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Greenhouse gas fluxes in a no-tillage chronosequence in Central Ohio

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ABSTRACT

A no-till chronosequence study was conducted to assess the impact of continuous no-till (NT) on greenhouse gases (CO_2, CH_4 and N_2O) emission and the global warming potential (GWP) of agroecosystems. Five paired sites in Central Ohio (USA) under plow till (PT) and NT for 9, 13, 36, 48 and 49 years were selected, and GHG fluxes were measured over a 2-year period. Nearby deciduous forests were included for comparative purposes. Results showed higher CO_2 emission under PT than NT (5.74 vs 4.55 Mg CO_2-C ha^{-1}). Annual CH_4 flux averaged -0.1 and -0.07 kg CH_4-C ha^{-1} respectively under NT and PT, and was influenced by location and years under NT (greater rate of CH_4 uptake with longer duration of NT). Yet, the rate of CH_4 uptake in the agricultural soils was always <15% of the rate in nearby forest soils (-1.16 kg CH_4-C ha^{-1} y^{-1}). Annual N_2O emission was generally higher under PT than NT (6.70 vs 4.68 kg N_2O-N ha^{-1}), but an important deviation was observed at one site located on a poorly-drained silt loam soil where N_2O emission was 1.8-fold greater under NT than PT, likely due to wet soil conditions and labile organic carbon availability near the soil surface. The GWP of agroecosystems at the study sites averaged 23.1 and 19.9 Mg CO_2 equivalents ha^{-1} y^{-1} under PT and NT, respectively; N_2O emission accounted for 5 to 60% of the GWP and that contribution increased with NT duration. These results underscore the significance of N_2O in defining the climate mitigation potential of agriculture, and also highlight the need for improved N fertilizer management practices (eg. split application, injection) to minimize N_2O emission from fields under long-term NT. Even without consideration of agricultural inputs (i.e. fuel, fertilizers, pesticides) and change in soil C storage, the GHG flux data showed that sustained application of NT can help decrease the GWP of agroecosystems, further demonstrating the potential climate mitigation benefits of NT farming.

Keywords Greenhouse gases, global warming potential, no-till duration, plow till

1. Introduction

Accumulation of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere alters the earth's energy balance and contributes to the accelerated "greenhouse effect". Further, emission of CH_4 and N_2O has also implication for atmospheric chemistry given their participation in stratospheric ozone depletion (IPCC, 2014). Land-use change and agricultural activities (e.g., plowing, fertilization, biomass burning, livestock and rice production) contribute an estimated 25%, 65% and 90% of the total anthropogenic CO_2, N_2O and CH_4 emissions, respectively (Montzka et al., 2011). Globally, agricultural emissions of CH_4 and N_2O, two of the most potent GHG, were increased by 17% from 1990 to 2005 (Smith et al., 2008). Land management practices and weather conditions determine the capacity of agricultural lands to produce, consume and transport GHG, and thus determine the intensity and direction of GHG fluxes in croplands.

The production and emission of GHG from agricultural soils is impacted by crop production practices such as tillage and nitrogen management (Snyder et al., 2009; Alskaf et al., 2021). Unlike plow tillage (PT) that involves soil inversion, conservation tillage retains at least 30% of crop residue on the soil surface and involves minimal soil disturbance (Giannitsopoulos et al., 2020). No-till (NT) farming is a form of conservation farming that involves the elimination of pre-plant tillage operations, and the current crop is planted directly into the residues left by the previous crop (Lal, 2015). No-till farming has been proposed as an alternative land management practice to conventional tillage (PT) that could mitigate the environmental impact of agriculture through soil erosion control and improved soil organic carbon (SOC) storage, soil water-holding capacity and water use efficiency (Lopez and Arrue, 1997; Mishra et al., 2010; Lal, 2015) in addition to reducing GHG emissions (Wang et al., 2020).

The benefits of NT farming on soil quality are well documented, but there are conflicting reports regarding NT impact on the intensity of GHG emission and the determinants of GHG dynamics in croplands. Curtin et al. (2000) reported significantly higher rates of CO_2 emission from experimental plots under NT compared to PT. In contrast, Omonode et al. (2007) reported higher CO_2 emission rates from PT than NT fields under corn-soybean rotation. Mixed results have also been reported regarding NT impact on land-atmosphere CH_4 exchange, including both greater CH_4 uptake (Jacinthe et al., 2014) and increased CH_4 emission (Alluvione et al., 2009). While several studies have reported higher rates of N_2O emission under NT than PT (Robertson et al., 2000; Baggs et al, 2003), lower emission rates under NT were obtained in other studies (Jacinthe and Dick, 1997; Omonode et al., 2011). Grandy et al. (2006) reported similar rates of N_2O emissions in southern Michigan croplands under PT and NT, and detected no temporal trend in N_2O emissions with NT duration. This contrasted with the results of data synthesis that suggested a marked effect of NT duration on N_2O emissions (Six et al., 2004; van Kessel et al., 2013). Specifically, N_2O emissions were found to be higher under NT than PT during the first 10 years of NT adoption, but afterwards N_2O fluxes tended to be lower under NT. Rochette et al. (2008) reported enhancement in N_2O emissions when NT management is applied to fine-textured soils. Increased soil moisture has been evoked to explain the higher rates of N_2O emission under NT observed in some field studies (Ball et al., 1997; Baggs et al., 2003) and the capacity of biogeochemical models to predict N_2O emission from agricultural soils (Del Grosso et al., 2008; Foltz et al., 2019).

Long-term implementation of NT also results in improved soil structure and formation of soil macro-pores, soil properties that could translate into a more efficient soil-atmosphere exchange of gases and greater rates of CH_4 uptake (Ball et al., 1997; Jacinthe and Lal, 2006;

Prajapati and Jacinthe, 2014). Soils are the only known natural biological sink for CH_4 and there is evidence to suggest that this sink could become stronger with longer duration of NT (Jacinthe et. al., 2014). Although gas transport, as determined by diffusivity, is generally greater in NT than PT soils (Prajapati and Jacinthe, 2014), crop residue on NT soil surface can act as a diffusion barrier to gaseous exchange, and studies have shown an enhancement in CH_4 uptake following removal of these materials from the soil surface (Burke et al., 1997).

