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Reducing CO_2 Flux by Decreasing Tillage in Ohio: Overcoming Conjecture with Data

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Abstract

While the literature is clear about excessive tillage decreasing soil carbon (C) content, there are few experimental studies that document the comparative effects of soil and crop management on C sequestration. Using micrometeorology we measured CO_2 flux from a maize crop grown on both no-till and tilled soils in north-central Ohio. We used Bowen Ratio Energy Balance (BREB) systems to quantify the flux between the atmosphere and either the soil surface (at crop planting) or 0.2 m above the canopy once the crop was established and growing. The no-till plot sequestered 263 g CO_2 m^{-2} (90% confidence interval -432.1 to -99.9) while the tilled plot emitted 146 g CO_2 m^{-2} (90% confidence interval -53.3 to 332.2) during 104 days of the 2015 growing season; a net difference of 410 g CO_2 m^{-2}. The difference is statistically significant at the 90% confidence level (based on a bootstrap analysis). The results indicate that no-tillage practices can sequester C, maintain soil productivity, and ensure landscape sustainability.

Keywords: carbon dioxide, CO_2 flux, no-till, tillage, carbon sequestration, climate change mitigation, Bowen ratio

1. Introduction

The principal sinks for removing CO_2 from the atmosphere are usually assumed to be oceans and forests; however, oceans will absorb less CO_2 as they warm (Morrison et al., 2015) and forest area is shrinking due to agriculture and other land use changes (FAO, 2016). It has been shown that soil could be a strong sink for atmospheric CO_2 (Paustian et al., 2016), partially offsetting increasing global greenhouse gas (GHG) emissions (Tubiello et al., 2015; EPA, 2014; Scripps Institution of Oceanography, 2016). Jenny's (1941) classic work provides the basis for the collective understanding of the processes by which soils emit and sequester C through soil-climate-vegetation interactions. These processes depend on many factors including soil type, climate, crop, and agricultural management practices.

While agriculture is a major contributor to increases in GHG emissions, careful implementation of agricultural practices to enhance C sequestration presents an opportunity to manage soils to mitigate climate change. In particular, the practice of reduced tillage, especially no-till, has been found to reduce CO_2 emissions from soils and potentially sequester C (Schlesinger, 1999; West & Post, 2002; O'Dell et al., 2014). Studies suggest that tillage can influence plant physiology including increased rooting depth from decreased moisture in surface layers of tilled soil (Dwyer et al., 1996) or decreased mechanical resistance (Cox et al., 1990). Other studies indicate that tillage effects on plant physiology may interact with climate as Yu et al. (2016) found that no-till likely increased yield during drought periods by conserving soil moisture. Since arable land represents more than

10% of the global land base (FAO, 2011), arable soils could provide a C sink to offset fossil fuel emissions (Paustian et al., 2016; Lal, 2004).

Yet recent literature provides a conflicting story of the potential impact of different agricultural practices on soil C. While West and Post (2002) found significant increases in soil organic C (SOC) in the top 7-cm of soil in no-till practices compared to tillage across 67 long-term studies, Vanden Bygaart et al. (2003) and Angers et al. (1997) did not find any differences between no-till and conventional tillage when sampling to a deeper soil depth. Vanden Bygaart and Angers (2006) note the obstacles in comparing measured SOC values due to differences in equivalent soil sampling depth, bulk density, landscape, climate, soil type and experiment duration. Another confounding factor is the lack of a standardized description of tillage, and the variety of related practices used in many research reports. Measurement difficulties also complicate the issue—changes in soil C can take up to a decade to detect if trends are measured using destructive sampling (Smith, 2004). Recently, several publications have been critical of conservation agriculture and no-till because some studies concluded that no-till does not increase C sequestration or increase crop yields (Baudron et al., 2012) especially in low yield environs common in Sub-Saharan Africa (Cheesman et al., 2016).

Some older research papers and textbooks provide examples of results obtained in the USA showing that tilling enhances CO_2 emissions (*e.g.*, Reicosky et al., 1995; Bear, 1953; West & Marland, 2002). Similarly, recent work found greater C sequestration with no-till during the crop growing season using BREB in Lesotho and greater no-till sequestration when comparing fallow treatments with cover crops in Zimbabwe (O'Dell et al., 2014; O'Dell et al., 2015). Baker and Griffis (2005) compared the net ecosystem exchange (NEE) of contrasting tillage regimes and cover crops in a maize (*Zea mays* L.)-soybean (*Glycine max* L.) rotation using eddy covariance (EC) but found no significant differences in the NEE of strip tillage with a cover crop compared to conventional tillage with no cover crop. Hollinger et al. (2005) reported that maize sequestered C, while soybean emitted C during two years of a six-year maize-soybean rotation EC study. Using EC, Taylor et al. (2013) found that oat (*Avena sativa* L.) crops grown on fields converted from perennial hay/pasture were net emitters for more than three years while a control hay/pasture field sequestered C.

Many researchers rely on SOC changes by soil depth as the means to determine if C is being accumulated. Yet without accurate surveying measurements from the bedrock to the soil surface any total SOC estimates will be incomplete and the resulting determinations of changes in accumulated carbon will be questionable. An obvious example could be the subsidence post measuring soil depth from the bedrock at the Everglades Agricultural Area in Belle Glade, FL where oxidation of SOC in a histosol profile has resulted in dramatic soil loss as evidenced by the subsidence post markings (Shih et al., 1998).

