ELSEVIER

Soil & Tillage Research 52 (1999) 153–165

Soil & Tillage Research

www.elsevier.com/locate/still

Effects of residue management and controlled traffic on carbon dioxide and water loss

D.C. Reicosky[a,*,1], D.W. Reeves[b], S.A. Prior[b], G.B. Runion[c], H.H. Rogers[b], R.L. Raper[b]

[a]USDA, Agriculture Research Service, North Central Soil Conservation Research Laboratory, 803 Iowa Avenue, Morris, MN 56267, USA
[b]USDA, Agriculture Research Service, National Soil Dynamics Laboratory, 411 S.Donahue, Auburn, AL 36831-3439, USA
[c]Auburn University, School of Forestry, Auburn, AL 36849, USA

Received 25 August 1998; received in revised form 6 April 1999; accepted 19 July 1999

Abstract

Management of crop residues and soil organic matter is of primary importance in maintaining soil fertility and productivity and in minimizing agricultural impact on the environment. Our objective was to determine the effects of traffic and tillage on short-term carbon dioxide (CO_2) and water (H_2O) fluxes from a representative soil in the southeastern Coastal Plain (USA). The study was conducted on a Norfolk loamy sand (FAO classification, Luxic Ferralsols; USDA classification, fine-loamy siliceous, thermic Typic Kandiudults) cropped to a corn (*Zea mays* L.) — soybean (*Glycine max* (L.) Merr) rotation with a crimson clover (*Trifolium incarnatum* L.) winter cover crop for eight years. Experimental variables were with and without traffic under conventional tillage (CT) (disk harrow twice, chisel plow, field cultivator) and no tillage (NT) arranged in a split-plot design with four replicates. A wide-frame tractive vehicle enabled tillage without wheel traffic. Short-term CO_2 and H_2O fluxes were measured with a large portable chamber. Gas exchange measurements were made on both CT and NT at various times associated with tillage and irrigation events. Tillage-induced CO_2 and H_2O fluxes were larger than corresponding fluxes from untilled soil. Irrigation caused the CO_2 fluxes to increase rapidly from both tillage systems, suggesting that soil gas fluxes were initially limited by lack of water. Tillage-induced CO_2 and H_2O fluxes were consistently higher than under NT. Cumulative CO_2 flux from CT at the end of 80 h was nearly three times larger than from NT while the corresponding H_2O loss was 1.6 times larger. Traffic had no significant effects on the magnitude of CO_2 fluxes, possibly reflecting this soil's natural tendency to reconsolidate. The immediate impact of intensive surface tillage of sandy soils on gaseous carbon loss was larger than traffic effects and suggests a need to develop new management practices for enhanced soil carbon and water management for these sensitive soils.

Keywords: Tillage; Organic matter; Soil carbon; Greenhouse effect; Gas exchange

* Corresponding author. Tel.: 16125893411; fax: 16125893787
E-mail address: dreicosky@mail.mrsars.usda.gov (D.C. Reicosky)

[1] All programs and services of the US Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, age, marital status, or handicap.

0167-1987/99/$ – see front matter
PII: S0167-1987(99)00065-3

1. Introduction

Minimizing agriculture's impact on the global increase in atmospheric carbon dioxide (CO_2) requires that soil management strategies be adopted that sequester carbon (C) to maintain high levels of soil organic matter. Information is needed on the variation and magnitude of tillage-induced soil CO_2 loss in relationship to C fixation through photosynthesis within agricultural production systems. Recent studies have indicated major gaseous loss of soil C as CO_2 immediately after tillage (Reicosky and Lindstrom, 1993). Differences in CO_2 loss as a result of tillage methods can be related to physical soil fracturing (i.e. that facilitates movement of CO_2 out of and oxygen into the soil) and to biological changes (i.e. increased residue to soil contact which enhance microbial activity). Because of accelerated loss of soil organic matter, intensive tillage may play a major role in decreasing soil quality which in turn impacts environmental quality.

One method of measuring management effects on accelerated soil C loss is with gas exchange chambers. Limited understanding of chamber performance over freshly tilled and nontilled surfaces and the lack of a universally accepted calibration technique leads to uncertainty interpreting gas fluxes. Denmead and Raupach (1993) suggested chamber microclimate may interfere with the natural process of gas exchange. Rochette et al. (1992) showed fluxes measured with a dynamic chamber were greater than a same sized static chamber. Reicosky et al. (1997) showed substantial differences between a large dynamic canopy chamber and a small dynamic soil chamber over tilled surfaces, while differences over surfaces not tilled were small. Flux differences between these chambers was attributed to size, placement, increased turbulence and dynamic pressure fluctuations in the canopy chamber. Thus, flux differences among chamber types and interactions with tillage-induced changes in soil properties require careful interpretation.

Roberts and Chan (1990) used simulated tillage techniques in laboratory studies to examine the importance of tillage-induced increases in soil respiration as a mechanism for organic matter loss. They measured CO_2 evolution from soil cores after applying a simulated tillage and found the C losses that could be directly attributed to tillage ranged from 0.0005% to 0.0037% of the total C. They concluded that the increase in microbial respiration due to tillage was probably not a major factor leading to losses of soil organic matter in soils under intensive cultivation.

Rovira and Greacen (1957) studied the effect of aggregate disruption on the activity of microorganisms in the soil and found that by breaking apart aggregates they could release 21 kg C ha^{-1}, which was close to the maximum loss reported in the work by Roberts and Chan (1990) using simulated tillage methods. Rovira and Greacen (1957) concluded that an increase in the decomposition of organic matter was induced by tillage and was a factor in decline of organic matter in tilled soils. However, this mechanism is reportedly small compared to other mechanisms of C loss and is not clearly understood in soils of the southeastern USA. There have been a few reported attempts to measure CO_2 evolution immediately after tillage in the field. Hendrix et al. (1988) were unable o detect any stimulation of CO_2 release immediately after plowing using 0.1 m aluminum cylinders and the alkali-absorption method. Soil CO_2 evolution using alkali-absorption increased by about 30% during a month following tillage compared with NT after sorghum harvest, but was unaffected following wheat and soybean harvests (Franzluebbers et al., 1995).