Available data indicate that the rate of C sequestration in NT soils generally decreases with NT duration. For example, in Mediterranean agroecosystems, >75% of the SOC gain attributable to NT was found to occur during the first 11 years of NT adoption (Alvaro-Fuentes et al., 2014). Similarly in agricultural soils of Canada, SOC sequestration rates after 20 years of NT adoption declined to 36% of the rates measured during the first decade under NT (Liang et al., 2020). Therefore, once a soil under NT approaches or reaches equilibrium regarding C sequestration, the viability of NT as a land management practice to mitigate climate warming could depend largely on the magnitude and direction of GHG exchange between the atmosphere and NT soil surface. To fully assess the impact of NT practice, annual emission of CO_2, CH_4 and N_2O is often summarized as the global warming potential (GWP), calculated as the sum of net emissions of GHG by converting each gas unit to CO_2 equivalents at a 100-yr time scale using a conversion factor of 1 for CO_2, 298 for N_2O and 34 for CH_4 (IPCC, 2013). The net GWP of an agroecosystem can be calculated as the total CO_2 emission equivalents minus the SOC change (Ma et al., 2013). If SOC level is at equilibrium, net GWP is attributed almost entirely to CH_4 and N_2O cycling. Robertson et al. (2000) concluded that, among tillage practices, NT was the closest to mitigating all sources of GWP. Grandy et al. (2006) came to similar conclusions from their comparison of NT and PT practices in southern Michigan, stating that adoption of NT increased SOC stocks without N_2O emission tradeoffs. Johnson et al. (2005) developed a series of scenarios to determine rates of GHG emission that could offset SOC sequestered in NT soils. Although CH_4 fluxes were not included in their analysis, their results suggested that N_2O emissions must increase by 32-97% to offset the average current rate of C sequestration (0.3 Mg C ha^{-1} y^{-1}) in US Midwest soils under NT.

Although NT adoption has grown in many parts of the world (Kassam et al., 2009), it is often not practiced continuously, but is rotated with either full inversion tillage or tillage involving mixing of the soil without inversion. Little information is available on how soil processes, and especially GHG emissions and GWP, change as the duration of continuous NT management is increased. Yet this chronosequence information is extremely important as more farmers adopt and continuously maintain their fields under NT management. The C sequestration benefits of NT farming can be negated if the practice results in enhanced GHG emission. However, most field studies relating tillage practices and GHG dynamics do not account for the duration of NT implementation, and when NT duration is considered (van Kessel et al., 2013), interpretation of results is often confounded by differences in climate and soil types among study sites.

Here, we report on a 2-year GHG monitoring study conducted at five locations in Central Ohio (USA). The fields were under continuous NT for varying periods of time (0-49 years), thus allowing assessment of the effect of NT duration on GHG flux. The study sites were established on similar soil types and located within the same eco-region, and included farmer-managed NT fields and long-term experimental plots. At each location, adjacent PT fields and secondary growth forests were also sampled to serve as benchmarks against which the NT practice could be compared. The specific objectives of the study were to: (i) compare GHG emissions and GWP from paired NT and PT fields, (ii) determine the effect of NT duration on that comparison, and (iii) examine relationships between GHG, soil properties and environmental factors. We hypothesized that long-term application of NT practices will result in an overall reduction in GWP compared to PT under the typical corn-soybean rotation of the US Midwest.

2. Material and methods

2.1. Description of the study sites

The study sites, in Ohio (USA) were located near the municipalities of Bucyrus (Crawford County), Mount Gilead (Morrow County), Centerburg (Knox County), Wooster (Wayne County) and South Charleston (Clark County). At each location, cultivated fields under NT and PT management were selected, along with a nearby secondary growth forest (Table 1). The NT fields form a chronosequence consisting of croplands which, at the time the experiment was initiated in 2009, were under continuous NT for 9 (Mount Gilead), 13 (Bucyrus), 36 (Centerburg), 48 (South Charleston) and 49 (Wooster) years. The PT treatment consisted of fall plowing (20-25 cm) followed by surface (7.5-10 cm) disking in the spring. A brief description of each site, including geographical coordinates, crop rotation, dominant soil types and drainage characteristics, is provided in Table 1. Additional information, including crop yield and soil properties, regarding the experimental plots is available elsewhere (Kumar et al., 2012; Campbell et al., 2014; Nakajima et al., 2016).

The Bucyrus, Mount Gilead and Centerburg study sites consisted of farmer-managed fields under corn (*Zea mays*, L)-soybean (*Gycine max*, L.) rotation. The Wooster and South Charleston sites were experimental plots established to evaluate the effect of tillage practices on crop production and soil properties. The plots selected for this study (at each location, 3 plots per tillage) were under continuous corn (CC) with either no-till (NT) or conventional plow tillage (PT). The forested areas, dominated by maple (*Acer* spp.), oak (*Quercus* spp.), ash (*Fraxinus* spp.) and hickory (*Carya glabra*, Mill.), were included to obtain GHG emissions from unmanaged non-agricultural sites in the region.

During the corn years at the Bucyrus, Mount Gilead and Centerburg sites, the farmer fields typically received inorganic N fertilizer (5-10 kg N ha^{-1}) at planting, and then an anhydrous ammonia side-dress about one month later for a total of 150-180 kg N ha^{-1}. There was no N fertilizer application during the soybean crop. Fertilizer application rates at the Wooster and South Charleston experimental plots were similar consisting of 16 kg N ha^{-1} at planting and 184 kg N ha^{-1} as anhydrous ammonia (side-dress) in mid-June.

Soils at all the study sites are Alfisols developed from Wisconsinan-age glacial till (Table 1). Soil texture is silt loam on surface with silty-clay-loam, sometimes intermixed with gravel, in the subsurface. Climate is temperate with long-term (30 y) mean annual temperature of 9.9 ^{o}C and precipitation of 1,023 mm. Mean annual precipitation ranges between 905 and 1045 mm, respectively, in Wooster and South Charleston, the most northern and southern locations of the transect. Weather data for the study sites were obtained from the Midwestern Regional Climate Center (http://mcc.sws.uiuc.edu/) and from the Ohio Agricultural Research and Development Center weather network (http://oardc/ohio-state.edu/newweather).

2.2. Greenhouse gases monitoring

At each farmer’s field, three sampling areas per tillage practice were delimited. Demarcation of sampling areas was made using available soil maps to ensure that sampling areas were within the same or very similar soil series. At the Wooster and South Charleston locations, three experimental plots per tillage practice were selected.

Gas fluxes were monitored between August 2009 and August 2011 (two full calendar years) using the static chamber technique (Jacinthe and Dick, 1997). At each of the three sampling areas four chambers were deployed (for a total of 12 chambers per each farmer's managed field). At each of the secondary growth forests, 6 chambers were deployed. Chambers (volume: 12 L) were made of a white polyvinyl chloride (PVC) pipe that was beveled to facilitate insertion into the ground (5 cm deep). Chambers were installed at least one week prior to conducting GHG flux measurement and remained in place for the entire growing season (except for harvest and other scheduled farming operations). The bases of the chambers were positioned between crop rows (typical row spacing: 75 cm; Fernández et al., 2015). Inter-row placement of the chambers was selected to maximize the distance from growing crops, and thus minimize the effect of microbial activity in the rhizosphere on measured CO_2 fluxes. Current methodologies for assessing the GWP of agroecosystems recommend the exclusion of root respiration from the computation (Sainju, 2016). In studies where chambers (width: 60-78 cm) reached adjacent crop rows, root respiration was found to account for 30-40 % of CO_2 efflux during the growing season (June-October) (Rochette et al., 1999; Mosier et al., 2006). Thus, the chambers (diameter: 30 cm) deployed in the present investigation were designed and located with this potential interference in mind. Our interrow chamber placement was similar to the procedure used by Ussiri et al. (2009) in a study examining the climate mitigation potential of tillage practices in US Midwest agriculture.

