EFFECT OF IMPLEMENT ON SOIL CO_2 EFFLUX: FALL VS. SPRING TILLAGE

S. A. Prior, R. L. Raper, G. B. Runion

ABSTRACT. *Assessing strategies to help mitigate the rise in atmospheric CO_2 includes evaluation of management decisions concerning tillage practices that influence soil carbon loss. Information is lacking on seasonal CO_2 efflux patterns, as affected by degree of soil disturbance/residue mixing and time of tillage operations. An experiment was conducted following a grain sorghum [*Sorghum bicolor*] (L.) Moench.] crop on a Norfolk loamy sand (Typic Kandiudults) in east−central Alabama to characterize soil CO_2 efflux patterns as affected by tillage implement (disk−type, chisel−type, and undisturbed) and time of soil disturbance (fall and spring). Soil CO_2 efflux assessment began immediately following fall tillage and continued for a period of about six months. Measures were also taken in the spring after imposing tillage treatments on another set of plots. Concurrent measures were also made on undisturbed plots. For fall measurements, increased CO_2 efflux was related to degree of soil disturbance. Losses were similar for the chisel and undisturbed treatments and lower than the disk treatment; cumulative efflux estimates also reflected such differences. With spring tillage, CO_2 losses for the undisturbed and disk treatment were similar, while the chisel treatment exhibited a slightly lower loss. Results suggest that selection of fall tillage equipment that maintains surface residue and minimizes soil disturbance could help reduce CO_2 loss. However, such considerations for spring tillage operations would not result in a substantial reduction in CO_2 loss.*

Keywords. *Carbon, Chisel, CO_2, Disk, Flux, Tillage.*

Increases in trace gases such as atmospheric CO_2 (Keeling and Whorf, 1994) have raised concerns about the potential for global climate change. Carbon dioxide is the principal mobile form of carbon (C) in the atmosphere, and its rise has been attributed to anthropogenic causes such as accelerated use of fossil fuels and land use change. The implication of land use change contributing to this increase underscores the importance of understanding C dynamics in terrestrial ecosystems. Agroecosystems are often viewed as CO_2 sources since long−term cultivation has reduced soil C (Houghton et al., 1983). Soil C reduction is principally driven by tillage−induced volatile losses of soil CO_2 to the atmosphere. However, there is interest in the potential of agricultural soils to store surplus atmospheric CO_2 as soil C, since residue management decisions that limit tillage intensity can influence soil C dynamics (Kern and Johnson, 1993; Paustian et al., 2000).

Sound residue management decisions are needed to protect the global environment and land resources, while ensuring desired crop production goals (Phillips et al., 1980). Farming practices that reduce soil tillage and surface residue incorporation can help conserve soil structure due to higher organic matter (Campbell and Zentner, 1993), improve water holding capacity of soils (Hudson, 1994), and reduce soil erosion (Blevins et al., 1984; Unger and McCalla, 1980). Furthermore, such practices can provide these benefits while potentially enhancing soil C storage by limiting CO_2 emissions to the atmosphere. Residue management decisions that reduce tillage intensity could offset decreased soil C noted in degraded agricultural soils caused by the long−term intensive cultivation associated with conventional tillage practices.

Characterization of CO_2 loss patterns associated with different tillage practices is needed to evaluate tillage and management practices that could reduce soil C loss. Short−term CO_2 efflux patterns associated with tillage operations have recently been studied (e.g., Reicosky and Lindstrom, 1993; Reicosky et al., 1997, 1999; Ellert and Janzen, 1999; Prior et a1., 2000; La Scala et a1., 2001). Some reports indicate that increased CO_2 losses associated with fall tillage methods were due to a higher degree of soil disturbance and residue incorporation into the tilled soil (Reicosky and Lindstrom, 1993; La Scala et al., 2001). Soil tillage initially facilitates the physical release of CO_2 from soil pores after the disturbance event, followed by increased soil biota activity due to increased aggregate exposure and residue−soil contact from soil mixing. Similar findings have been reported by others assessing efflux associated with spring tillage operations (Reicosky et al., 1997, 1999; Ellert and Janzen, 1999; Prior et al., 2000). Collectively, these studies have shown that the rapid release or peak in CO_2 efflux was brief; Ellert and Janzen (1999) reported that increasing the number of tillage passes (following initial tillage) did not substantially increase soil CO_2 losses. Although Hendrix et al. (1988) did not detect an immediate release of CO_2 following spring tillage operations, they and others (Buyanovsky and Wagner, 1983) have

---

Article was submitted for review in May 2003; approved for publication by the Power & Machinery Division of ASAE in December 2003.