Micrometeorological methods including BREB systems and EC provide alternative methodologies for investigating changes in crop and soil carbon inventories. These methods have been used to quantify the differences in CO_2 flux between agricultural practices (Dugas et al., 1993; Taylor et al., 2013; O'Dell et al., 2015). The exchange (flux) of CO_2 between the surface and the atmosphere can alternatively be measured using static or dynamic chambers. Chamber systems have spatial and temporal challenges somewhat similar to soil sampling (Norman et al., 1997; Davidson et al., 2002; Reicosky, 1997; Reicosky & Lindstrom, 1995), and are therefore less frequently used in contemporary studies. While the EC and BREB approaches are technically demanding, we believe them to be the optimal approach to evaluate how soil C sequestration can be manipulated to intensify management impacts. EC and BREB systems measure the flux of CO_2 between the atmosphere and the terrestrial system and by summing this flux, the NEE can be determined for a type of ecosystem over a period of time (Chapin et al., 2006). For the purposes of this paper the term sequestration is used to reflect the capture of atmospheric CO_2 by the ecosystem or treatment, *e.g.*, through photosynthesis, while CO_2 emissions refers to a release of CO_2 by the ecosystem to the atmosphere, such as through respiration. While the ecosystem includes soil, organic matter, plants and other biota, the NEE does not distinguish between the components of the ecosystem. The objective of the present study was to determine tillage effects on CO_2 emissions during the maize growing season using the BREB methodology.

2 Materials and Methods

2.1 Site Description

This study site was in north-central Ohio, USA (40.606° N, -82.674° W, 426 m asl.). Micrometeorological and soil properties were measured from 6 May to 17 August 2015. The soil series on the 9 ha research site are classified as Bennington (fine, illitic, mesic Aeric Epiaqualfs), Amanda (fine-loamy, mixed, active, mesic Typic Hapludalfs), Centerburg (fine-loamy, mixed, active, mesic Aquic Hapludalfs), and Condit (fine, illitic, mesic Typic Epiaqualfs) in USDA Soil Taxonomy (USDA Soil Survey Staff, 1999). The surface soil texture is a silt loam and the study site has a slope of 2-6%. The climate is classified as humid continental (Dfb) according to Köppen climate classification, with mean annual rainfall of 955 mm. The study site was managed as an annual row crop production system under no-till for seven years prior to the present study. The prior year's crop was maize.

The study site consisted of two adjacent square plots approximately 4.5 ha each; one plot managed as no-till and the other tilled. A BREB micrometeorological station was erected near the center of each plot. On the no-till plot, maize was planted directly without any tillage except for opening the seed slot (row cleaners were removed). The tilled plot was tandem disked (to manage crop residues), moldboard plowed to a depth of 15 cm, then tandem disked again followed by planting.

Both plots were planted with maize (*Zea mays* L.) on 8-10 May 2015 at a population density of 84,000 plants ha^{-1} using 0.76-m rows using a John Deere 7200 6-row Conservation planter. Nitrogen (N) fertilizer was applied to both plots on 3 June 2015 as granular urea (46-0-0) at the rate of 224 kg N ha^{-1}, phosphorus (P) was applied as triple super phosphate (0-45-0) at 112 kg P ha^{-1} and potassium (K) was applied as potash (0-0-60) at 112 kg K ha^{-1} prior to planting.

2.2 Micrometeorological Measurements and Data Analysis

Air temperature, vapor pressure and CO_2 concentrations were measured before and after planting by the BREB systems, at 0.2- and 1.8-m height above the soil or canopy (note: the BREB units were raised incrementally as the maize crop grew, see below). The BREB units had shielded horizontal air intake tubes facing the direction of prevailing winds (west). Temperature was measured with negative temperature coefficient bead type thermistors, vapor pressure was measured with relative humidity probes (model HC2-S3-L, Rotronic, Switzerland supplied by Campbell Scientific, Inc, Logan, UT) and CO_2 concentrations were measured with non-dispersive infrared gas analyzers (model LI-820, LI-COR Inc., Lincoln, NE). Five-second sensor data were averaged and recorded every five minutes using a data logger (Model CR3000, Campbell Scientific Inc.). To overcome sensor bias at the two heights, the intake tubes housing the sensors were attached at the end of a centrally mounted rotating arm that swapped the position of the atmospheric sensors every five minutes. To allow for equilibration after sensor rotation, the data logger waited two minutes before collecting 5-s readings in determining the 5-min average. As the crop grew, the BREB temperature, humidity and CO_2 sensors were elevated so that the lowest sensor remained about 0.2 m above the crop canopy, with the height differential (1.6 m) between sensor intake points remaining constant.

The BREB stations also measured net radiation, soil heat flux, soil temperature, and wind speed. Net radiation was measured with a net radiometer (NR Lite2, Kipp & Zonen, Delft, The Netherlands), soil heat flux with soil heat flux plates (model HFT3-L, Radiation Energy Balance System (REBS), Seattle, WA) and soil temperatures with four Type "T" thermocouples, two buried at 1.5 cm and two at 4.5 cm below the surface. Volumetric soil moisture content was measured 3 cm below the surface with a water content reflectometer (model CS616, Campbell Scientific, Inc, Logan, UT). Wind direction and speed were measured at the till BREB station with a wind monitor (Model 05305-5, R. M. Young, Inc. Traverse City, MI), and wind speed was measured at the no-till BREB station with a 3-cup anemometer (model 014A, Met One Instruments, Inc., Grants Pass, OR). Rainfall was measured at the no-till BREB station with a tipping bucket rain gauge (model TE525, Texas Electronics, Dallas, TX). Atmospheric pressure was recorded with one silicon altimeter/barometer pressure sensor (model MPX4115, Freescale Semiconductor, Inc., Tempe, AZ). All sensors except thermistors and thermocouples were new and factory-calibrated. Thermistors were created and calibrated in the laboratory; thermocouples were created and calibrated in the field.