During sampling, chambers were covered with PVC lids secured to the base with latch clamps. The lid was fitted with a gasket at its underside edge to make an air-tight seal, and a butyl rubber septum was inserted into the center to form a sampling port. Air samples were withdrawn from chamber headspace at 30-min intervals with a syringe and stored in pre-evacuated glass vials capped with gray butyl rubber septa (Microliter, Suwanee, GA). Sampling generally took place between 11:00 and 13:00 h local time, and at each site sampling was made at about the same time of the day. Fluxes were monitored bi-weekly with more frequent sampling during the winter-to-spring transition, and during the 2-3 weeks following fertilizer application. Less frequent measurements were made during the dormant season. During the monitoring period, GHG fluxes were measured 26-32 times at each site.

Air samples were analyzed for CO_2, CH_4 and N_2O with a CP-3800 gas chromatograph (GC) (Varian, Palo Alto, CA) equipped with thermal conductivity (TCD), flame-ionization (FID) and electron capture (ECD) detectors, and interfaced with a Combi-Pal headspace auto-sampler (CTC Analytics, Zurich, Switzerland). The GC was also equipped with four time-programmed 6-port valves that control the direction of carrier gas flow between analytical columns and detectors and, through backflushing, prevent compounds such as water vapor and oxygen (which could impact ECD performance) from reaching that detector (Wang and Wang, 2003; Zheng et al., 2008). Operating conditions of the gas chromatograph (GC) were as follows: carrier gas (UHP He at 20 mL min^{-1} for CO_2 and CH_4, and UHP N_2 at 60 ml min^{-1} for N_2O), oven temperature (90 ^oC), detector temperature (TCD and FID at 150 ^oC, and ECD at 300 ^oC). The stationary phase consisted of a pre-column (L: 0.3 m; id: 2 mm) and analytical columns (L: 1.8 m; id: 2 mm) packed with either with Porapak Q (80-100 mesh; connected to TCD and FID) or Hayesep D (80-100 mesh; connected to ECD). Certified gas standards, obtained from Alltech (Deerfield, IL), were used for instrument calibration (detection limit: 20 µL CO_2 L^{-1}, 0.12 µL CH_4 L^{-1}, 0.05 µL N_2O L^{-1}).

Daily fluxes of gases were calculated from the change in gas concentrations inside the chamber over the measurement period (dC/dt = μL L^{-1} min^{-1}) and the chamber dimensions (volume or V = 12 L, surface area covered or A = 0.0706 m^2).

$$F = (\frac{dC}{dt})(\frac{V}{A})(\frac{M_w}{RT})k(1 - \frac{e_w}{P}) \quad (1)$$

where M_w is the molecular weight (for example 44 x 10^3 mg mol^{-1} for CO_2), R is the universal gas constant (0.08206 L atm K^{-1} mol^{-1}), T is average air temperature (K), k is time conversion factor (1440 min d^{-1}), e_w is the water vapor partial pressure (kPa), and P is the barometric pressure (kPa).

The daily rate of GHG emission was calculated by averaging fluxes measured in the individual chambers associated with each treatment (n=12 for agricultural fields; n=6 for forests). Cumulative GHG emission during each crop phase and over the entire 2-year study was computed for each chamber by linear interpolation and integration between consecutive sampling dates using the trapezoidal rule to determine the area under the curve (Fisher et al., 2014). Cumulative GHG emission during the study period was converted to CO_2-C equivalents per hectare by taking into account the GWP of CH_4 (34 times) and N_2O (298 times) relative to CO_2 (IPCC, 2013).

2.3. Soil properties

Soil samples collected from each site in the fall of 2009 were used to assess soil properties (Table 2). Composite samples (five points per sampling area) were taken from each of the experimental plots and study areas described above. Intact soil cores were also obtained to determine soil bulk density. Soil pH was measured using a soil-to-water ratio of 1:2. Organic C and N concentration was determined by dry combustion (960 °C) using a Vario-Cube analyzer

(Elementar Americas, NJ) fitted with an NDIR detector. Detail information about other physico-chemical properties of soils and C sequestration at the study sites are reported elsewhere (Jacinthe et al., 2014; Nakajima et al., 2016).

Soil samples (composite of four points per sampling area) were occasionally collected (5 to 10 times during the study period) to measure the mineral N (NH_4^+, NO_3^-) pool. Inorganic N was extracted using 1 M KCl (2:1 solution to soil ratio), and the extract was analyzed using a photometric analyzer (Aquakem 20, EST Analytical, Fairfield, OH). All results are reported on a soil mass basis (i.e., soil dried at 105 °C for 48 h). At the Wooster and South Charleston sites, soil temperature (TMB-M006) and moisture probes (SMA-M005; Onset Corp., MA), interfaced with data loggers, were installed (20 cm deep) for continuous measurement of soil moisture and temperature.

2.4. Statistical analysis

Analysis of variance (ANOVA) was conducted to assess the effect of crop type, tillage practice and NT duration on daily fluxes and annual GHG emissions from the study sites. For the daily fluxes, the data were analyzed for each location separately since sampling did not always occur on the same date. Statistical analysis was performed using PROC GLM and PROC REG available in the SAS 9.4 (SAS Institute, Cary, NC). Unless otherwise noted, statistical significance was determined at the $P < 0.05$ level.

3. Results

3.1. Environmental conditions

During the study period, mean air temperature averaged 10±0.3 ºC at the study sites.

Annual rainfall across the region averaged 1,060±58 mm, but there were some noticeable variations. During the peak of the growing season (May-July over 2 years), total rainfall averaged 400±1 mm at Mount Gilead and 339±18 mm at Centerburg. At the Bucyrus site, the early season rainfall varied from 515 mm in 2010 (55% above normal of 334 mm) to 374 mm in 2011.

3.2. Soil characteristics at the study sites

Soil pH values (0-30 cm depth) for the forest sites were the lowest except for the PT field at Centerburg (Table 2). At three sites (Bucyrus, Centerburg, and Wooster), the plowed fields had pH values below 6.0 and could benefit from a lime application. Bulk density was also the lowest while organic SOC and total N were the highest in the forest soils.

Soil moisture was on average lower (0.21 g water g^{-1} soil) in the PT than in the NT (0.23 g water g^{-1} soil) fields and the forested areas (0.29 water g^{-1} soil) (Table 3). The pool of mineral N (NH_4 + NO_3) was generally higher in PT than in NT soils (8.22 vs 6.15 mg N kg^{-1} soil).