Decreases in soil C as a result of intensive tillage are well documented (Haas et al., 1957; Greenland and Nye, 1959). A decrease in soil organic matter as a result of intensive tillage is more pronounced in the soils of the southeastern USA that are already very low in organic matter, generally attributed to the duration of higher soil temperatures. However, Greenland and Nye (1959) have shown soil C can increase under natural fallow conditions. Even in thermic udic regimes, soil C can be increased using combinations of conservation tillage and intensive cropping frequencies and cover crops (Wood et al., 1991; Reeves and Wood, 1994; Bruce et al., 1995). Thus, there is hope for improved management to increase soil C levels in existing agricultural soils and to reduce soil C decrease in newly cultivated soils. There is optimism that management can include high residue production techniques, using perennial forage crops, elimination of bare fallow periods, and reduced tillage, to promote C sequestration in the soil.

Coarse textured soils of the southeastern USA Coastal Plain often limit crop production because of poor water-holding capacity and surface and subsoil compaction. Deep tillage (especially subsoiling) often results in yield increases for crops grown on these soils (Trouse, 1983; Kamprath et al., 1979; Reeves and Touchton, 1986; Reeves et al., 1990). Alternative tillage practices, including controlled traffic, affect crop yield on these highly compacted soils. Previous research with CT systems was focused on single components of the compaction problem, either tillage or traffic (Lee et al., 1996). Improving environmental quality requires understanding the interaction between tillage and wheel track compaction on short-term CO_2 flux and soil C storage.

The role of surface tillage and residue management in nutrient transformation and cycling has been a subject of much interest in the southeastern USA, yet the role of soil compaction on these transformations has not been studied in detail. Information is needed on the impact of wheel track compaction as it affects the short-term release of CO_2 following surface tillage events. The objective of this study was to determine the effect of wheel traffic soil compaction and tillage management on short-term CO_2 and H_2O fluxes from a Coastal Plains soil.

2. Materials and methods

2.1. Experimental site

This research was conducted as part of a continuing long-term study (1988–1995) described in detail by Reeves et al. (1992) and Torbert et al. (1996) on a Norfolk loamy sand at the E.V. Smith Research Center of the Alabama Agriculture Experiment Station in east central Alabama, USA (N 32°25.467′, W 85° 53.403′). The experimental area was divided into two groups of plots, referred to as Field 1 and Field 2, to accommodate the two phases of the crop rotation. Most of the tillage related data collected in this study was from Field 1. The soil is highly compactible and has a well developed hard pan at the 18–30 cm depth. Soil bulk density in the hard pan ranges from 1.51 to 1.76 Mg m^{-3} with a predominance of sand in the profile. Cation exchange capacity averaged 2.02 cmol kg^{-1}, organic matter averaged 10.0 g kg^{-1}, and soil pH averaged 6.4. Other soil and residue properties are summarized in Table 1.

Crop rotation consisted of corn in 1993, followed by a winter cover crop of crimson clover and soybean in 1994 with a winter cover crop of crimson clover. The above ground soybean non-grain biomass averaged 3400 kg ha^{-1} the previous fall and was not readily apparent at the start of this study due to overwinter decomposition. Cover crop was terminated with a burn-down herbicide [glufosinate–ammonium]. Fertilizer and lime recommendations were based on Auburn University Soil Testing Laboratory data (Adams et al., 1994).

2.2. Tillage treatments

The experimental layout and design were previously described in detail by Reeves et al. (1992). Experimental variables were with and without traffic under conventional tillage (CT) (disk harrow twice, chisel plow, field cultivator) and no tillage (NT) arranged in a split-plot design with four replicates. The treatments for this study were selected from a higher level split within the experiment. Thus, there were four combinations of traffic and tillage in a split-plot design of four replications. Main plots were traffic and subplots were tillage. Fluxes of CO_2 and H_2O were analyzed with time (immediately before and after tillage) and included in the model as the sub-subplot factor. Data for each operation were subjected to analysis of variance using SAS (Littell et al., 1991 SAS Institute Inc., 1988). Means were separated using Fisher's protected LSD at the $P < 0.10$ level of significance, chosen a priori.

Conventional spring tillage included disking twice to 10–12 cm, chisel plowing to 15–18 cm and field cultivation to 10 cm. The no-tillage treatment required no surface tillage. In both CT and NT an eight-row (76 cm row width) NT planter was used to simulate the planting operation (planters were not loaded with seed). The planter was equipped with interlocking steel-fingered row cleaners set to float just above the soil surface to skim excessive residues from a 10 cm band width over the planting row.

All tillage and planting operations for the no-traffic plots were done with an experimental wide-frame tractive vehicle (6.1 m wide) described by Monroe and Burt (1989). In the trafficked plots, a 4.6 Mg tractor with tires (470 mm × 970 mm) inflated to an average pressure of 125 kPa immediately followed the

Table 1
Summary of soil (0–20 cm depth) and surface residue properties (mean and standard deviation) on conventional and no-tillage plots

Field 1 — Main study area														Field 2[a] — Adjacent tier "Live Clover"					
Traffic	Tillage	Residue, DM ($kg\ ha^{-1}$)		Residue, N ($g\ kg^{-1}$)		Residue, C ($g\ kg^{-1}$)		Soil, N ($g\ kg^{-1}$)		Soil, C ($g\ kg^{-1}$)		Cone resistance (MPa)		Residue, DM ($kg\ ha^{-1}$)		Residue, N ($g\ kg^{-1}$)		Residue, C ($g\ kg^{-1}$)	
		$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd	$\bar{x}$	±sd
No	No-till	2648	1145	27.8	3.6	415	39.9	0.91	0.44	6.23	2.99	0.34	0.26	3036	501	23.3	0.9	424	3.5
No	Till	–[b]	–	–	–	–	–	0.78	0.28	6.11	1.46	0.23	0.26	3426	1224	23.5	1.7	423	1.0
Yes	No-till	1771	848	26.8	2.0	409	9.0	0.98	0.49	7.00	4.29	0.58	0.49	1599	338	22.5	1.3	420	6.9
Yes	Till	–[b]	–	–	–	–	–	0.83	0.31	5.76	1.20	0.34	0.36	2468	684	23.4	1.3	424	2.6

[a] Field 2 was an adjacent area with the same treatment history as the alternate phase of the rotation in the long-term study.
[b] Tillage applied before residue collected.
DM = dry matter.

wide-frame tractive vehicle to simulate tractor traffic in a field operation. In previous years (1988–1994) random traffic patterns were applied each fall for land preparation and planting of the cover crop. Uniform traffic patterns were established in the corn or soybean to simulate operations done by a farmer with four-row equipment each year. Thus, every simulated planting row in the traffic plots had a traffic and a non-traffic interrow.