Five-second micrometeorological measurements were averaged to calculate 30-min CO_2 fluxes according to BREB system theory (Bowen, 1926; Kanemasu et al., 1979; Webb et al., 1980; Held et al., 1990; McGinn & King, 1990; Dugas, 1993; Perez et al., 1999, Rosenberg et al., 1983) using the following equations as reported by O'Dell et al. (2015). Values of the Bowen ratio (β) were derived as:

$$\beta = [P \times C_P(\Theta_L - \Theta_U)]/[\lambda \times \varepsilon (e_L - e_U)] \quad (1)$$

where, P is measured atmospheric pressure, C_p the specific heat capacity of air, Θ_L and Θ_U are the potential temperatures calculated from air temperatures measured at lower and upper positions, λ the latent heat of vaporization of water, ε the ratio of the molecular weights of air and water, and e_L and e_U are the vapor pressures at lower and upper positions.

Latent heat flux, LE (W m^{-2}) was calculated as:

$$LE = (R_n - G_0)/(1 + \beta) \quad (2)$$

where, R_n is the measured net radiation and G_0 is the soil heat flux at the soil surface. The correction of soil heat flux for heat storage above the depth of the soil heat flux measurement, ΔS, where, $G_0 = G_{0.06m} + \Delta S$ was calculated as:

$$\Delta S = C\,(\Delta T/\Delta t)\,z \tag{3}$$

where, ΔS is the change in heat storage above the soil heat flux plate, C the volumetric heat capacity of the soil, ΔT the change in temperature (current minus previous) of the soil above the heat flux plate taken from average soil temperature measurements at 1.5 and 4.5 cm depths, Δt is the time step (s), z is the depth of the soil heat flux plate (6 cm). C was calculated (de Vries, 1963) as:

$$C = C_m\,(1 - \phi_f) + C_w \times \theta \tag{4}$$

where, the volumetric heat capacity for dry soil is C_m (2.35 MJ m^{-3} K^{-1} (Ochsner et al., 2001)) the volumetric heat capacity of water is C_w (4.18 MJ m^{-3} K^{-1}), and soil volumetric water content, θ was based on measurements from soil moisture sensors in both the tilled and untilled plots. Soil porosity, ϕ_f, was calculated as:

$$\phi_f = 1 - (\rho_b/\rho_s) \tag{5}$$

where, ρ_b is soil bulk density, measured at 1.31 and 1.5 Mg m^{-3} for the till and no-till plots respectively. Soil particle density, ρ_s, was assumed to be 2.65 Mg m^{-3}.

In practice, two additional terms enter into consideration in the surface energy budget: (a) the storage of heat in the canopy biomass and its water content and (b) the energy used in photosynthesis. Meyers and Hollinger (2004) report a combined influence on the surface energy budget comprising about 15% of the net radiation for a fully developed maize canopy in daytime. For the Ohio study reported here, canopy biomass was estimated from yield and the harvest index factor for rainfed maize (Djaman et al., 2013). Heat storage in the canopy at the final stage of plant growth at the end of the experiment was found to rarely exceed 1% of net radiation. The photosynthetic energy used was also estimated to be small, and hence both terms have been omitted from the simple surface energy budget on which the analysis to follow rests. Sensible heat flux, H (W m^{-2}) was calculated as:

$$H = R_n - G_0 - LE \tag{6}$$

Turbulent diffusivity for sensible heat, K_h (m^2 s^{-1}) was calculated as:

$$K_h = (H/\rho_b C_p) \times (\Delta z/\Delta \Theta) \tag{7}$$

where, $\rho_b C_p$ is the volumetric heat capacity for air, Δz is the sensor separation distance (1.6 m).

The CO_2 flux, A, (kg m^{-2} s^{-1}) was then calculated as:

$$A = K_c\,(\Delta\rho_c/\Delta z) \tag{8}$$

where, K_c is the turbulent diffusivity for CO_2 (m^2 s^{-1}), assumed to be equal to the turbulent diffusivity for sensible heat, and $\Delta\rho_c$ is the average difference in CO_2 density between measurement heights.

The CO_2 flux was corrected for temperature and vapor density differences in terms of latent and sensible heat flux using the following equation (Webb et al., 1980):

$$A_{corr} = A + (\rho_c/\rho_a) \times (0.649 \times 10^{-6} \times LE + 3.358 \times 10^{-6} \times H) \tag{9}$$

where, A_{corr} and A are in kg m^{-2} s^{-1}, ρ_c is the average CO_2 density at both measurement heights, ρ_a is the density of dry air. In practice, the correction is sufficiently small that its consequences are within the error bounds associated with the measurements made.

As expressed above, the purpose of the study was to explore the role of tillage within the context of CO_2 emissions and/or sequestration. In view of the experimental complexity and the unavoidable requirement for continuing instrument maintenance, we limited the study to the crop growth period. Sensor data recording began on 6 May 2015 (before seedling emergence) and extended to 17 August 2015 (crop senescence); therefore the 104-day experimental period encompassed the entire period of crop growth. The sign conventions used in this analysis follow standard micrometeorological practice wherein CO_2 flux is positive when CO_2 is emitted from the surface and negative when sequestered/absorbed. Data recorded while rain was falling or when sensor failures resulted in incomplete datasets were omitted.