3.3. Carbon dioxide emission

At all the study sites (Figs. 1-5), CO_2 emissions closely followed the temporal trend in air temperature. Emission of CO_2 progressively increased from early spring reaching its maxima during the warmer months of the year between June and August. Emissions dropped to almost zero during the months when soils were frozen or snow covered, and GHG monitoring was discontinued during these months. There was some difference among sites regarding CO_2 flux. For example, among the cultivated fields, the Bucyrus (Fig. 2) and Wooster (Fig. 4) sites exhibited much greater daily CO_2 flux (2.60 g CO_2-C m^{-2} d^{-1}) compared to the other sites (1.76 g CO_2-C m^{-2} d^{-1}) (Figs. 1-5). The PT fields generally showed sharper CO_2 emission peaks compared to the broader peaks at the NT fields. Averaged over the study period, daily flux of CO_2 was generally higher (though not statistically) under PT compared to NT.

Annual CO_2 flux from the agricultural fields ranged from 2.40 to 8.25 Mg CO_2-C ha^{-1} with no significant statistical difference regarding crop type and a borderline effect of tillage (Table 4). However, with the exception of the Centerburg site, annual CO_2 emission during the corn crop trended higher by 1.3-fold under PT than NT (5.74 vs 4.55 Mg CO_2-C ha^{-1}). Averaged across tillage practices and study sites, annual CO_2 emission was lower (1.2-fold) during the soybean crop (4.15 Mg CO_2-C ha^{-1}) than during corn (4.89 Mg CO_2-C ha^{-1}) (Table 4).

At the forested sites, annual CO_2 flux averaged 5.6 Mg CO_2-C ha^{-1} and, similar to the ranking observed with the agricultural fields, CO_2 flux was the highest at Bucyrus (6.4 Mg CO_2-C ha^{-1} y^{-1}) and Wooster (6.67 Mg CO_2-C ha^{-1} y^{-1}) compared to the other sites (5.03 Mg CO_2-C ha^{-1} y^{-1}; Table 5 and Fig. 6). Using the data from the Wooster and South Charleston sites (temperature was continuously measured), regression analysis showed exponential relationships between daily flux of CO_2 and soil temperature (Fig. 7). To express the temperature sensitivity of soil respiration, Q_{10} (proportional increase in CO_2 flux per 10 ^{o}C increase in temperature) was derived from the exponential relationships ($y = \alpha exp^{\beta x}$ and $Q_{10} = exp^{10\beta}$). For the PT, NT and forest, Q_{10} values of soil respiration averaged 3.11±0.0.2, 4.05±0.43 and 1.82±0.93, respectively.

3.4. Methane flux

Soils at the study sites were predominantly sinks for CH_4 except for a few occasions in May (late spring) when soils became saturated by rainfall and there were still significant amounts of litter or crop residues available to fuel the activity of methanogens (i.e., CH_4-producing microorganisms). In general, CH_4 flux was influenced by location and tillage regime (Fig. 1-5).

At the Bucyrus location, the NT and PT fields were a net source of CH_4 during the soybean phase of the rotation which was a wet year (55% above normal during the growing season) (Fig. 2; Table 4). Likewise, the PT fields at the South Charleston site were a small net source of CH_4. Across study sites and crops, annual CH_4 flux averaged -0.1 and -0.07 kg CH_4-C ha^{-1} under NT and PT, respectively. If the South Charleston site is excluded, a negative relationship was found between annual CH_4 flux (y) and NT duration (x, years) ($y=-0.01x - 0.10$, R^2: 0.71, $P<0.09$).

The forest soils were strong sinks for CH_4 with annual uptake averaging -1.16 kg CH_4-C ha^{-1} (Table 5), with the forest in Wooster exhibiting an uptake rate 2 times greater than the study-wide average. At best, CH_4 uptake in the agricultural soils represented 15% of uptake measured in the forests.

3.5. Nitrous oxide flux

Emission of N_2O varied greatly among the study sites (note the differences in scale for each site; Fig. 1-5). A significant emission peak (>30 mg N_2O-N m^{-2} d^{-1}) was observed at the sites with longer-term NT practice (i.e. Centerburg, South Charleston and Wooster) (Figs. 1-5). In all cases, the N_2O peaks corresponded with a combination of N fertilizer application (to corn crop) and a major rainfall event. Under NT practice, these brief periods (~7-10 days) of peak emission accounted for 70%, 72% and 87% of annual emission at the Centerburg, Wooster and South Charleston sites, respectively. Under PT practice, corresponding contribution of these emission bursts was 50%, 32% and 82% respectively at these sites. In general, N_2O emission was near zero in late fall to early winter.

Annual rate of N_2O emission was influenced by crop type and tillage practice. Across site and tillage practice, annual N_2O emission was significantly ($P<0.034$) higher during the corn than the soybean crop (7.72 vs 2.30 kg N_2O-N ha^{-1}; Table 4). Likewise, across site and crop type, annual N_2O emission was 1.4 times higher under PT than NT (6.70 vs 4.68 kg N_2O-N ha^{-1}; Table 4), but it should be noted that emission at the Bucyrus and South Charleston sites deviated from that general trend, with greater N_2O emission measured under NT than PT (Table 4). Duration of NT also influenced the magnitude of N_2O emission. For example, for the corn phase of the rotation, a significant positive relationship was found between annual N_2O emission (y) and NT duration (x, years) (y=0.20x – 0.27, R^2: 0.79, P<0.04).

At the forested sites, annual N_2O flux averaged 0.63 kg N_2O-N ha^{-1} (Table 5), representing about 11% of the emissions measured in the agricultural fields. Consistent with their higher soil moisture and mineral N (Table 3), N_2O flux was the highest at the Centerburg and South Charleston forests (0.98 kg N_2O-N ha^{-1} y^{-1}) than at the other forested sites (0.39 kg N_2O-N ha^{-1} y^{-1}). Annual N_2O emission (y) was linearly related to the average concentration of nitrate (x) in the surface soil layer (PT: y=0.93x – 2.63, R^2: 0.68, P<0.08; NT: y=1.94x – 10.1, R^2: 0.91, P<0.01; Forest: y=0.1x – 0.13, R^2: 0.82, P<0.03).

3.6. Global warming potential (GWP)

The climate impact of tillage practices as expressed by GWP ranged from 10.5 to 37.4 Mg CO_2 equivalents ha^{-1} y^{-1}, averaging 23.1 and 19.9 Mg CO_2 equivalents ha^{-1} y^{-1} under PT and NT, respectively. Methane uptake provided a negligible (<12 kg CO_2 equivalents ha^{-1} y^{-1}) level of mitigation. The N_2O emissions accounted for between 6 and 63% of the GWP, with the largest contribution at the PT fields in Centerburg. Among the NT fields, the relative contribution of N_2O to GWP increased with duration of NT (Fig. 8).