The authors are **Stephen A. Prior,** Research Plant Physiologist, **Randy L. Raper, ASAE Member Engineer,** Research Agricultural Engineer, and **G. Brett Runion,** Research Plant Pathologist/Soil Microbiologist, USDA−ARS National Soil Dynamics Laboratory, Auburn, Alabama. **Corresponding author:** Dr. Stephen A. Prior, USDA−ARS National Soil Dynamics Laboratory, 411 South Donahue Drive, Auburn, AL 36832; phone: 334−844−4741, ext. 143; fax: 334−887−8597; e−mail: sprior@acesag.auburn.edu.

emphasized the importance of considering how changes in soil temperature and moisture conditions influence seasonal CO_2 efflux patterns. There are indications that soil microbial activity was impacted more by temperature, whereas soil moisture had a greater impact on the decomposition of surface residues (Hendrix et al., 1988). Soil CO_2 concentration has been shown to be influenced by soil temperatures above 15°C, while the effect of soil water content was most evident at temperatures greater than 10°C (Buyanovsky and Wagner, 1983). Such considerations are especially important in the southeastern U.S. where duration of higher soil temperatures and frequency of rainfall events are greater during the winter or fallow periods. Typically, soil C levels can be low in this region due to such factors in combination with the intensive conventional tillage practices that have been traditionally employed.

The objective of this work was to determine seasonal CO_2 efflux patterns associated with different tillage implement operations conducted in the fall vs. spring. Such data are needed to formulate recommendations that may lead to adoption of optimum management methods and times of operation, which can increase net soil C sequestration and ensure improvements in soil quality and crop productivity.

MATERIALS AND METHODS

The study was conducted on a Norfolk loamy sand (fine−loamy, siliceous themlic, Typic Kandiudults; FAO classification Luxic Ferralsols) at the E.V. Smith Research Center of the Alabama Agricultural Experiment Station in east central Alabama (32° 25.467′ N, 85° 53.403′ W). Except for one year of switch grass (*Panicum virgatum*) in 1993, the study area has a long−term history (over 10 years) of fallow conditions and was disked in the spring of each year for weed control. Grain sorghum seed (Dekalb 55) were sown using a John Deere Model B grain drill with 0.18 m spaced rows on 9 June 1998. The final stand density was 37 plants m^{-2}. Fertilizer application rates were based on standard soil tests conducted by the Auburn University Soil Testing Laboratory. In addition, subsamples of soil from two depths (0 to 15 cm and 15 to 30 cm) were sieved (2 mm mesh) to remove residue fragments, dried (55°C), ground to pass a 0.15 mm sieve, and analyzed for total nitrogen (N) and carbon (C) content (CN 2000, Leco Corp., St. Joseph, Mich.). The respective mean N and C values were 0.43 and 6.0 g kg^{-1} for the 0 to 15 cm depth increment and 0.30 and 4.6 g kg^{-1} for the 15 to 30 cm depth increment. Estimates of aboveground non−yield residue and grain yield at maturity (24 September 1998) were 3125 and 955 kg ha^{-1}, respectively (Raper, 2001). Weed control was conducted in the winter fallow season with glyphosate (N−[phosphonomethyl] glycine) herbicide.

Characterization of soil CO_2 efflux patterns was initiated about 60 days after harvest. Equipment−induced soil gas efflux was measured at midday immediately following implement operations and periodically thereafter using a Li−Cor 6200 gas exchange system (Li−Cor, Inc., Lincoln, Neb.) equipped with a Model 6000−09 soil chamber (0.75×10^{-3} m^3 volume, 0.1 m diameter) using procedures described by Prior et al. (1997). Triplicate readings were taken at random locations in all plots. The soil chamber was scrubbed to a CO_2 level below ambient (250 μLL^{-1}) and allowed to equilibrate for 30 to 45 s prior to initiation of measurements. Soil CO_2 efflux rate was determined by the change in CO_2 concentration over a 30s period. Soil temperature was determined (0.1 m depth) at the time of efflux measurement. Soil water content was gravimetrically determined on composite samples collected from the surface to 0.15 m with a standard soil probe. Local weather data (rainfall and air temperature) were provided by a station located approximately 0.5 km from the study site.

Tillage intensity levels were obtained by the use of commercial implements, a John Deere 210 tandem disk harrow (double−offset; Deere & Company, Moline, Ill.) and a DMI Tiger−Mate II high−residue field cultivator (DMI, Inc., Goodfield, Ill.), both operated at a depth of approximately 8 cm and a width of 3.8 m. The tandem disk harrow had front and rear disk angle adjustments to vary aggressiveness. The front disk gangs were adjusted to the medial setting of 16.5°, and the rear gangs were adjusted to the most aggressive setting of 14.3°. The disk blades were spaced at 0.23 m and had a diameter of 0.51 m. The field cultivator had 25 sweeps of 0.18 m width, spaced approximately 0.61 m apart on five toolbars of the frame. These could be classified as disk−type and chisel−type implements and will be referred to as “disk” and “chisel” in the treatment descriptions. All operations used a John Deere 8300 tractor (8402 kg, 149 kW), and the speed of operation was constant (5 km h^{-1}).