2.3. Residue measurements

Residue was collected from 0.25 m^2 samples taken from an immediately adjacent area to the CO_2 measurement with NT. The bulk of the residue was from crimson clover cover crop that was desiccated 10 days earlier. Most of the preceeding year's soybean residue had already decomposed. We mistakenly imposed tillage on the CT plots before residue samples were collected. However, as an indication of the variation in residue that would have been present under CT, we collected samples the following day from the adjacent tier that had not been desiccated (Field 2). These residue properties are designated as ''live clover'' in Table 1 and should approximate the difference between treatments before tillage in the main study area (Field 1).

2.4. Soil measurements

Soil samples from 0 to 20 cm depth were collected, dried and finely ground (<0.15 mm particle size) using a conveyor-belt roller grinder apparatus (Kelley, 1994). Residue samples were dried and ground to pass a 1 mm screen on a Wiley mill. Soil and plant residue samples were analyzed for C and nitrogen (N) using an automated combustion technique (Yeomans and Bremner, 1991).

Cone resistance was determined from within the CO_2 measurement area with a simultaneous five-shaft recording penetrometer with 20.27 mm diameter base cone size (ASAE, 1998). Three insertions were made within each plot. Cone index forces were recorded at 3 mm depth intervals and were averaged for the 0–20 cm depth.

Gravimetric soil water was determined on 3 April 1995, one day prior to irrigation of the plots, and also on 5 April 1995. Six 25 mm diameter cores from 0 to 20 cm depth were composited from within each CO_2 measurement area in each plot.

2.5. Gas flux measurements

Gas fluxes from the soil surface were measured during the period 3–6 April 1995 using a large, portable closed chamber as described by Reicosky and Lindstrom (1993) and Wagner and Reicosky (1996). The chamber (area $= 2.71$ m^2 and volume $= 3.25$ m^3), with the mixing fans running, was placed over the soil surface 3 m from end of plot, lowered and data collected at one second intervals for a total of 60 s to determine the rate of CO_2 and H_2O increase. Other data measured included solar radiation, photosynthetically active radiation, air temperature and wet bulb temperature. After appropriate lag and mixing times, data for a 30 s calculation was selected to convert volume concentrations of H_2O and CO_2 to a mass basis, then regressed as a function of time using linear and quadratic functions to estimate the gas fluxes (Wagner et al., 1997).

Potential methodological limitations of the canopy chamber described by Reicosky et al. (1997) may have been exacerbated on this loamy sand. While the absolute fluxes may be questioned, relative tillage treatment differences appeared reasonable based on previous work (Reicosky and Lindstrom, 1993). Recent unpublished work on possible chamber limitations due to turbulent mixing has identified both positive and negative pressures with an average net negative pressure inside the chamber of -1.5 Pa that may, when combined with tillage-induced changes in soil air permeability, contribute large short-term fluxes. No effort was made in this work to account for air pressure and/or soil porosity effects that are the subject of continuing research.

Timing of gas exchange measurements on both CT and NT was related to the tillage and planting operations in CT. The major events over the four days of this study in the CT system were: (1) disk harrow twice, (2) 25 mm irrigation, (3) chisel plow, (4) field cultivation, and (5) planting. Additional measurements were completed between these events as time permitted. Triplicate gas exchange measurements were made in the same area prior to and immediately after the specific tillage event on all four replicates.

Gas exchange measurements were initiated prior to the first tillage operation, which included two disk harrow operations on 3 April 1995 (Day 93). On 4 April 1995 (Day 94) during mid-day a 25 mm irrigation during 20 min was applied using small hose and pumps from water wagons over a 10×10 m area at the west end of each plot. On Day 95, CT plots were chisel plowed twice. On 6 April 1995 (Day 96), the CT plots were field cultivated once and then planted with a no-till planter. Every effort was made to measure gas exchange on all four replicates as soon as possible after each tillage operation. However, the plot layout and travel time between plots with the portable chamber precluded making the measurements as rapidly as the area was tilled. Thus, the four replicates for a specific treatment were all completed within 30 min of the time of each tillage.

To account for possible temporal changes, an undisturbed reference or control area for gas flux measurements was established on an adjacent area that was disk harrowed five days earlier and was free of surface residues and weeds. The soil surface was nearly air dry to 10 cm and reflected a standard condition that did not change appreciably during this experiment.

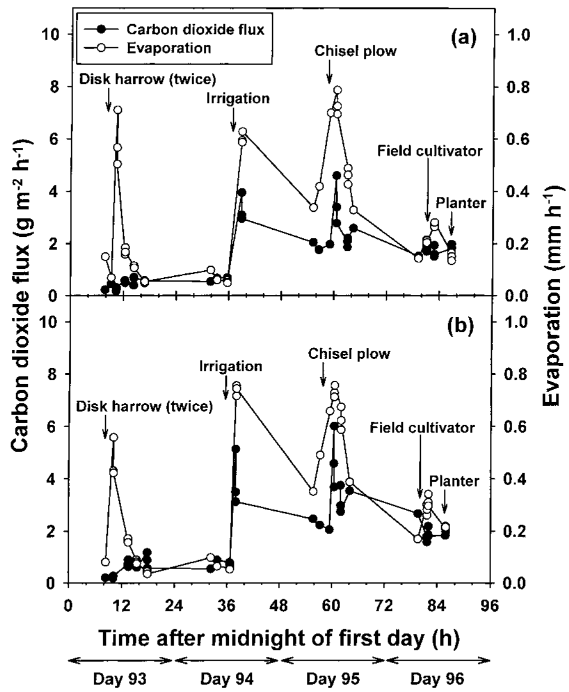

Fig. 1. The CO_2 flux and evaporation rate as a function of time for a selected conventional tillage plot (a) with traffic and (b) without traffic.

3. Results and discussion

Since much of the CO_2 evolution is from biological sources, water content and temperature at the time of tillage is important. Soil temperature (data not shown) at the 5 cm depth on the day of first tillage was as low as 17.8°C around 1100 h under NT and as high as 25°C under CT after the initial disking. Maximum temperature recorded ranged from 20°C under NT to 29°C under CT around 1500 h.