4. Discussion

A primary objective of this study was to compare GHG fluxes between adjacent NT and PT crop fields at five different locations and identify underlying drivers of these differences. Results showed clear effects of tillage practices on GHG dynamics, but these effects were modulated by location, soil drainage characteristics and NT duration. Overall, we found higher CO_2 emission under PT than NT. Emissions of N_2O were also higher under PT than NT, but the reverse was observed where NT was established on poorly-drained soil. Emission of N_2O also increased with NT duration, and consequently the contribution of N_2O to GWP was greater in the older NT fields.

4.1. Tillage disturbance and CO_2 emission

Tillage practices influenced CO_2 emission, with greater intensity of emission and lower SOC retention generally associated with frequent tillage (i.e., soil disturbance) (Alvaro-Fuentes et al., 2014; Nakajima et al., 2016; Liang et al., 2020). Crop biomass input, soil temperature and physical disturbance are common contributing factors to CO_2 production in soils (Nishigaki et al., 2020). In the context of this study, tillage disturbance may have played a primary role. Plowing can increase CO_2 emission by aerating the soil and mechanically breaking down soil aggregates, causing the release of protected organic C fractions (Jacinthe and Lal, 2005).

In comparison to PT, some studies have reported higher CO_2 emissions from NT (Ball et al., 1999; Rochette et al., 2008), while others have reported lower emissions from NT (Chatskikh and Olesen, 2007; Gregorich et al., 2008; Wang et al., 2020). Zhang et al. (2009) analyzed the impacts of NT and PT on the distribution and stability of SOC and showed that, in the 0-5 cm depth, long-term NT soils contained more SOC relative to PT soils, and the SOC pool was also more labile in the former than in the latter. That interpretation is consistent with our findings (Table 2) of lower C/N ratios of soil organic matter in PT soil (compared to NT and forest soils), suggesting that annual plowing may have resulted in increased mineralization of soil organic matter in the PT fields (Laine et al., 2018). As measured in the present study (Table 3), that would translate into increased availability of mineral N and possibly increased production of N_2O if plant N uptake is limited and moist soil conditions develop. In fact, a close inspection of the data presented in Table 4 shows that the ratio of emission of N_2O-to-CO_2 averaged 1.48 and 0.96 under PT and NT, respectively. In order words, for each unit of soil respiration, 1.5 times more N_2O is released under PT compared to NT practice. The higher CO_2 emissions under PT than NT was expected and is supported by results of several past studies (Curtin et al. 2000; Reicosky and Archer, 2007; Alluvione et al., 2009). Lower CO_2 fluxes under NT than under PT were attributed to slower decomposition of crop residues placed on the surface of NT soil, compared to residue incorporated under PT. It is also presumed that the NT soil sequesters more SOC and the PT soil emits more CO_2 into the atmosphere. Curtin et al. (2000) measured CO_2 fluxes from a 13-year old tillage treatment plot in Canada, and concluded that the mean annual CO_2 flux was 20 to 25% lower under NT than PT. Likewise, Alluvione et al. (2009) reported a 14% reduction in cumulative CO_2 emission under NT than PT during the growing season.

4.2. Complex effect of no-till on methane uptake in agricultural soils

The impact of NT farming on CH_4 uptake is variable and complex, and can be influenced by several soil biological and physical processes. Surface accumulation of crop residue under NT can increase soil wetness and thus could lead to greater rate of CH_4 production under NT compared to PT systems. But it is also possible that long-term implementation of NT could increase soil macro-porosity, lead to the evolution of an active population of methanotrophs, and ultimately result in enhanced CH_4 uptake (Ball et al., 1997; Prajapati and Jacinthe, 2014). Thus, CH_4 flux measured at the soil surface is the balance between the intensity of these biological and physical processes.

Past studies conducted across various soil types and regions have reported mixed responses of tillage practices on CH_4 flux. It is widely understood that intensive agriculture can negatively impact the CH_4 oxidation capacity of soils, and these results have largely been ascribed to application of ammonia-based fertilizer (competition between NH_4-oxidizers and methanotrophs) and soil structure disturbance (due to plowing), resulting in disruption of the soil methanotrophic community (Powlson et al., 1997; Hutsch, 2001). While several studies have reported an increase in CH_4 consumption under NT (Venterea et al., 2005; Ussiri et al., 2009; Jacinthe et al., 2014), difference in CH_4 fluxes between PT and NT is often modest and insignificant (Yamulki and Jarvis, 2002; Jacinthe and Lal, 2005; Mosier et al., 2006).

In the present study, an overall net improvement in soil CH_4 uptake was observed with NT adoption. Annual rate of CH_4 uptake was higher under NT compared to PT (-0.23 vs -0.01 kg CH_4-C ha^{-1}). The most pronounced effect of NT was observed at the Centerburg and Wooster locations where mean uptake rates ranging between -0.14 and -0.41 kg CH_4-C ha^{-1} were measured under NT (Figs. 3-4 and Table 4). These rates represent 12-20% of the CH_4 uptake rate measured in forested areas at these locations (Fig. 6 and Table 4), and this observation is consistent with the general expectation of increased CH_4 sink strength with NT duration (Powlson et al., 1997; Jacinthe et al., 2014; Prajapati and Jacinthe, 2014). In a more detailed analysis of laboratory-measured CH_4 oxidation from these same chronosequence of sites, Jacinthe et al. (2014) reported that the longer a soil was maintained under NT, the greater was its ability to serve as a sink for CH_4. Results of that laboratory investigation have shown that, after 48 years of continuous NT, the CH_4 sink capacity of NT soils was about 37% of that of the forest soils. While results of both the laboratory experiments (Jacinthe et al. 2014) and the present study (Table 4) clearly indicate improved CH_4 consumption of soils under NT, field-level expression of that capacity appeared to have been limited by soil physical properties. Past results (Prajapati and Jacinthe, 2014) have suggested that, due to higher soil gas diffusivity of NT than PT soils, field-scale expression of the CH_4 consumption potential is less impeded by gas transport under long-term NT. In the present study, such a restriction was most pronounced at the S. Charleston site where fields under NT for 49 years were minor sinks for CH_4 (Table 4) despite indications of CH_4 oxidation potential from laboratory measurements (Prajapati and Jacinthe, 2014). Increased soil wetness due to abundant rainfall in May of 2010 may also have caused the poorly-drained Crosby silt-loam soils in South Charleston to become a net source of CH_4 (Fig. 5). Without that period, the study-wide daily rate of CH_4 flux would have been -0.004 (PT) and -0.015 mg CH_4-C m^{-2} d^{-1} (NT). Similar to the results of the present investigation, a previous study at that same site in South Charleston (Ussiri et al., 2009) showed that the NT fields were net CH_4 sinks whereas the PT fields were CH_4 sources.