The experimental design was a randomized complete block with four replications. The treatments were: (l) fall disk, (2) fall chisel, (3) spring disk, (4) spring chisel, and (5) undisturbed. The fall CO_2 efflux measurements were initiated immediately following tillage (2 December 1998) and monitored periodically until termination of the study (approximately 180 days). The same tillage treatments were imposed (6 April 1999) on another set of plots (undisturbed since harvest), and efflux quantities were monitored until termination of the study (approximately 60 days). Soil CO_2 efflux was concurrently measured on plots left undisturbed from harvest to termination of the study, which occurred on 25 May 1999. This study did not assess CO_2 losses associated with the actual growing season due to the difficultly of differentiating root respiration from microbial respiration. Estimates of cumulative efflux were calculated using a basic numerical integration technique (i.e., trapezoidal rule). It is important to note that these calculations were made strictly for overall treatment comparisons and were not intended to generate quantitative numbers of soil C losses. The latter was beyond the scope of our efforts and would have required more resources to increase the frequency of efflux measurements or employment of other techniques. Total cumulative efflux for the fall treatments was determined for the time interval covering the period from fall tillage initiation to end of the study. Cumulative efflux for the spring treatments was determined for the time interval encompassing the period from spring tillage initiation to end of the study. The total cumulative efflux for the spring tillage treatments (including efflux from the overwintering period when soil was undisturbed) was also calculated (i.e., harvest to end of study). This calculation assumed that the cumulative efflux for the undisturbed treatment during the overwintering period is equivalent or representative of CO_2 losses from undisturbed disk and chisel plots for the same interval. Statistical analyses of data were performed using the Mixed Procedure of SAS (Littell et al., 1996). A significance level of $P < 0.10$ was established *a priori*.

Soil CO_2 efflux was regressed onto soil temperature and water content data using two techniques. First, the raw data (sorted by season, treatment, and replicate) were tested using linear regression, and the resulting slope and intercept variables were then tested for differences among treatments. Second, soil temperature data were "averaged" for 2.0°C intervals, regardless of day of year. Averaging served to reduce the influence of outliers on the response of soil CO_2 efflux to temperature throughout the experiment. The data were then subjected to analysis using linear and non−linear regression techniques (SAS, 1985) to determine the relationship between soil CO_2 efflux and soil temperature. A similar procedure was used to investigate the relationship between soil CO_2 efflux and soil water content (at 2% intervals).

RESULTS AND DISCUSSION

FALL TILLAGE

Upon introducing implement operations on residue−covered plots, CO_2 efflux rates increased due to soil disturbance (fig. 1a), a finding that supports previous reports on short−term CO_2 efflux patterns (Reicosky and Lindstrom, 1993; Ellert and Janzen, 1999; Reicosky et al., 1999; Prior et al., 2000). Chisel use resulted in the highest initial efflux rate. The disk