Soil water content before and after tillage is summarized in Table 2. There was no rainfall for 14 days prior to this study with the last substantial rain of 56 mm occurring 26 days (on 8 March 1995) prior to the study.

3.1. Temporal trends and events

Two representative plots were selected to show overall temporal trends in Figs. 1 and 2. Because of

Table 2
Soil water content (mean and standard deviation, 0–20 cm depth) before and after irrigation on 4 April 1997 (Day 94)

Traffic	Surface tillage	Soil water (g kg^{-1})			
		Before		After	
		$\bar{x}$	±sd	$\bar{x}$	±sd
No-traffic	No-tillage	38.4	5.63	79.4	9.99
No-traffic	Conv. tillage	45.5	4.08	83.7	4.24
Traffic	No-tillage	43.8	11.94	82.4	10.24
Traffic	Conv. tillage	42.1	4.71	85.3	12.61

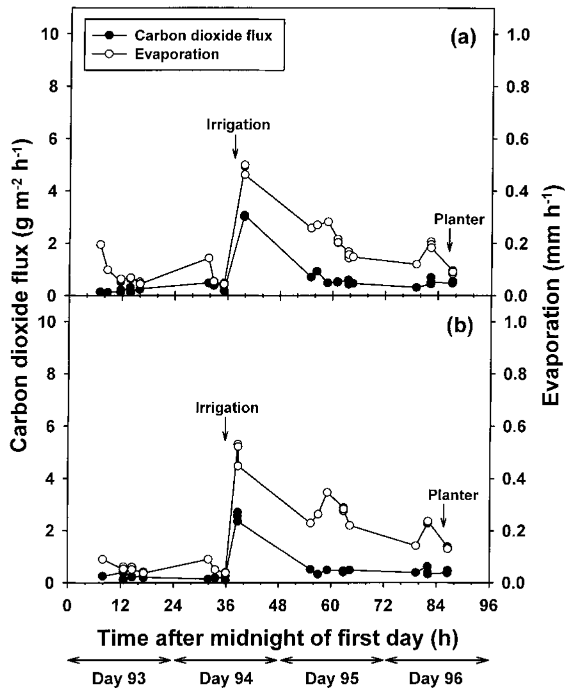

Fig. 2. The CO_2 flux and evaporation rate as a function of time for a selected no-tillage plot (a) with traffic and (b) without traffic.

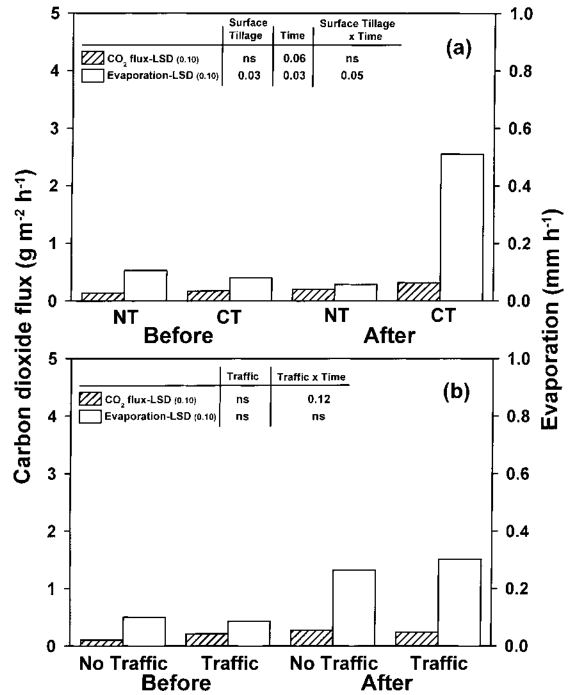

Fig. 3. Gas fluxes before and after disk harrow operation for (a) surface tillage effect and (b) traffic effect (ns: not significant).

the data scatter, no discernable effect of traffic vs. no-traffic on CO_2 flux was observed, possibly due to differences in timing of the measurements. Gas fluxes from both CT and NT showed a substantial increase after the irrigation on Day 94. Fluxes gradually declined as the soil dried during the next two days. These flux data show limited temporal trends and need to be interpreted with caution due to limited measurement times around each tillage event and lack of measurements during the night.

3.1.1. Disk harrow

CO_2 flux was greater after than before disk harrowing, regardless of tillage (Fig. 3a and b). CO_2 flux was significantly lower without than with traffic prior to disk harrowing but similar after disk harrowing.

Tillage history had no effect on evaporation rates prior to disk harrowing. After disk harrowing, evaporation rate dramatically increased. Traffic had no effect on evaporation rate (Fig. 3b). The CO_2 flux prior to the disk operation ranged as high as 0.21 g CO_2 m^{-2} h^{-1}, which were relatively low fluxes because of dry conditions. Although evaporation increased following disk harrowing, CO_2 flux did not increase presumably because soil was too dry for significant microbial activity.

3.1.2. Irrigation

Gas fluxes before and after a 25 mm irrigation on Day 94 are summarized in Fig. 4a and b. The CO_2 flux in CT was higher than in NT before irrigation, probably as a result of the previous disk harrow operation. Evaporation prior to irrigation was about the same in both CT and NT due to the extremely low water content. Irrigation significantly increased CO_2 flux, regardless of tillage or traffic. There was a trend ($P < 0.17$) for greater average fluxes from plots without traffic compared to those with traffic, regardless of irrigation.

After irrigation, dramatic increases in both CO_2 and H_2O fluxes were evident within minutes after the event. Flux increases after irrigation were greater under CT than under NT. Isolating the traffic effect after irrigation showed greater evaporation occurred

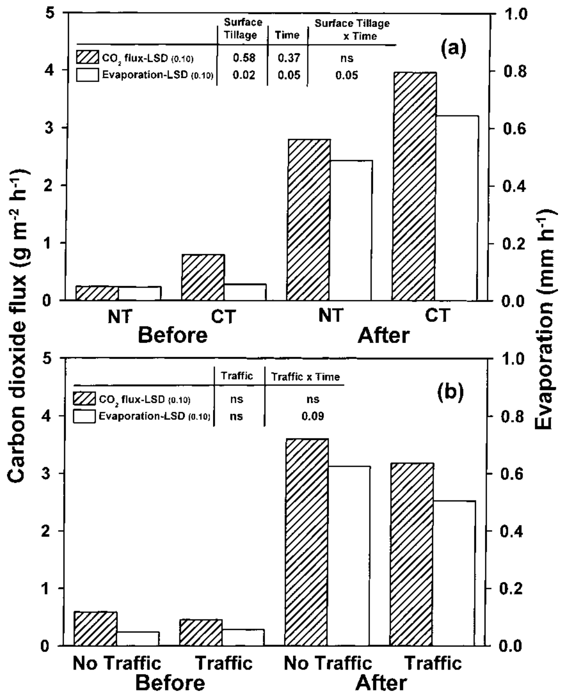

Fig. 4. Gas fluxes before and after 25 mm of irrigation for (a) surface tillage effect and (b) traffic effect (ns: not significant).