4.3 Soil and climatic drivers of N_2O emission

Agriculture has long been identified as a major source of N_2O, a potent greenhouse gas (IPCC, 2013). Denitrification is the main N_2O-forming process in agricultural soils, and generally stimulated by availability of mineral N, high soil moisture and organic C content (Palma et al., 1997). As N_2O is almost 300 times more potent than CO_2 as a GHG, the benefits of adopting NT as an approach to mitigate atmospheric CO_2 could be offset by increased N_2O emission. Our results have shown instances of lower N_2O flux under NT than PT, but there were important site-specific trends needing further examination.

While some studies indicate higher N_2O emissions from NT (Ball et al., 1999; Rochette, 2008; Rochette et al., 2008; Garland et al., 2011), others have reported lower emissions from NT (Chatskikh and Olesen, 2007; Gregorich et al., 2008) in comparison to PT soils. Other studies have observed no difference between PT and NT treatments (Choudhary et al., 2002; Yamulki and Jarvis, 2002). Results from Campbell et al. (2014) have shown that the comparative effect of tillage practices on N_2O emission depends on soil type. In the present study, overall annual N_2O emissions (kg N_2O-N ha^{-1}) were significantly ($P<0.041$) lower under NT (5.42) than under PT (11.91) at 3 out of 5 locations (Table 4). The Bucyrus and South Charleston deviated from that general trend. Consistent with these results, ANOVA showed that the effect of tillage on N_2O flux depends on the location (significant tillage x location interaction). Among other factors, the effect of location includes NT duration, rainfall distribution and soil hydrology. Higher N_2O under NT at the Bucyrus location can be traced to a "hot-moment" of N_2O emission in June 2010 triggered by above-normal precipitation and nitrogen side-dressing of corn (Fig. 2).

In general, at the locations where NT practice was in place for <15 years (Mount Gilead, Bucyrus), the difference in N_2O emission between NT and PT was relatively small (<2 kg N ha^{-1} y^{-1}; Table 4). At the older NT sites (>35 years; Centerburg and Wooster), annual N_2O emission was substantially lower under NT than PT (difference >6.5 kg N ha^{-1} y^{-1}; Table 4). However, at the South Charleston location where soils are poorly-drained, the reverse was observed, with significantly greater N_2O emission under NT than PT. Closer inspection of the data (Fig. 5) further showed that N_2O emission difference (between NT and PT) was most substantial when the cumulative amount of rainfall in the 8-day following N fertilizer application exceeds 30 mm. In contrast, at the Wooster location where soils are well-drained, notable N_2O emission difference between tillage practices was observed when cumulative rainfall exceeds 70 mm following N fertilizer application. These results argue for careful timing of N fertilizer application to poorly-drained fields under NT management in order to minimize episodes of vigorous N_2O release. As noted previously, these “hot moments” can account for 55% and 76% of annual emissions under PT and NT, respectively.

Emissions of N_2O contributed the most to the GWP of the agroecosystems investigated (Fig. 8), and this contribution was also found to increase with NT duration and poor soil drainage characteristics. These results indicate that more judicious N fertilizer management is needed for fields under long-term NT to aid in the control of N_2O emissions. While mineral N availability is necessary to maintain crop yield (and indirectly SOC sequestration via crop residue return), these benefits can be offset by increased N_2O emission. For most of the US Midwest, nitrogen fertilizer recommendations were developed at a time when NT farming was not as prevalent as it is today. Our results argue for the emergence of a new paradigm in N fertilizer management that is more suited to cropland under NT management. At our study sites, N application during the corn crop averaged 180 kg N ha^{-1}, and our results showed that 1% to 7.6% of that amount lost as N_2O. Results of a study conducted in Michigan have shown an exponential increase in N_2O emission when N application to corn crops was in excess of 135 kg N ha^{-1} (Hoben et al., 2011). These results indicate that N fertilizer application rate to corn needs to be adjusted to strike the right balance between optimum crop yield and air quality. Nonetheless, more research needs to be conducted on other soil types and fields under NT for various lengths of time to determine these adjustments. There is also a need to develop a quantitative understanding of N cycling processes (N mineralization, N immobilization, N-use efficiency) in long-term NT soils to determine their N-supplying capacity in relation to the N requirements of new corn varieties, and integrate this information into the formulation of N fertilizer recommendations that are better optimized for NT production systems. Ultimately, the goal is to preserve the environmental quality benefits of NT farming (C sequestration, water-use efficiency, soil protection, etc) while minimizing N_2O emission.

5. Conclusions

A two-year study was conducted at five locations in Ohio (USA) to directly compare the effect of long-term NT and PT practices on CO_2, N_2O and CH_4 emissions from the predominant cropping systems (i.e., continuous corn and corn-soybean) in the US Midwest. Compared to PT, NT generally led to decreased CO_2 emission and greater rates of CH_4 uptake – although uptake rates were on average 9% of the level measured in adjacent forests. Nitrous oxide emission during the growing season was significantly affected by crop rotation and tillage, with the tillage effect varying with soil hydrology. Emission of N_2O under corn-soybean rotation was 20% lower relative to continuous corn. Annual N_2O emission was lower (although not always statistically significant) under NT than under PT, but a marked deviation was observed (higher N_2O emission under NT than PT) at a site (South Charleston) located on poorly-drained soils. These results were ascribed to hot-moments of N_2O emission associated with wet soil conditions and the timing of N fertilizer application. While long-term maintenance of NT has the potential to reduce the overall global warming potential of agroecosystems (compared to PT), better understanding of the N cycling processes (N mineralization, N immobilization, N-use efficiency) in long-term NT soils is needed in order to optimize N fertilization practices that will help minimize N_2O

emission, and preserve the economic and environmental benefits of NT farming (i.e., better yields, C sequestration, water-use efficiency, soil protection, and less fuel use, etc.).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure captions

Fig. 1 Air temperature and rainfall (panel A), and fluxes of carbon dioxide (panel B), methane (panel C) and nitrous oxide (panel D) measured at the farmer-managed cropped fields near Mount Gilead, Ohio. Each data point is the average of n = 12 measurements with error bars indicating standard deviations. On a given sampling date, gas fluxes are not significantly different ($P < 0.05$) if the letters above the error bars are different. Cropped fields were under conventional tillage (PT, empty circle) or no-till (NT, filled circle) for 9 years at the beginning of the monitoring period.

Fig. 2 Air temperature and rainfall (panel A), and fluxes of carbon dioxide (panel B), methane (panel C) and nitrous oxide (panel D) measured at the farmer-managed cropped fields near Bucyrus, Ohio. Each data point is the average of n = 12 measurements with error bars indicating standard deviations. On a given sampling date, gas fluxes are not significantly different ($P < 0.05$) if the letters above the error bars are different. Cropped fields were under conventional tillage (PT, empty circle) or no-till (NT, filled circle) for 13 years at the beginning of the monitoring period.