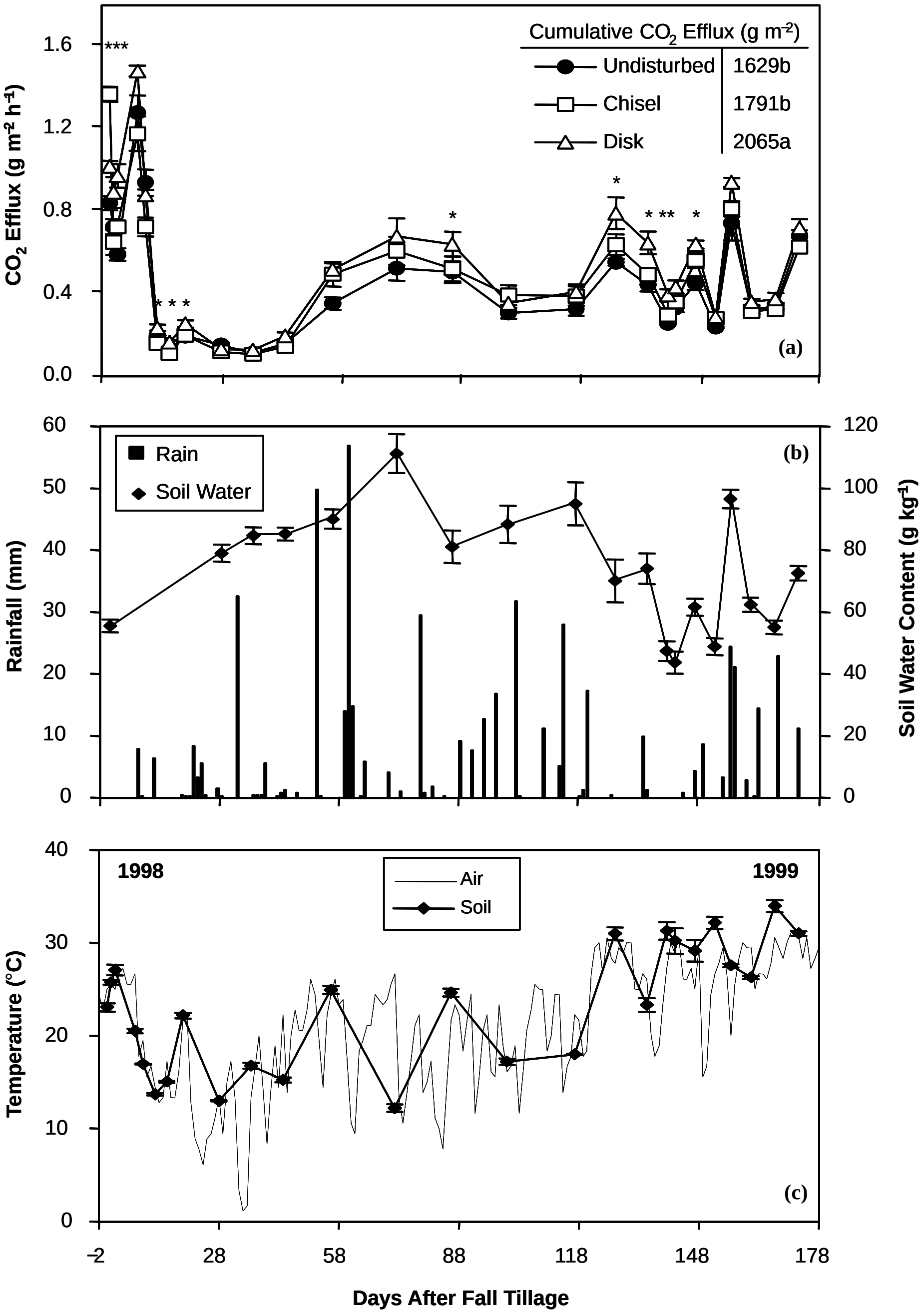

Figure 1. (a) Soil CO_2 efflux, (b) soil water content and rainfall, and (c) soil temperature and maximum air temperature during the sampling period associated with fall tillage treatments. Means and standard errors are shown. Asterisks in the efflux graph indicate significant tillage effect (p = 0.10), and the insert lists estimated cumulative CO_2 effluxes for the various treatments (means followed by the same letter are not significantly different from each other).

treatment exhibited an intermediate value, followed by the undisturbed treatment, which had the lowest efflux rate. Visual differences in soil disturbance between implements were noted. The disk treatment had the appearance of more uniform soil disturbance and residue mixing. In contrast, the chisel treatment appeared to incorporate less residue and increase soil surface roughness. This implies an increased surface area and the possible presence of more soil fissures, leading to more rapid physical release of soil CO_2 upon tillage (Reicosky and Lindstrom, 1993). It is important to note that, while no quantitative measure of soil surface roughness was made in this study, Raper (2002) reported that a chisel−type implement buried less crop residue than a disk−type implement.

Efflux rates decreased over the following few days after the initial tillage event. However, during this period, the disk treatment exhibited greater CO_2 efflux compared to the other two treatments (fig. 1a). The sharp increase in efflux rates noted on 7 DAFT (days after fall tillage) was related to rainfall, but CO_2 efflux rates were similar across treatments. Some short−term studies have reported a stimulation of CO_2 efflux following rainfall events (Prior et al., 1997; Reicosky et al., 1999), while others have observed that rainfall can temporarily depresses CO_2 efflux in tilled areas (for a few days) and that peak efflux values are much lower compared to those observed immediately following tillage (Reicosky and Lindstrom, 1993). Efflux rates in this study were as high (or higher) than those observed after the initial tillage event. Subsequently, a sharp drop was observed at 9 DAFT that leveled off at 12 to 19 DAFT. During this period, efflux rates were substantially lower (than values observed immediately following tillage) and generally showed that the disk treatment had the highest efflux rates. From 28 to 117 DAFT, little treatment differences were observed except on 86 DAFT, where again the disk treatment had the highest efflux rate. During the period of 127 to 147 DAFT, the disk treatment generally exhibited the highest efflux rates, but afterwards (to termination of study) no treatment differences were observed.

To facilitate the comparison of all treatment trends as a function of time, estimates of cumulative CO_2 efflux were calculated using a basic numerical integration technique (i.e., trapezoidal rule). The greatest CO_2 loss occurred from the disk treatment, while the chisel treatment showed an intermediate value relative to undisturbed conditions (see insert in fig. 1a). The higher loss noted in the disk treatment reflects an overall increase in microbial respiration caused by greater incorporation of crop residue into the soil. In contrast, the lower losses observed in the other treatments reflect conditions in which residue−soil contact was minimized (more residue remained on the soil surface), resulting in a lower decomposition rate. These data support the contention that avoiding tillage action that promotes the aggressive mixing of crop residue with soil can help conserve soil carbon (Kern and Johnson, 1993; Paustian et al., 2000).