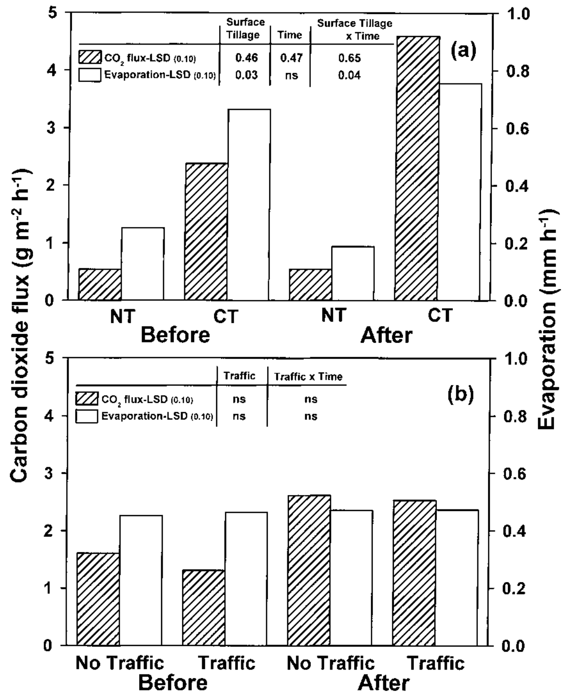

Fig. 5. Gas fluxes before and after chisel plowing for (a) surface tillage effect and (b) traffic effect (ns: not significant).

with no-traffic compared to traffic. The traffic by time interaction showed evaporation was less for no traffic than with traffic before irrigation; however, after irrigation, no traffic had greater evaporation than traffic plots. These results are unclear, but possibly suggest a slightly lower surface porosity in the traffic plots that retained the water near the surface to account for the higher post-tillage evaporation. The complex interactions of temporal dynamics of drying and sampling sequence with a single chamber may have also contributed to the uncertainty. The rapid response of evaporation to irrigation was expected. Rapid initial response of CO_2 flux may have been due to infiltrated water that displaced soil CO_2. However, the continued response of CO_2 flux suggests rapid microbial responses to irrigation. The increase in CO_2 fluxes due to irrigation on the NT plots confirms previous dry soil conditions limited microbial activity in the surface layer. These results also indicate a time response of soil microbes of 1 h or less in response to irrigation of sandy soils. It is possible in the short-term that irrigation water displaced soil air rich in CO_2 and physically forced out CO_2 to the atmosphere.

3.1.3. Chisel plow

The chisel plow operation occurred on Day 95, about 20 h after irrigation. A significant chisel plow by time interaction occurred in that the average CO_2 fluxes in no-tillage plots remained the same before and after the chisel plow operation occurred in the CT plots (Fig. 5a and b). However, there was a 93% increase in average CO_2 flux following chisel plowing in CT. The higher fluxes on CT plots were attributed to a combination of the previous disk harrow operation mixing the residue and soil, leaving the surface rough, and the subsequent irrigation that resulted in ideal conditions for microbial activity and evaporation. By this time, traffic had no effect on CO_2 flux or evaporation.

Within no-tillage plots, evaporation was significantly greater prior to the chisel plow operation which occurred in the CT plots than after this operation was completed about 2 h later (Fig. 5a). Prior to chisel plowing, the soil surface had already started to dry. Evaporation from NT plots was about half that after irrigation on the previous day, while that from CT plots was nearly the same (Figs. 4a and 5a). After the chisel plow operation, both CO_2 and H_2O fluxes in CT increased significantly, partly due to evaporative demand but mainly due to moist soil being brought to the surface and increased surface roughness following tillage. Evaluating the surface tillage effect, both CO_2 and H_2O fluxes on CT were larger as a result of the vigorous chisel plow operation. Rapid drying of the soil surface/residue interface in the NT plots caused a slight reduction in H_2O fluxes (Fig. 5a). The magnitude of these fluxes after chisel plowing are somewhat lower than observed under Midwest conditions (Reicosky and Lindstrom, 1993), suggesting large soil differences in response to tillage. In those conditions, Reicosky and Lindstrom (1993) found, for a Hamerly clay loam soil with 34 g kg^{-1} C content, the CO_2 flux after chisel plow was 9.0 g CO_2 m^{-2} h^{-1} while the Norfolk loamy sand with 4.0 g kg^{-1} C showed only 4.6 g CO_2 m^{-2} h^{-1}. Many other soil differences, e.g. texture, clay mineral type, organic carbon, cation exchange capacity and other factors likely explain the different fluxes for the two locations. Noteworthy was the decrease in the average CO_2 flux 20 h after irrigation in NT from 2.8 (Fig. 4a) to 0.55 g CO_2 m^{-2} h^{-1} (Fig. 5a) corresponding to the decrease in evaporation from 0.49 to 0.25 mm h^{-1}. This rapid decline in both fluxes suggests a beneficial soil-residue contact and drying regime that minimizes carbon and water loss in the NT system.

3.1.4. Field cultivation

The fourth event in the CT system was a field cultivator operation about 20 h after chisel plowing and immediately prior to planting on Day 96. This operation was not a vigorous tillage, but further smoothed the soil surface and caused some soil reconsolidation. Differences between the average fluxes from CT and NT prior to the field cultivator operation are noted in Fig. 6a. The CO_2 fluxes under NT were equivalent before and after the time of field cultivating, but were reduced 18% from those following CT chisel plowing. Field cultivation significantly reduced CO_2 flux in CT, although fluxes were 37% lower than following chisel plowing. The CO_2 fluxes in CT following field cultivation were nearly four times higher than those in NT 20 h later. Traffic had no effect on either CO_2 or H_2O fluxes.