Flux calculations during the night and transition periods (sunrise and sunset, when temperature differences were close to zero) are problematic, resulting in many periods of large uncertainty which produced spikes in calculations of CO_2 flux, as also reported elsewhere (*e.g.*, Gilmanov et al., 2003; Massman & Lee, 2002; Aubinet, 2008; Savage et al., 2009). We utilized an algorithm to remove data spikes in the half-hour CO_2 flux data using a median filter similar to that used with eddy covariance data (Papale et al., 2006). The strength in this approach lies with the median's resistance to local outliers. While a median filter can distort the flux signal, it is possible to adjust the window width and threshold value as a means to tune the median filter and limit this distortion. This limitation is solved with the use of a median filter extension called the Hampel identifier (Davies & Gather, 1993; Hampel, 1985). This filter depends on both the window width and an additional tuning parameter: a threshold. If the threshold value is reduced to zero the Hampel identifier functions as a typical median filter and if the threshold approaches infinity the filter effectively becomes an identity filter (Pearson, 1999). The parameters of the Hampel identifier for the two datasets were tuned by trial and error to best exclude outliers. The half width window was chosen to be 5 data points meaning that the window was in total 2.5 hours (five 30-min data points). The threshold value was chosen as 5. Spikes remaining after the application of the median filter may be a reflection of atmospheric phenomenon or artifacts of the BREB method, especially during night and transition periods.

Once the data spikes were identified they were removed and the data gaps were linearly interpolated. The maximum range of removed and/or missing values interpolated was limited to two hours or less (four 30-min data points). "Absent data" for periods longer than two hours were not interpolated. For consistent comparison, the total sum of CO_2 flux was calculated for the period when flux data was available for both till and no-till instruments.

A non-parametric bootstrap procedure (Efron, 1979) was used to determine the variance around the time evolving accumulation of CO_2, as described in O'Dell et al. (2015) and was performed with Stata version 14.1 (Stata Corporation, College Station, Texas, USA).

3. Results and Discussion

Figure 1 provides graphs showing continual 30-min CO_2 flux for each month. During May there were positive CO_2 fluxes (emissions) from both the till and no-till plots with greater emissions from the tilled treatment. The tilled plot was plowed on 6 May 2015 (Day of Year (DOY) 126) and planted 8-10 May 2015 (DOY 128-130) and Figure 1 shows positive CO_2 fluxes after plowing in May and during the period of emergence. For five days following tillage on DOY 126 the average daytime CO_2 flux (between 1000 and 1600 hrs) for till and no-till were similar in magnitude at 0.61 +/- 0.03 and 0.40 +/- 0.02 g CO_2 m^{-2} hr^{-1} respectively (plus or minus standard error of the mean). During the subsequent five-day period in May (DOY 132-137) 9.1 mm of rain fell. Whereas before the rainfall the soil temperatures were similar (19.4 +/- 0.22 and 19.3 +/- 0.22 ^{o}C for till and no-till respectively), during the nine-day period (DOY 138-146) following the rainfall soil temperatures averaged over 2 ^{o}C greater in the till than the no-till (17.4 +/- 0.29 and 15.2 +/- 0.20 ^{o}C respectively) due to collective effects of residue cover, albedo and greater evaporative cooling at the soil surface. The average daytime CO_2 flux over the tilled plot (0.73 +/- 0.02 g CO_2 m^{-2} hr^{-2}) during this nine-day period following rain was three times greater than over the no-till (0.21 +/- 0.01 g CO_2 m^{-2} hr^{-2}), consistent with expected rates of microbial decomposition (Swift et al., 1979). Greater emission of CO_2 is expected following intensive tillage due to aerobic and anaerobic decomposition of exposed organic matter that was occluded in aggregates and unavailable to degradation prior to tillage (Elliott & Coleman, 1988; Beare et al., 1994; Six et al., 2000).