SPRING TILLAGE

Efflux patterns were different in the spring tillage treatments on residue−covered plots (left undisturbed since the fall) compared to those observed in the fall tillage plots (figs. 1a and 2a). The dramatic increase in CO_2 efflux rates seen in the fall tillage operations was not found following spring operations. In fact, the chisel treatment exhibited a decrease in efflux rate relative to undisturbed and disk treatments, which were similar to each other. The reason efflux patterns were different in spring (vs. fall) for the chisel treatment is unclear. Possibly, there was a greater build−up of CO_2 in the soil at the time of fall tillage due to microbial breakdown of easily decomposable organic substrate. Spring plots may have had a smaller soil CO_2 reservoir (by the time of spring tillage) due to winter losses attributable to both microbial respiration and physical displacement of soil CO_2 from frequent rainfall. Furthermore, organic substrate in these study plots may have become more recalcitrant with time (Parr and Papendick, 1978).

Efflux rates decreased over the next few 1 to 2 days after spring tillage (DAST). During this period, both the disk and chisel treatments had lower rates compared to the undisturbed treatment (fig. 2a). On 7 DAST, the chisel treatment again exhibited the lowest efflux rate, and similar trends were observed in the following two sample periods. On 17 DAST, the disk treatment had a higher efflux rate compared to the other treatments, which were similar to each other. From 22 to 42 DAST, the general pattern was for the chisel treatment to have the lower efflux rate. On the final day of measurement, the disk treatment had the highest efflux rate, but the other two treatments were similar to each other.

Estimates of cumulative CO_2 were also calculated for spring tillage operations (see insert in fig. 2a) to facilitate comparison of treatment trends. Cumulative losses of CO_2 from the undisturbed and disk treatments, from spring tillage to termination of study, were similar to each other; however, the chisel treatment exhibited a slightly lower value. The lower cumulative efflux for the chisel treatment was most likely due to less residue burial (compared to disk use), as reported by Raper (2002). Visual observations of plots after chisel use showed less residue−soil contact, indicating that residues may have been more susceptible to surface drying, thereby hindering decomposition (Hendrix et al., 1988).

The total cumulative efflux for the spring tillage treatments, inclusive of losses occurring during the overwintering period when soil had been left undisturbed (125 days), was also calculated (i.e., fall to end of study, 175 days). This allowed for a direct comparison of cumulative efflux from fall and spring treatments (fig. 3). For the spring tillage treatments, total loss of CO_2 for the disk treatment was similar to that of the undisturbed treatment, and the chisel treatment exhibited a trend for a slight reduction in total CO_2 loss. It is clear that the cumulative efflux for the longer time interval of fall to spring tillage (125 days) represented the greater loss compared to the period of spring tillage to end of the study (50 days). With fall tillage, chisel use resulted in less residue mixing (Raper, 2002), which probably accounts for the cumulative efflux being similar to that observed for undisturbed conditions. In comparison, the disk treatment had the highest total loss, which reflects a greater degree of soil disturbance/residue mixing. This comparison suggests that selection of implement usage during fall operations could impact soil C loss patterns; however, such considerations for spring operations would have a minimal impact.

SOIL TEMPERATURE AND WATER

Fall and spring treatment effects on soil water content and temperature were infrequent; changes were small and did little to help interpret differences in CO_2 efflux patterns between treatments. Thus, data shown are overall means of all treatments. In general, CO_2 efflux followed changes in soil water content and temperature over time (figs. 1 and 2).