Evaporation in CT was reduced to 39% of that following chisel plowing but the field cultivation increased evaporation 99% compared to that measured

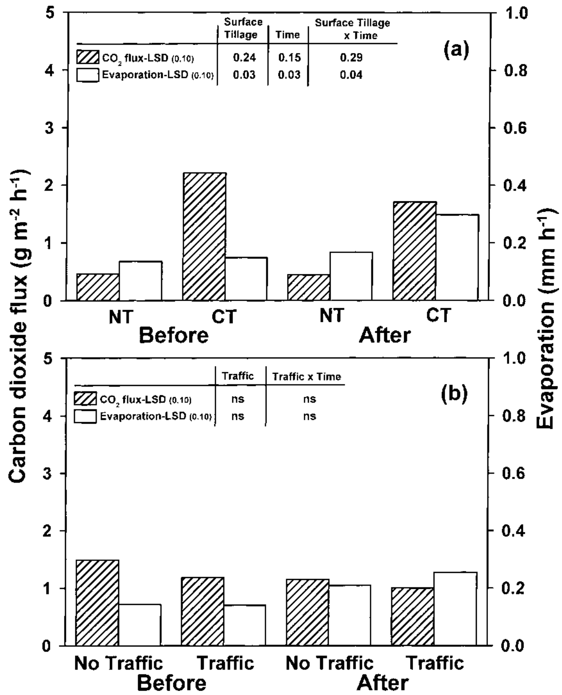

Fig. 6. Gas fluxes before and after the field cultivator for (a) surface tillage effect and (b) traffic effect (ns: not significant).

immediately before the operation. Evaporation in CT following field cultivation was 1.8 times larger than in NT. The decrease in CO_2 flux in CT may be attributed to some soil reconsolidation following field cultivation while the small increase in evaporation may be attributed to moist soil brought to the surface. However, the large difference between NT (0.44 g CO_2 m^{-2} h^{-1}) and CT (1.71 g CO_2 m^{-2} h^{-1}) after about 44 h of drying shows substantial CO_2 loss as a result of soil disturbance which suggests increased microbial activity and rapid decomposition of incorporated crop residues. Corresponding changes in evaporation showed slightly higher evaporation immediately following the field cultivator as moist soil was uncovered and leveled, but with a declining magnitude reflecting cumulative water loss the previous two days.

3.1.5. Planting

The last operation was planting. Average CO_2 and H_2O fluxes after soil disturbance caused by the planter on Day 96 are summarized in Fig. 7a. The fluxes before planting were the same as those after the field

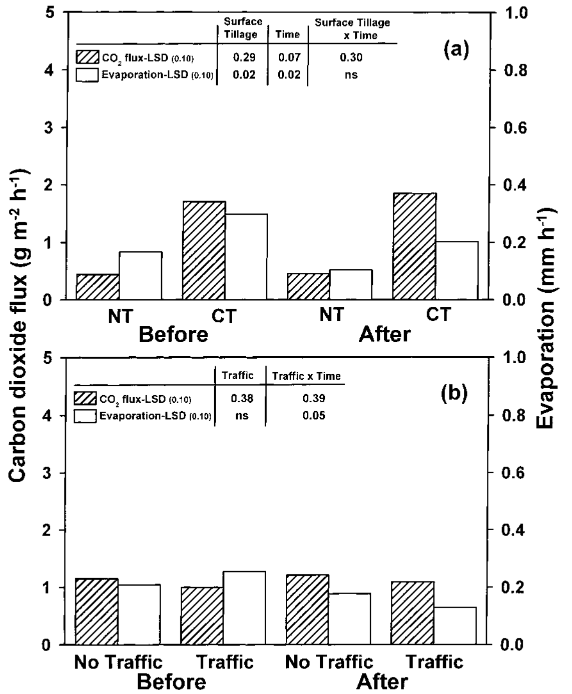

Fig. 7. Gas fluxes before and after the planter for (a) surface tillage effect and (b) traffic effect (ns: not significant).

cultivator operation in Fig. 6 some 2–3 h later. CO_2 fluxes after planting were slightly (7%) but significantly increased compared to those just prior to planting regardless of tillage system. Averaged across time (just prior to and immediately following the planting operation), CO_2 fluxes were significantly (approximately four times) greater in CT than in NT (Fig. 7a). Traffic had no effect on CO_2 fluxes.

There was a significant traffic by tillage by time interaction on evaporation during the planting operation ($P < 0.005$, data not shown). This was the only three-way interaction that occurred in the study. This was due to evaporative fluxes being similar in effect and magnitude (slightly decreased following the planting operation) within no-tillage plots, regardless of traffic; and to the fact that within surface tilled plots, without traffic, evaporation was similar before and after the planting operation while with traffic, evaporation doubled (from 0.15 to 0.35 mm h^{-1}) following the operation. The decreases in evaporation following planting in NT, regardless of traffic, and in CT plots with traffic were likely due to further soil drying during the short interval as well as to differences in bulk density as suggested by the cone penetrometer differences between these plots and the field cultivated CT plots without traffic (see Table 1). The single grained nature of this soil and natural tendency to reconsolidate complicates the interpretation. External causes of reconsolidation such as rainfall or wheel traffic contribute to the variation in a complex way. These results suggest that the planting operation with a no-till planter results in little extra CO_2 loss as a result of the small disturbance in the narrow band where the seed is placed and the soil re-compacted for seed-soil contact. Tillage implements appear to be the main cause of CO_2 loss in this study. The effect of traffic before and after the planter operation was not evident on CO_2 fluxes.

Equipment wheel traffic compaction effects showed no clear cut trends in CO_2 fluxes. The traffic effect on CO_2 flux was not discernable before and after the initial disk harrow operation or in any of the other operations. However, before and after irrigation, there was a tendency for fluxes from the NT, no-traffic plots to be slightly higher than the no-till trafficked areas. This was true both before and after the initial irrigation, suggesting a tendency for wheel traffic compaction to increase cone penetrometer resistance (Table 1) and as a result decrease the gas fluxes. However, flux differences were not significant and suggest that natural reconsolidation, random variation and sample variability may preclude firm conclusions about traffic compaction effects.