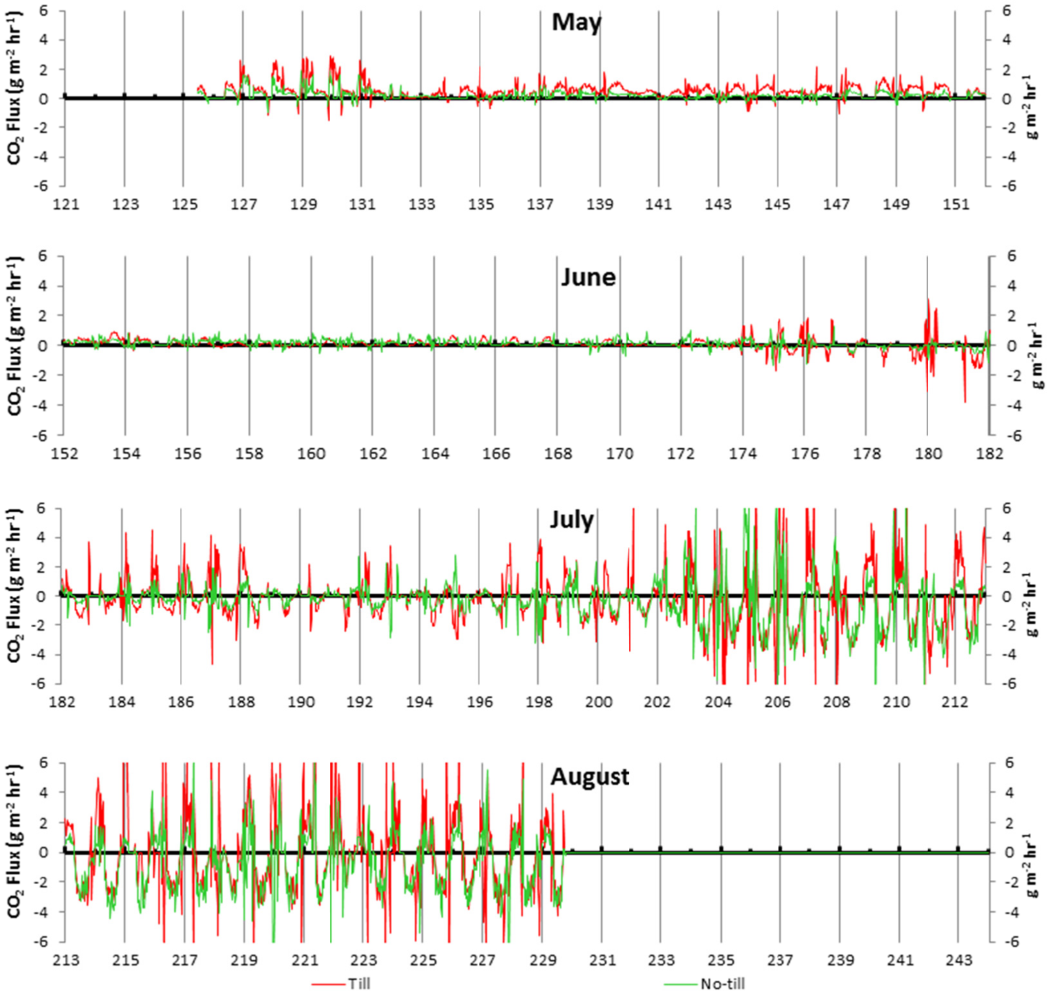

Figure 1. Plots of continual 30-min calculated CO_2 flux for each month of the experiment for the till treatment (red) and no-till treatment (green) beginning on 6 May to 17 August 2015 (DOY 126-229)

Figure 2 shows the mean CO_2 flux during May by time of day for the till (in red) and no-till (in green) treatments. The mean 30-min CO_2 flux by time of day for the till and no-till treatments was then averaged and compared during four distinct periods: daytime between 0900 and 1800 hrs, nighttime between 2200 and 0500 hrs, the sunrise transition period between 0500 and 0900 and sunset transition period between 1800 and 2200 (Table 1). The mean CO_2 flux during each of these periods in May was significantly different when till was compared to no-till using the Student's t-test ($p < 0.01$).

Table 1. Mean CO_2 flux (g CO_2 m^{-2} hr^{-1}) for each time of day period by month and treatment, when mean flux was significantly different between treatments according to a t-test ($P < 0.01$). Mean flux when no significant difference found between treatments are shaded in gray

Month	Time Period	Till	No-till	Significant Difference	Net Sequestration	Net Emission
May	Daytime[a]	0.651	0.292	Y	N	Y
	Nighttime[b]	0.690	0.360	Y	N	Y
	Morning Transition[c]	0.542	0.284	Y	N	Y
	Evening Transition[d]	0.416	0.159	Y	N	Y
June	Daytime	0.128	0.161	N	N	Y
	Nighttime	0.0841	0.179	Y	N	Y
	Morning Transition	0.166	0.245	N	N	Y
	Evening Transition	0.216	0.0624	Y	N	Y
July	Daytime	-1.16	-1.33	N	Y	N
	Nighttime	1.04	0.412	Y	N	Y
	Morning Transition	0.451	-0.017	Y	Y	Y
	Evening Transition	0.171	-0.116	Y	Y	Y
August	Daytime	-2.17	-2.40	Y	Y	Y
	Nighttime	2.21	0.701	Y	N	Y
	Morning Transition	0.695	0.375	N	N	Y
	Evening Transition	-0.166	-0.341	N	Y	N

Note. [a] Daytime hours between 0900 and 1800; [b] Nighttime hours between 2200 and 0500; [c] Morning transition hours between 0500 and 0900; [d] Evening transition hours between 1800 and 2200.

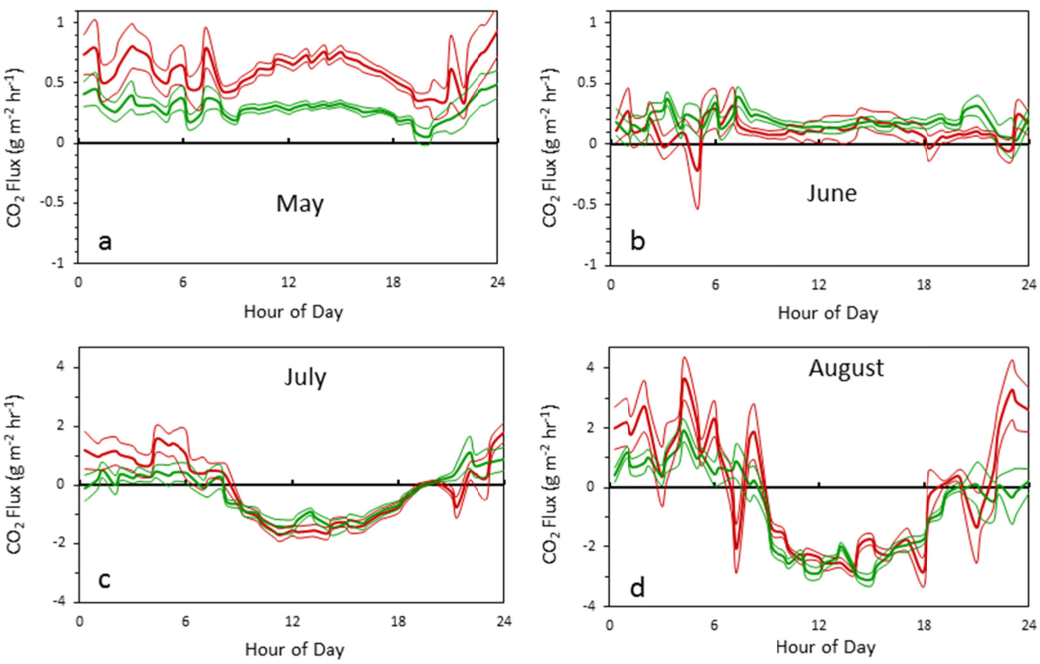

Figure 2. Mean CO_2 flux plus/minus one standard error for the till (red) and no-till (green) treatments by time of day for each month