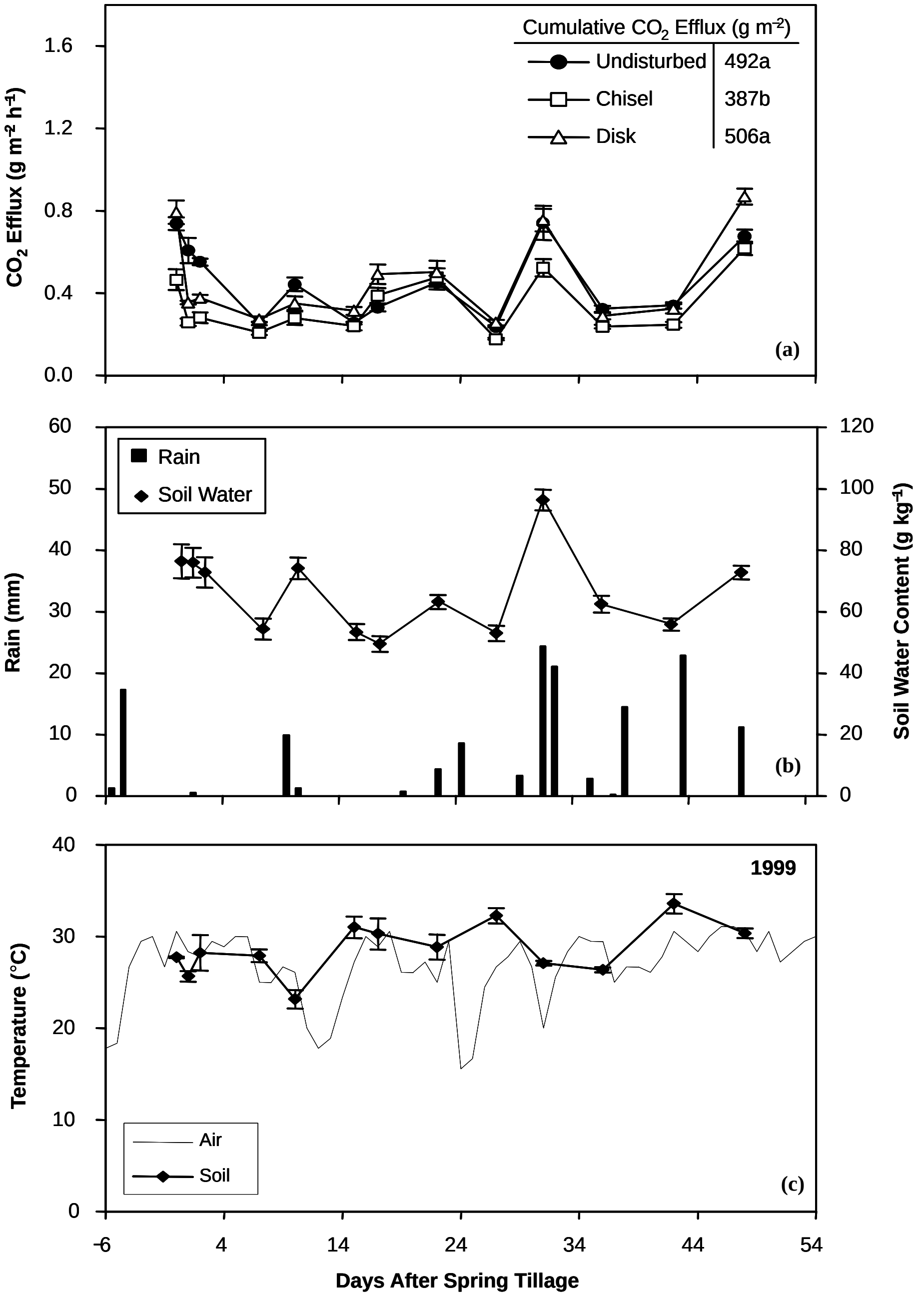

Figure 2. (a) Soil CO_2 efflux, (b) soil water content and rainfall, and (c) soil temperature and maximum air temperature during the sampling period associated with spring tillage treatments. Means and standard errors are shown. Asterisks in the efflux graph indicate significant tillage effect ($p = 0.10$), and the insert lists estimated cumulative CO_2 effluxes for the various treatments (means followed by the same letter are not significantly different from each other).

Fall tillage treatment effects on soil water content were rare (i.e., 7 and 156 DAFT). Lack of clear treatment effects may be related to frequent rainfall events (fig. 1b) coupled with experimental variability. There were 60 rainfall events (total of 524 mm) ranging from 0.25 to 56.9 mm (average of 8.7 mm). Soil water content ranged from 44 to 111 g kg^{-1} (74 g kg^{-1} average). Likewise, treatment effects on soil temperature were sporadic. Soil temperature at the time of CO_2 efflux measurements ranged from 12.9°C to 34.0°C (23.2°C average), while the range of average daily maximum temperature was 1.1°C to 31.1°C with a 20.7°C average (fig. 1c). Toward the end of the study (April−May), there were a few cases (127, 142, 152, 167 DAFT) where the undisturbed soil temperature exhibited trends that were lower than in the other tilled treatments, but differences were small (data not shown). It has been reported that soils in no−tillage systems exhibit cooler temperatures (vs. tilled soils), which can create seed germination and early stand development problems (Swan et al., 1987; Bradford and Peterson, 2000). However, it is important to note that in our study, "undisturbed" denotes lack of tillage during one overwintering period, rather than a long−term history of no−tillage. Use of no−tillage management at this site (multiple seasons) could result in more consistently lower soil temperatures due to surface residue accumulation.