3.2. Cumulative fluxes

Difficulty in viewing the individual plot trends as a function of time led to the calculation of the cumulative fluxes of CO_2 and H_2O for the 80 h period of this study summarized in Fig. 8. Cumulative losses as a result of all tillage and irrigation operations were calculated using a simple numerical integration technique (Trapezoidal rule) and reflect the area under the curves of the flux vs. time illustrated in Figs. 1 and 2. Insufficient data were collected to accurately show smooth non-linear trends for data summation. As a result, data points were connected by simple linear interpolation and will represent a first approximation. Values were averaged across tillage systems in Fig. 8a and traffic treatments in Fig. 8b. Cumulative flux values need to be interpreted with caution because

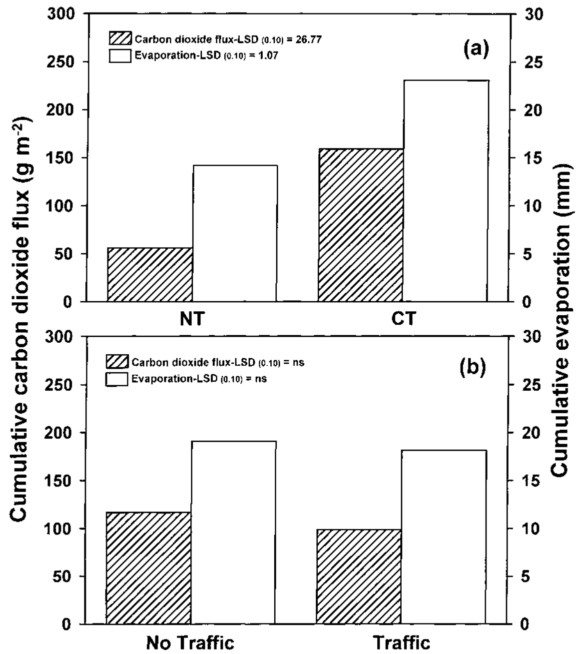

Fig. 8. Cumulative CO_2 and H_2O fluxes for 80 h after the first tillage event for (a) surface tillage effect and (b) traffic effect (ns: not significant).

of the long period during the night when no data were collected. However, based on other diurnal data, the trends shown are reasonable and represent a first approximation. Even with these limitations, the cumulative data show substantial differences between CT and NT treatments. There was nearly a threefold increase in the cumulative CO_2 flux on the CT averaged over traffic and no-traffic (159 g CO_2 m^{-2}) compared with NT averaged over traffic and no-traffic (56 g CO_2 m^{-2}) (Fig. 8b). Corresponding cumulative losses on the non-irrigated reference area for the same 80 h period were 26 g CO_2 m^{-2}, substantially lower due to limited water. The low surface soil water content on this area resulted in relatively low CO_2 and H_2O fluxes. However, the CO_2 fluxes from this loamy sand were larger than some of those measured from NT treatments on clay loam soils higher in organic matter in west central Minnesota (Reicosky and Lindstrom, 1993). Conventional tillage without traffic had a slightly higher cumulative flux of CO_2 than the CT with traffic. However, small differences noted for both CT and NT were not significant (Fig. 8a). These findings are similar to those of Entry et al. (1996) who showed tillage and wheel traffic compaction had no consistent effects on active microbial and fungal biomass and organic matter decomposition.

Cumulative H_2O fluxes summarized in Fig. 8b show a quantitative trend similar to the CO_2 fluxes. Substantial differences occurred when averaged across traffic between CT (23 mm of H_2O) and NT (14 mm of H_2O). Since potential evaporative demand was similar for both treatments, surface residue cover in NT and direct tillage effects in CT accounted for the evaporation differences. Differences in H_2O loss due to surface tillage were slightly smaller relative to CO_2 losses because both CT and NT were irrigated. Evaporation shortly after irrigation was nearly the same early on all treatments controlled primarily by the evaporative demand. The next day, treatment effects caused the evaporation to separate as drying continued to account for cumulative differences. Irrigation had a substantial effect on cumulative loss of water vapor due to high evaporative demand. The corresponding cumulative loss from the non-irrigated reference area for the same 80 h period was 1.4 mm of H_2O. Differences in gas exchange between CT and NT were substantial throughout this short-term study and suggest that improved management practices using NT or conservation tillage techniques can minimize CO_2 loss and conserve water.

4. Summary

In summary, surface tillage-induced fluxes of CO_2 and H_2O from CT were higher than from NT in the short-term. Due to the initially dry soil, irrigation caused a rapid increase in the fluxes of CO_2 and H_2O from both tillage systems. However, short-term flux differences became larger as the fluxes decreased faster in NT than in CT. Surface residue effects were likely reflected in the lower CO_2 and H_2O fluxes from NT plots with the surface residue serving as a "mulch" for reducing soil evaporation. Residues on the NT surface also minimized the soil-residue contact to result in a lower decomposition rate, that may have also been caused by lower surface soil temperatures. While cone index data indicated compaction differences due to prior traffic and NT, the effects were not discernable on gas fluxes. Little effect of traffic compaction vs. no-traffic was noted on the fluxes of CO_2

and H_2O with tillage and irrigation events and suggests particle size distribution and single-grained nature of this soil allows it to naturally reconsolidate without equipment compaction. Traffic compaction effects were not consistent and appeared to be complicated by the large in-plot variation in penetration resistance profiles in both traffic and no-traffic plots. The CO_2 fluxes tended to be only slightly higher without traffic. Water vapor fluxes were the same with or without traffic.

There was nearly a threefold increase in the cumulative CO_2 flux on CT averaged over traffic and a 1.6-fold increase in the cumulative H_2O flux over NT, primarily due to tillage enhanced evaporation suggesting that forms of NT or conservation tillage can be useful in conserving soil water as well as minimizing the soil C loss through tillage-induced gas exchange. Both C and H_2O conservation are critical in crop stand establishment on this drought prone soil. The positive benefits of the NT system will be enhanced soil and environmental quality and short-term water conservation for sustainable crop production on these fragile soils.

