cary, NC.

Shih, S.F., B. Glaz, and R.E. Barnes, Jr. 1998. Subsidence of organic soils in the Everglades Agricultural Area during the past 19 years. Soil Crop Sci. Soc. Fla. Proc. 57:20–29.

Snyder, G.H. 1994. Soils of the EAA. p. 27–41. *In* A.B. Bottcher and F.T. Izuno (ed.) Everglades Agricultural Area (EAA). Univ. Press of Florida, Gainesville.

Snyder, G.H., H.W. Burdine, J.R. Crockett, G.J. Gascho, D.S. Harrison, G. Kidder, J.W. Mishoe, D.L. Myhre, F.M. Pate, and S.F. Shih. 1978. Water table management for organic soil conservation and crop production in the Florida Everglades. Bull. 801. Univ. of Florida Agric. Exp. Stn., Gainesville.

Snyder, G.H., K.R. Reddy, and C.W. Lindau. 2002. Methane evolution from Histosol-grown rice. Paper 293. *In* 17th World Congr. Soil Sci., Bangkok, Thailand [CD-ROM]. 14–21 Aug. 2002. Int. Union of Soil Sci., Bangkok, Thailand.

Sparling, G.P., C.W. Feltham, J. Reynolds, A.W. West, and P. Singleton. 1990. Estimation of soil microbial C by a fumigation-extraction method: Use on soils of high organic matter content, and a reassessment of the k_{ec} factor. Soil Biol. Biochem. 22:301–307.

Stephens, J.C., L.H. Allen, Jr., and E. Chen. 1984. Organic soil subsidence. Geol. Soc. Am. Reviews in Engin. Geology 6:107–121.

Tao, J., R. Littell, M. Patetta, C. Truxillo, and R. Wolfinger. 2002. Mixed models analyses using the SAS system course notes. SAS Institute, Cary, NC.

Tate, R.L. III. 1979. Microbial activity in organic soils as affected by soil depth and crop. Appl. Environ. Microbiol. 37:1085–1090.

Tate, R.L. III. 1980. Microbial oxidation of organic matter of Histosols. Adv. Microb. Ecol. 4:169–201.

Terry, R.E. 1980. Nitrogen mineralization in Florida Histosols. Soil Sci. Soc. Am. J. 44:747–750.

USEPA. 1987. Handbook of methods for acid deposition studies: Laboratory methods for surface water chemistry. U.S. Gov. Print. Office, Washington, DC.

Volk, B.G. 1973. Everglades Histosol subsidence: 1. CO_2 evolution as affected by soil type, temperature, and moisture. Soil Crop Sci. Soc. Fla. Proc. 32:132–135.

Voroney, R.P., and J.P. Winter. 1993. Soil microbial biomass C and N. p. 277–286. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publ., Boca Raton, FL.

Waksman, S.A., and K.R. Stevens. 1929. Contribution to the chemical composition of peat: V. The role of microorganisms in peat formation and decomposition. Soil Sci. 28:315–340.

Williams, R.T., and R.L. Crawford. 1983. Effects of various physiochemical factors on microbial activity in peatlands: Aerobic biodegradative processes. Can. J. Microbiol. 29:1430–1437.

Zibilske, L.M. 1994. Carbon mineralization. p. 835–864. *In* R.W. Weaver et al. (ed.) Methods of soil analysis. Part 2: Microbiological and biochemical methods. SSSA Book Ser. No. 5. SSSA, Madison, WI.