During June the maize plants were approaching exponential growth in biomass. The positive fluxes (emission) measured over both plots began to decrease (Figure 1) and negative fluxes began to appear near the end of June (roughly day 179-182). These trends are especially revealing because of the unusually heavy rainfall—nearly 200-mm above average rainfall (Table 2). Of the monthly total of 300 mm, 232 mm fell during a ten-day period between June 12-20 (DOY 162-171) (Figure 3). It seems likely that this period of heavy rain resulted in denitrification and subsequent N loss for the cropping season. June was followed by below average rainfall for the rest of the growing season (including periods of drought stress during R1 growth stage).

Table 2. Monthly precipitation measured at experiment site compared to monthly total and 30 year mean recorded at Mansfield Ohio weather station 21.2 km NE of experiment site (NOAA National Centers for Environmental Information, 2016)

	May	June	July	August
	------------------------- mm -----------------------			
Monthly precipitation measured at experiment site	83.1	300	93.0	27.4
Monthly precipitation at Mansfield, OH weather station	112	189	37.8	32.3
30-year mean monthly precipitation at Mansfield, OH weather station	115	121	111	111

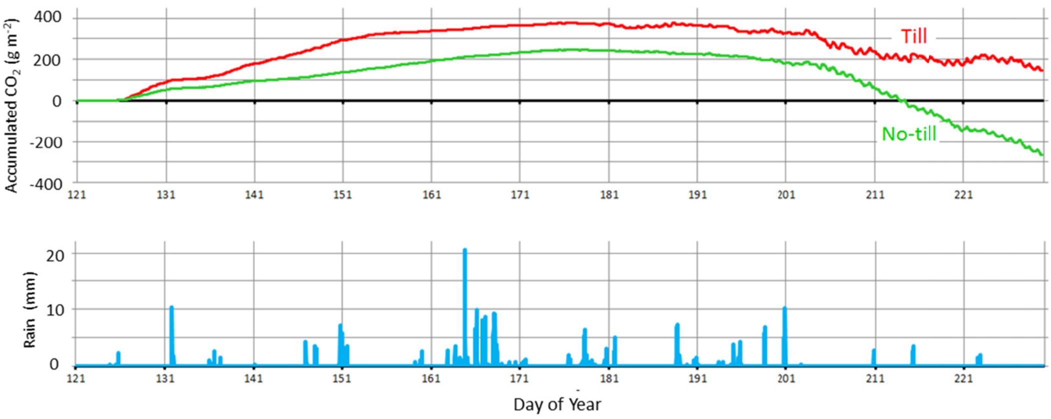

Figure 3 Upper graph is the accumulated sum of CO_2 flux for duration of experiment and lower graph is rainfall for the same period

Towards the end of June (DOY 175-181) both plots began to sequester CO_2 during the day. The 30-min flux graph for June (Figure 1) shows greater sequestration by the tilled plot than the no-till plot, which corresponded with greener and taller plants. On the whole, during June the no-till plot emitted 98.7 g CO_2 m^{-2} while the till emitted 59.2 (Table 3). This was the only month during which the no-till plot emitted more CO_2 than the tilled. CO_2 flux data for June (Figure 2 and Table 1) show no significant differences between the tilled and no-till treatments, except during the nighttime and evening when the no-till plot emitted more than the tilled.

Table 3. Summation of 30-minute CO_2 flux by month and treatment between May 6 and August 17

Treatment	May	June	July	August	Sum of period
	---------------------------------- g CO_2 m^{-2} per period -------------------------------				
Till	300	59.2	-145	-68.1	146
No-till	141	98.7	-221	-282	-263

Rainfall during the experiment was erratic and excessive. June had near record rainfall at the research site that continued into the first half of July (Table 2). As the soils drained and began to dry out there were some days of strong sequestration for both plot treatments, mainly occurring after 22 July 2015 (DOY 203) (see Figure 1). Precipitation measured in the field was 300 and 93.0 mm for June and July, respectively. The C accumulations during July (Figure 3) were flat until after the rains ceased. At that time, sequestration rates paralleled increased crop growth as the crop approached the near exponential growth period. July shows negative CO_2 fluxes (Figure 1) during the day with higher emissions at night for the tilled plot (Table 1). Abnormally high rainfall resulted in marginally chlorotic (lighter green color) and shorter maize plants in several rows of both tillage treatments. These observations effectively predicted lower than normal crop productivity. While no-till has many benefits to long-term soil health and environmental sustainability, no-till fields are impacted greatly by high rainfall because the soil surface cover prevents the soil from drying which slows soil warming, retards crop growth and development, and enhances denitrification conditions. Linn and Doran (1984) found maximum production of CO_2 by soil microbes when the percentage of water-filled pores approached 60% and they found on average greater percentages of water-filled pores in no-till compared to tilled soils. Greater precipitation during the first part of June likely contributed to greater microbial respiration on the no-till plot during that month.