Acknowledgements

The authors would like to acknowledge the cooperation of the support staffs and research associates that included Bobby Washington, Greg Pate, Rufus Felton and Jack Jarrell from the USDA, Agriculture Research Service, National Soil Dynamics Lab, Auburn, AL; Tammy Counts, School of Forestry, Auburn University, Auburn, AL; and Chris Wente and Al Wilts from the USDA, Agriculture Research Service, North Central Soil Conservation Research Lab, Morris, MN for their assistance in this data collection effort. We would also like to acknowledge Dane Williams, superintendent of the E.V. Smith Research Farm and members of the support staff for their assistance during this study. The authors would like to acknowledge the helpful comments of two anonymous reviewers.

References

Adams, J.F., Mitchell, C.C., Bryant, H.H., 1994. Soil test recommendations for Alabama crops. Agronomy and Soils Departmental Series No. 178. Ala. Agric. Exper. Stn., 68 pp.

American Society of Agricultural Engineers (ASAE), 1998. Standard S313.2 Soil Cone Penetrometer. ASAE, St. Joseph, MI, pp. 820–821.

Bruce, R.R., Langdale, G.W., West, L.T., Miller, W.P., 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. Am. J. 59, 654–660.

Denmead, O.T., Raupach, M.R., 1993. Methods for measuring atmospheric gas transport in agricultural and forest systems. In: Harper, L.A., Mosier, A.R., Duxbury, J.M., Rolston, D.E. (Eds.), Agricultural Ecosystem Effects on Trace Gases and Global Climate Change, Am. Soc. Agron. Special Publication No. 55. Am. Soc. Agron, Madison, WI, pp. 19–43.

Entry, J.A., Reeves, D.W., Backman, C.B., Raper, R.L., 1996. Influence of wheel traffic and tillage on microbial biomass. residue decomposition and extractable nutrients in a Coastal Plain Soil. Plant Soil. 180, 129–137.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage and crop effects on seasonal dynamics of soil CO2 evolution, water content, temperature and bulk density. Appl. Soil Ecol. 2, 95–109.

Greenland, D.J., Nye, P.H., 1959. Increases in carbon and nitrogen contents of tropical soils under natural fallows. J. Soil Sci. 10, 284–298.

Haas, H.J., Evans, C.E., Miles, E.F., 1957. Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. Technical Bull. 1164, USDA, State Agriculture Exper. Stns., 111 pp.

Hendrix, P.F., Chun-Ru, F., Groffman, P.M., 1988. Soil respiration in conventional and no-tillage agroecosystems under different winter cover crop rotations. Soil Tillage Res. 12, 135–148.

Kamprath, E.J., Cassel, D.K., Gross, H.D., Dibb, D.W., 1979. Tillage effects on biomass production and moisture utilization by soybeans on coastal plain soil. Agron. J. 71, 1001–1005.

Kelley, K.R., 1994. Conveyor-belt apparatus for fine grinding of soil and plant materials. Soil Sci. Soc. Am. J. 58, 144–146.

Lee, W.J., Wood, C.W., Reeves, D.W., Entry, J.A., Raper, R.L., 1996. Interactive effects of wheel traffic and tillage system on soil carbon and nitrogen. Comm. Soil Sci. Plant Anal. 27(18-20), 3027–3043.

Littell, R.C., Freund, R.J., Spector, P.C., 1991. SAS (R) System for linear models, 3rd ed. SAS Institute Inc., Cary, NC, 329 pp.

Monroe, G.E., Burt, E.C., 1989. Wide-framed tractive vehicle for controlled traffic research. Appl. Eng. Agric. 5, 40–43.

Reeves, D.W., Touchton, J.T., 1986. Subsoiling for nitrogen applications to corn grown in a conservation tillage system. Agron. J. 78, 921–926.

Reeves, D.W., Edwards, J.H., Elkins, C.B., Touchton, J.T., 1990. In-row tillage methods for subsoil amendment and starter fertilizer application to conservation-tilled grain sorghum. Soil Tillage Res. 16, 359–369.

Reeves, D.W., Rogers, H.H., Droppers, J.A., Prior, S.A., Powell, J.B., 1992. Wheel traffic effects on corn as influenced by tillage systems. Soil Tillage Res. 23, 177–192.

Reeves, D.W., Wood, C.W., 1994. A sustainable winter-legume conservation tillage system for maize: effects on soil quality.

Proceedings of the 13th of ISTRO, Aalborg, Denmark, pp. 1011–1016.

Reicosky, D.C., Lindstrom, M.J., 1993. The effect of fall tillage method on short-term carbon dioxide flux from soil. Agron. J. 85(6), 1237–1243.

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

Roberts, W.P., Chan, K.Y., 1990. Tillage-induced increases in carbon dioxide loss from soil. Soil Tillage Res. 17, 143–151.

Rochette, P., Gregorich, E.P., DesJardin, R.L., 1992. Comparison of static and dynamic closed chambers for measurement of soil respiration under field conditions. Can. J. Soil Sci. 72, 605–609.

Rovira, A.D., Greacen, E.L., 1957. The effect of aggregate disruption on the activity of microorganisms in the soil. Aust. J. Agric. Res. 8, 659–673.

SAS Institute Inc., 1988. SAS/STAT™ User's Guide, Release 6.03 Edition. Cary, NC, SAS Institute Inc., 1028 pp.

Torbert, H.A., Reeves, D.W., Mulvaney, R.L., 1996. Winter legume cover crop benefits to corn: Rotation versus fixed nitrogen effects. Agron. J. 88, 527–535.

Trouse, A.C., 1983. Observations on under-the-row subsoiling after conventional tillage. Soil Tillage Res. 3, 67–81.

Wagner, S.W., Reicosky, D.C., 1996. Mobile Research Gas Exchange Machine, MRGEM Instrumentation Update. In: Camp, C.R., Sadler, E.J.,Yoder, R.E. (Eds.), Evapotranspiration and Irrigation Scheduling. Proceedings of International Conference, 3–6 November, 1996, San Antonio, TX, pp. 781–786.

Wagner, S.W., Reicosky, D.C., Alessi, R.S., 1997. Regression models for calculating gas fluxes measured with a closed chamber. Agron. J. 89, 279–284.

Wood, C.W., Edwards, J.H., Cummins, C.J., 1991. Tillage and crop rotation effects on soil organic matter in a Typic Hapludult of northern Alabama. J. Sustainable Agric. 2(2), 31–41.

Yeomans, J.C., Bremner, J.M., 1991. Carbon and nitrogen analysis of soils by automated combustion techniques. Commun. Soil Sci. Plant Anal. 22(9/10), 843–850.