There were few differences in soil temperature and water content attributable to the spring tillage, and noted patterns were somewhat similar to fall treatment observations. Thus, data shown are overall means of all treatments (figs. 2b and

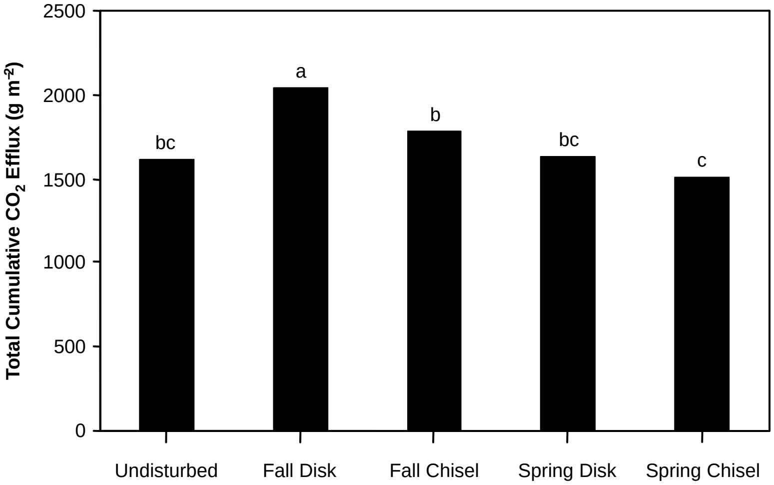

Figure 3. Total cumulative CO_2 efflux for fall and spring tillage treatments. Bars with the same letter are not significantly different from each other.

2c). During this period, 14 rainfall events (125.7 mm total) occurred; values ranged from 0.25 to 24.4 mm (9 mm average). Soil water content ranged from 49 to 96 g kg^{-1} (66 g kg^{-1} average). The soil temperature at the time of CO_2 efflux measurements ranged from 23.2°C to 33.6°C (28.7°C average), while the range of daily air maximum temperature was 15.6°C to 31.1°C (26.8°C average).

A further examination of the relationship of soil CO_2 efflux with soil temperature and water content utilized two regression techniques (data not shown). Linear regression of the raw data demonstrated low (<0.10) r^2 values for all data sets tested; this was due, primarily, to the high degree of variability across the time period of the experiment. Fall tillage (both chisel and disk) resulted in a steeper response of efflux to increasing temperature compared to the undisturbed treatment. The response of efflux in the fall to soil water content was steeper for the undisturbed treatment compared with chiseling. This analysis demonstrated that tillage intensity treatments did not affect the relationship of soil CO_2 efflux with either soil temperature or water content for the spring data set.

Soil CO_2 efflux, using the averaged data, showed a strong, positive linear response to soil water content in the spring (r^2 values >0.94). This analysis also confirmed the results of the test using the raw data, in that the response was similar for all treatments. The response of efflux to soil water content was more variable in the fall; the undisturbed treatment showed a fair linear response ($r^2 = 0.59$) followed by the chisel treatment ($r^2 = 0.31$), and the disk treatment had the poorest fit ($r^2 = 0.18$). An increased fit of efflux to soil water content for undisturbed and chiseling to both quadratic ($r^2 = 0.73$ and 0.80, respectively) and cubic ($r^2 = 0.91$ and 0.88, respectively) equations was observed; however, the disk treatment was not adequately described ($r^2 < 0.40$) by any polynomial equation tested. With the exception of the undisturbed treatment in the spring ($r^2 = 0.68$), no strong linear responses ($r^2 < 0.25$) of efflux to soil temperature were observed. Fit of efflux to soil temperature was slightly improved for both disk and chisel when fit to higher−order polynomials ($r^2 = 0.40$ to 0.60); however, no equation provided a high degree of fit, likely due to high variability across the measurement period. Soil CO_2 efflux has generally been shown to increase as an exponential function of temperature (Fang and Moncrieff, 2001); however, in our study, tests using an exponential function also failed to provide a good fit (i.e., $r^2 > 0.80$) of soil CO_2 efflux to soil temperature in the field.

CONCLUSIONS

This work demonstrates that tillage intensity, as induced by the use different tillage tool types, can influence loss of C from soil, but this was dependent on time of year that tillage was conducted. Results suggest that selection of fall tillage equipment that maintains surface residue and minimizes soil disturbance could help reduce CO_2 losses. For spring tillage operations, however, reductions in CO_2 loss would be small. The findings also underscore the importance of assessing CO_2 efflux during the overwintering period, since the greatest proportion of total loss occurred during this period.

ACKNOWLEDGEMENTS

The authors acknowledge Barry G. Dorman and Eric B. Schwab (USDA−ARS National Soil Dynamics Laboratory), H. Eric Hall (Department of Biosystems Engineering, Auburn University, Auburn, Ala.), Tammy K. Dorman (School of Forestry and Wildlife Sciences, Auburn University), and Robert M. Durbin (Superintendent, E. V. Smith Research Center) and his support staff for their assistance. Support from the Biological and Environmental Research Program (BER), U.S. Department of Energy, Interagency Agreement No. DE−AIO2−95ER62088 is gratefully acknowledged.

REFERENCES

Blevins, R. L., M. S. Smith, and G. W. Thomas. 1984. Changes in soil properties under no−tillage. In *No−Tillage Agriculture: Principles and Practices*, 190−230. R. E. Phillips, and S. H. Phillips, eds. New York, N.Y.: Van Nostrand Reinhold.