The BREB stations continued measuring fluxes through August 17 (Figure 1). The mean 30-min CO_2 flux graph illustrates large negative daytime fluxes as well as large positive night time fluxes, with the net accumulation being negative for both plots during August (Table 3). Table 1 shows that the crop and soil managed under no-till had on average less emission at night in August and greater sequestration during the day than soils that had been intensively tilled.

Monthly evapotranspiration (ET) was estimated from the BREB latent heat fluxes, calculated as ET = LE/λ, and was compared with monthly precipitation rates in Table 4, expressed in units of mm per period. Comparison of monthly ET with rainfall can indicate water availability for crop growth (Díaz-Zorita, et al., 2002; FAO, 1985). During May and June, precipitation exceeded ET; from May through July—the period with the most rain—the tilled ET was greater than no-till ET. During August—when ET was more than double the precipitation—the no-till and tilled ET were similar suggesting that most ET was from canopy transpiration and/or soil moisture conserved by the no-till residue that became available for the final period of crop growth during a dry period. Consistent with evapotranspiration, a comparison of sensible and latent heat flux showed greater latent heat flux for the till treatment and greater sensible heat flux for the no-till during May and June, while differences were not detected during July and August. A comparison of net radiation and soil heat flux did not show discernable differences between the two treatments.

Table 4. Monthly evapotranspiration computed from latent heat flux for each treatment compared with monthly measured precipitation

Treatment	May	June	July	August	Sum of period
	-- mm --				
Monthly precipitation	82.6	300	93.0	22.1	497
Till	71.3	89.4	109	58.9	329
No-till	49.1	62.8	97.3	58.1	267

Average CO_2 flux by time of day for each month (Figure 2) summarizes the diurnal flux patterns and their change over time. These graphs show a more consistent and smooth behavior for the daytime hours with greater variability at night, especially for the tilled treatment. During July and August, crop growth dominates the daytime flux resulting in smaller differences between treatments. However following the tillage in May, the tilled plot showed greater soil respiration (emission) than the no-till, a trend that continued through July and August at night. Calculated 30-min fluxes of CO_2 were totaled by month and for the period from May 6 through August 17 for the till and no-till plots (Table 3). These calculations show that no-till sequestered 263 g CO_2 m^{-2} while the tilled plot emitted 146 g CO_2 m^{-2} during the 104 days of measurement, a difference of 410 g CO_2 m^{-2}.

A rolling bootstrap simulation (Figure 4) was used to estimate the CO_2 accumulation variance for each treatment (at 90% confidence interval). Data for periods when either treatment did not have values for over two hours were removed leaving ca. 75% of the original data (we also removed the first 10 days to create the initial set for resampling data). The 90% confidence intervals of the bootstrap distribution are shown in grey (Figure 4). The bootstrap accumulation for this 104 day period was 146 g CO_2 m^{-2} (90% confidence interval -53.3 to 332) for the till plot and -263 g CO_2 m^{-2} for the no-till plot (90% confidence interval -432 to -99.9).

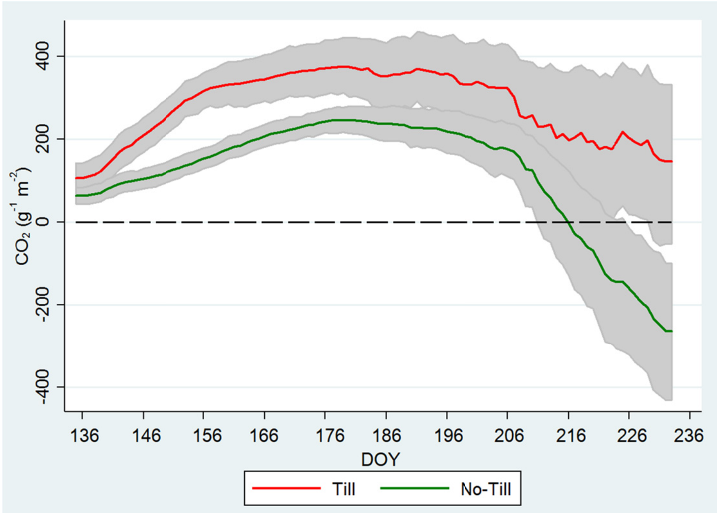

Figure 4. Comparison of accumulated sum of half-hour CO_2 for till and no-till plots (shaded areas are 90% bootstrapped confidence intervals)

The difference in total CO_2 flux between the two plots was 410 g CO_2 m^{-2} for 104 days. Our results suggest that no-till soil management practices have the potential to sequester C compared to soil management practices that use intensive tillage. The results also suggest that the extreme rainfall that occurred the year of this study may have lessened the beneficial impact of no-till practices within the context of CO_2 sequestration. While there is no such thing as a "normal" year, 2015 was a very wet year at the study site. The major rainfall event (in June (DOY 162-171), as indicated in Figure 3) was followed by a period of very dry weather during pollination that greatly impacted overall yields.

The crop produced below average yield—likely the lowest yields harvested in the recent history of the site—presumably due to above average rainfall in June and below average rainfall in August during the pollination and grainfill periods. Denitrification stunted plants resulting in low ear placement (< 0.3 m above the soil surface) and excessively high combine header loss due to low ear placement on the maize stalk. An adjacent experiment comparing the combine harvest totals with two hand harvesting methods measured a significantly lower ($p < 0.0001$) combine harvest yield at 1.70 t ha^{-1} than both hand harvest methods at 2.75 t ha^{-1} for a ten-plant method and 2.72 t ha^{-1} for an in-the-row method (Sullivan, 2016). This adjacent experiment also measured a significantly lower yield ($p < 0.0002$) for the no-till at 2.17 t ha^{-1} compared to 3.26 t ha^{-1} for the till plot. Despite the lower yield for no-till, there was still some advantage by the no-till practice in sequestering C. In a typical year with greater crop yields and normal rainfall one could expect sequestration rates to be higher. The whole farm maize yield exceeded 14 t ha^{-1} the following year (2016) with a better rainfall—more *normal*—pattern.