Fig. 3 Air temperature and rainfall (panel A), and fluxes of carbon dioxide (panel B), methane (panel C) and nitrous oxide (panel D) measured at the farmer-managed cropped fields near Centerburg, Ohio. Each data point is the average of n = 12 measurements with error bars indicating standard deviations. On a given sampling date, gas fluxes are not significantly different ($P < 0.05$) if the letters above the error bars are different. Cropped fields were under conventional tillage (PT, empty circle) or no-till (NT, filled circle) for 36 years at the beginning of the monitoring period.

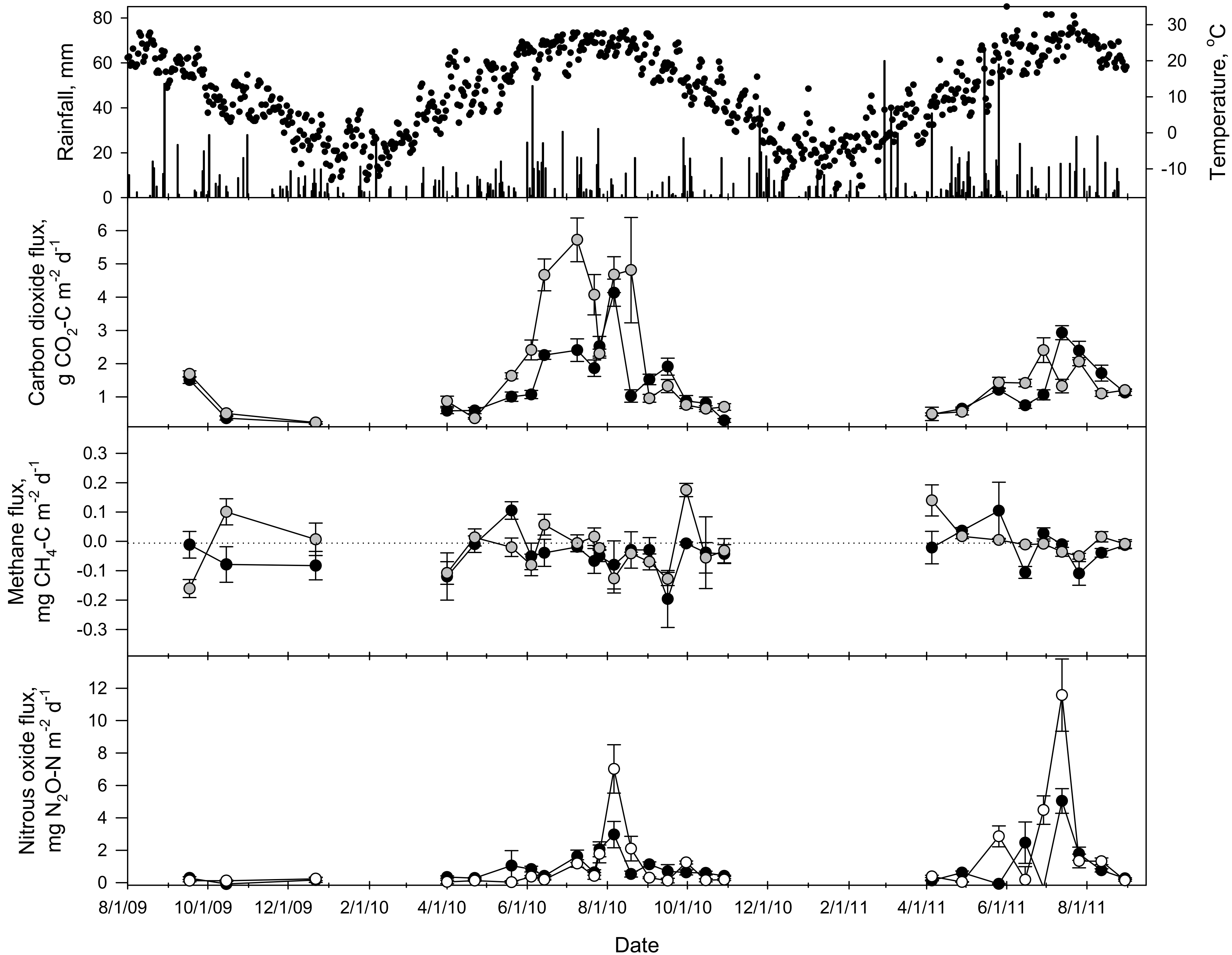
Fig. 4 Air temperature and rainfall (panel A), and fluxes of carbon dioxide (panel B), methane (panel C) and nitrous oxide (panel D) measured at experimental plots near Wooster, Ohio. Each data point is the average of n = 12 measurements with error bars indicating standard deviations. On a given sampling date, gas fluxes are not significantly different ($P < 0.05$) if the letters above the error bars are different. Plots were under conventional tillage (PT, empty circle) or no-till (NT, filled circle) for 48 years at the beginning of the monitoring period.

Fig. 5 Air temperature and rainfall (panel A), and fluxes of carbon dioxide (panel B), methane (panel C) and nitrous oxide (panel D) measured at experimental plots near South Charleston, Ohio. Each data point is the average of n = 12 measurements with error bars indicating standard deviations. On a given sampling date, gas fluxes are not significantly different ($P < 0.05$) if the letters above the error bars are different. Plots were under conventional tillage (PT, empty circle) or no-till (NT, filled circle) for 48 years at the beginning of the monitoring period.