Bradford, J. M., and G. A. Peterson. 2000. Conservation tillage. In *Handbook of Soil Science*, 247−270. M. E. Sumner, ed. Boca Raton Fla.: CRC Press.

Buyanovsky, G. A., and G. H. Wagner. 1983. Annual cycles of carbon dioxide level in soil air. *SSSA J.* 47(6): 1139−1145.

Campbell, C. A., and R. P. Zentner. 1993. Soil organic matter as influenced by crop rotation and fertilization. *SSSA J.* 57(4): 1034−1040.

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 Research* 50(1): 21−32.

Fang, C., and J. B. Moncrieff. 2001. The dependence of soil CO_2 efflux on temperature. *Soil Biology Biochem.* 33(2): 155−165.

Hendrix, P. F., C.−R. Han, and P. M. Groffman. 1988. Soil respiration in conventional and no− tillage agroecosystems under different winter cover crop rotations. *Soil Tillage Research* 12(2): 135−148.

Houghton, R. A., J. E. Hobbie, M. Melillo, B. More, B. J. Peterson, G. R. Shaver, and G. M Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecology Monographs* 53(3): 235−262.

Hudson, B. D. 1994. Soil organic matter and available water capacity. *J. Soil Water Conservation* 49(2): 189−194.

Keeling, C. D., and T. P. Whorf. 1994. Atmospheric CO_2 records from sites in the SIO air sampling network. In *Trends 1993: A Compendium of Data on Global Change*, 16−26. T. A. Boden, D. P. Kaiser, R. J. Sepanski, and F. W. Stoss, eds. Oak Ridge, Tenn.: CDIC, ORNL.

Kern, J. S., and M. G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. *SSSA J.* 57(1): 200−210.

La Scala, N., Jr., A. Lopes, J. Marques, Jr., and G. T. Pereira. 2001. Carbon dioxide emissions after application of tillage systems for a dark red latosol in southern Brazil. *Soil Tillage Research* 62(3−4): 163−166.

Littell, R. C., G. A. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. *SAS System for Mixed Models*. Cary, N.C.: SAS Institute, Inc.

Parr, J. F., and R. I. Papendick. 1978. Factors affecting the decomposition of crop residues by microorganisms. In *Crop Residue Management Systems*, 101−129. W. R. Oschwald, ed. ASA Special Publ. No. 31. Madison, Wisc.: ASA, CSSA, and SSSA.

Paustian, K., J. Six, E. T. Elliott, and H. W. Hunt. 2000. Management options for reducing CO_2 emissions from agricultural soils. *Biogeochem.* 48(1): 147−163.

Phillips, R. E., R. L. Blevins, G. W. Thomas, W. W. Frye, and S. H. Phillips. 1980. No−tillage agriculture. *Science* 208: 1108−1113.

Prior, S. A., H. H. Rogers, G. B. Runion, H. A. Torbert, and D. C. Reicosky. 1997. Carbon dioxide enriched agro−ecosystems: Influence of tillage on short−term soil carbon dioxide efflux. *J. Environ. Quality* 26(1): 244−252.

Prior, S. A., D. C. Reicosky, D. W. Reeves, G. B. Runion, and R. L. Raper. 2000. Residue and tillage effects on planting implement−induced short−term CO_2 and water loss from a loamy sand soil in Alabama. *Soil Tillage Research* 54(3−4): 197−199.

Raper, R. L. 2001. The influence of implement type and tillage depth on residue burial. In *Soil Erosion Research for the 21st Century: Proc. Int. Symp.*, 517−521. J. C. Ascough II and D. C. Flanagan, eds. St. Joseph, Mich.: ASAE.

Raper, R. L. 2002. The influence of implement type, tillage depth, and tillage timing on residue burial. *Trans. ASAE* 45(5): 1281−1286.

Reicosky, D. C., and M. J. Lindstrom. 1993. Fall tillage method: The effect of short−term carbon dioxide flux from soil. *Agronomy J.* 85(6): 1237−1243.

Reicosky, D. C., W. A. Dugas, and H. A. Torbert. 1997. Tillage−induced soil carbon dioxide loss from different cropping systems. *Soil Tillage Research* 41(1−2): 105−118.

Reicosky, D. C., D. W. Reeves, S. A. Prior, G. B. Runion, H. H. Rogers, and R. L. Raper. 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. *Soil Tillage Research* 52(3−4): 153−165.

SAS. 1985. *SAS User's Guide: Statistics*. Version 5 edition. Cary, N.C.: SAS Institute, Inc.

Swan, J. B., E. C. Schneider, F. Moncrief, W. H. Paulson, and A. E. Peterson. 1987. Estimating corn growth, yield, and grain moisture from air growing degrees days and residue cover. *Agronomy J.* 79(1): 53−60.

Unger, P. W., and T. M. McCalla. 1980. Conservation tillage systems. *Adv. Agronomy* 33: 1−58.