Studies have shown that surface residue decomposes more slowly than residue incorporated with greater soil contact (Coppens et al., 2004; Noack et al., 2014). Surface residue can act as an insulating barrier reducing soil temperatures and the no-till treatment also may have protected soil C with lower soil temperatures consistent with studies that found greater CO_2 emissions from soil covered with crop residue than from bare soil (Corradi et al., 2013; Al-Kaisi & Yin, 2005; Fortin et al., 1996). Fortin et al. (1996) showed a correlation between lower soil temperatures and lower CO_2 flux for no-till treatment, but this was not found in the present study.

In general, the CO_2 fluxes reported here are measurements made above the maize canopy. They represent the consequence of exchange with the soil plus exchange with crop biomass above the surface. If it was assumed that the measured CO_2 BREB fluxes at night indicate exchange with the soil, with negligible involvement of the plants (whose stomata are then closed), then it is apparent that the till soil must lose CO_2 considerably more rapidly than the no-till. Further, if this increased rate of CO_2 loss from the tilled soil continues through the daytime, then the present data would indicate a substantial difference between the accumulation of CO_2 by the growing canopies. An estimate of the rate of CO_2 accumulation in the growing biomass can be derived by simply subtracting the mean nighttime CO_2 flux from the daytime as shown in Table 5. While no more than a first-order approximation, the results show that when the crop is growing most rapidly in July and August, the tilled plot accumulated more biomass than the untilled—a conclusion that is compatible with farming expectations that tilling is economically beneficial over the short term.

Table 5. Accumulation rates of CO_2 by the canopy assuming that nighttime losses from the soil are representative of the daytime mean fluxes (g CO_2 m^{-2} hr^{-1}) as shown in Table 1

Till	May	June	July	August
Daytime flux	0.651	0.128	-1.16	-2.17
Nightime flux	0.69	0.084	1.04	2.21
Excess daytime vs night	-0.039	0.044	-2.2	-4.38
No-Till	May	June	July	August
Daytime flux	0.292	0.161	-1.33	-2.4
Nighttime flux	0.36	0.179	0.412	0.701
Excess daytime vs night	-0.068	-0.018	-2.74	-3.10

The present results indicate that no-till practices can reduce the loss of CO_2 from the crop surface during the growing season, when compared with soil tilled after seven years of no-till. When combined with cover crops, it is possible that no-till practices could produce a substantial net annual sequestration of CO_2. In the present study tillage resulted in increased CO_2 loss from the soil that appears to have continued throughout the study period. Tillage exhumes buried C sources and provides a means for the soil organisms to mineralize previously occluded organic matter and accelerate decomposition of recently buried crop residue. This study shows that more CO_2 flux can be lost from the terrestrial system to the atmosphere during the first year of a transition from a no-till to a conventionally tilled management practice, confirming that tilling increased the decomposition and respiration of crop residues during the growing season resulting in a net C loss from soils.

In addition to sequestering C, the retention of residues on the soil surface has many positive effects on soil by improving soil aggregation, reducing erosion, and the retention and transport of heat, water and air in the soil (Larson et al., 1978). Though there were periods of high rainfall during the growing season, during drought conditions no-till surface residue can reduce soil moisture loss (Anderson, 2015). While it appears that climate patterns are becoming more erratic and extreme—as evidenced in this study—no-till can be an important management tool to enhance the role of soil in mitigating increased atmospheric CO_2 levels. While C can be sequestered in humid areas under intensive agriculture, sequestering C in areas with marginal soils and rainfall will likely require that winter cover crops be used to further produce biomass that will be needed if soil C levels are to be improved.

4. Conclusions

The present study found that the CO_2 flux for a growing season over an experimental tilled plot was 410 g CO_2 m^{-2} greater than over an adjacent untilled plot. It is recognized that our maize yields were likely affected by excessive precipitation resulting in water-logged soil conditions, N loss, denitrification and retarded crop growth. Higher emissions under the tilled treatment were likely due to a release of organic matter built up during seven preceding years of no-till practice, as reported in other studies. Subsequent tillage could remove more stored organic matter but would result in lower emissions over time (less new previously occluded organic matter becoming available for mineralization). The ability of no-till to keep the soil cooler may reduce decomposition and preserve soil C providing a co-benefit in adapting to rising global temperatures. While our maize yields were much less than average yields for this area, our results show that no-till can be an important practice that not only minimizes C loss from soil but can also be an important tool for sequestering C in an environment becoming more and more CO_2 enriched.

Although the results of this experiment add observational data in support of no-till as a practice to sequester C, more data are needed to understand and quantify these differences under varying climate regimes. To understand the potential magnitude of emissions, factors that impact those emissions, and the overall potential for agriculture to become a recognized climate change mitigant warrants further study. While no-till could reduce CO_2 emissions when considering agricultural practices to offset emissions from other sectors, it can only be one small part of an agricultural program that ensures annual net agricultural C sequestration in high yield environs. Comparative studies of a suite of practices such as the use of cover crops, reduced tillage, and reduced fallow periods are likely necessary to reveal the extent of net soil C sequestration across a greater range of arable soils.

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