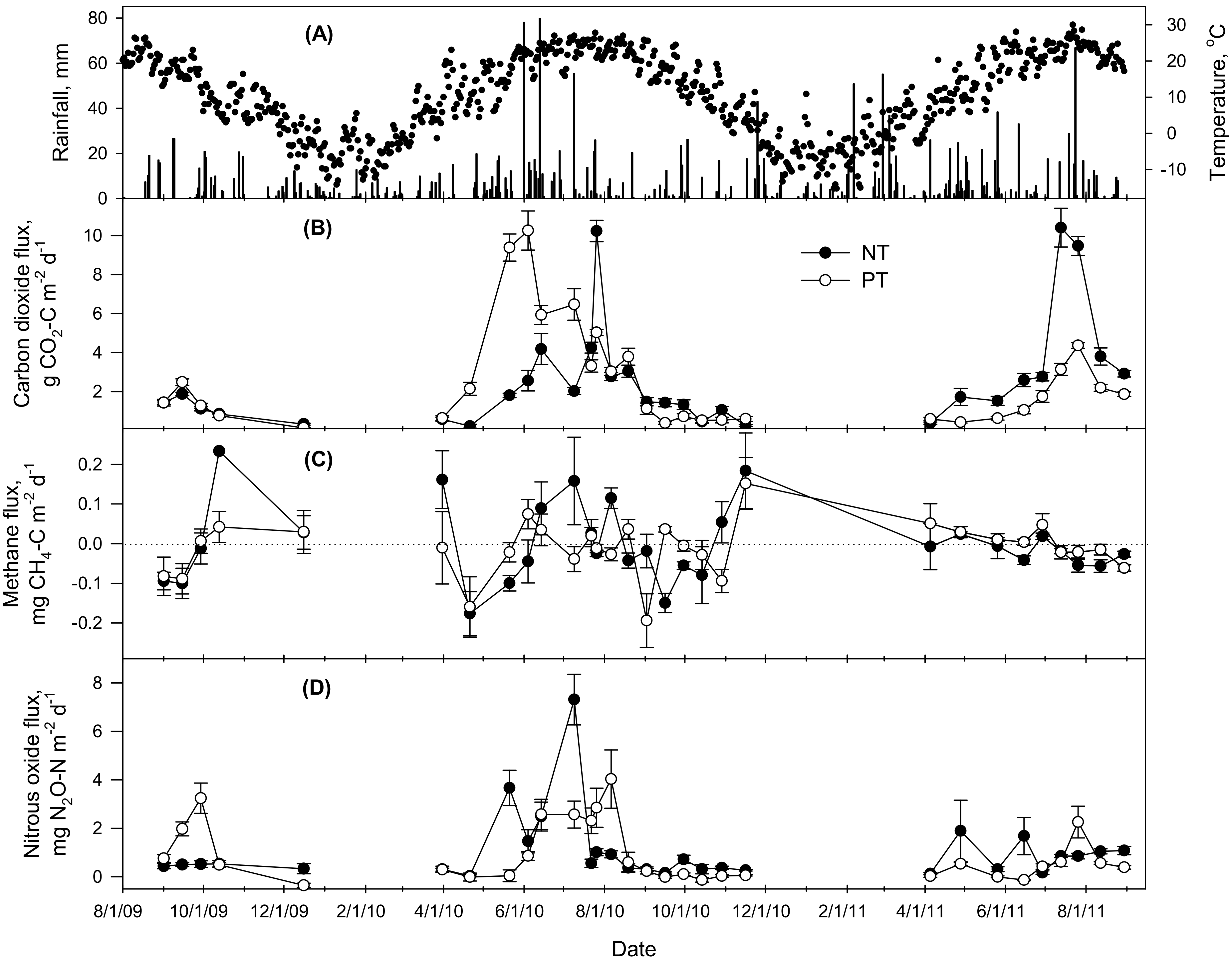
Fig. 6 Carbon dioxide (panel A), methane (panel B) and nitrous oxide (panel C) fluxes in secondary-growth forests in Central Ohio. Each data point is the average of n = 6 measurements with error bars indicating standard deviations. Gravimetric soil moisture content (0-30 cm) was measured on some occasions, and is reported in panel D.

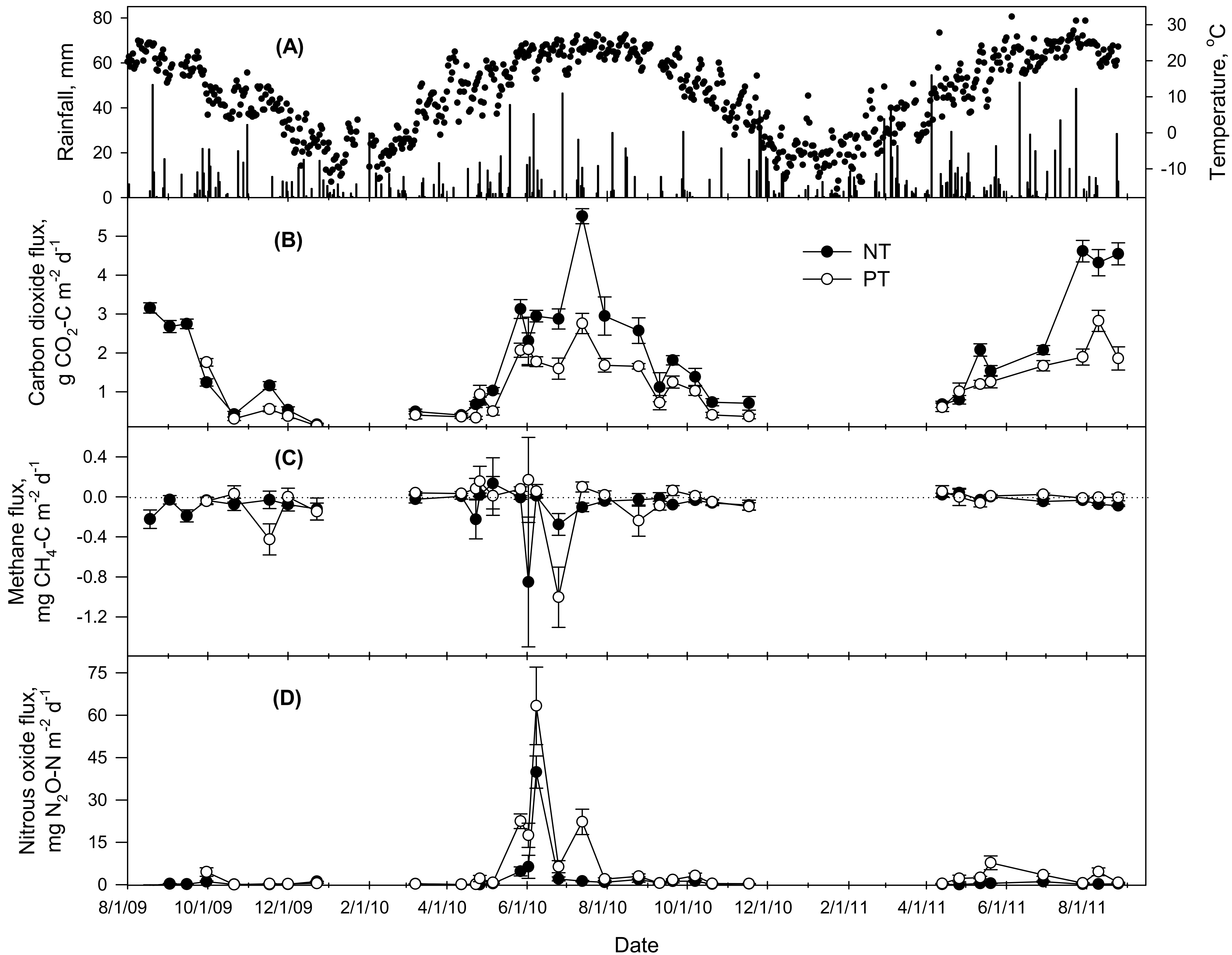
Fig. 7 Relationships between daily CO_2 flux and soil temperature (T) at the Wooster and S. Charleston sites. The dashed, dotted and solid lines are the best fit lines for the forest, PT and NT soils, respectively. Abbreviations: PT=plow-till, NT=no-till.

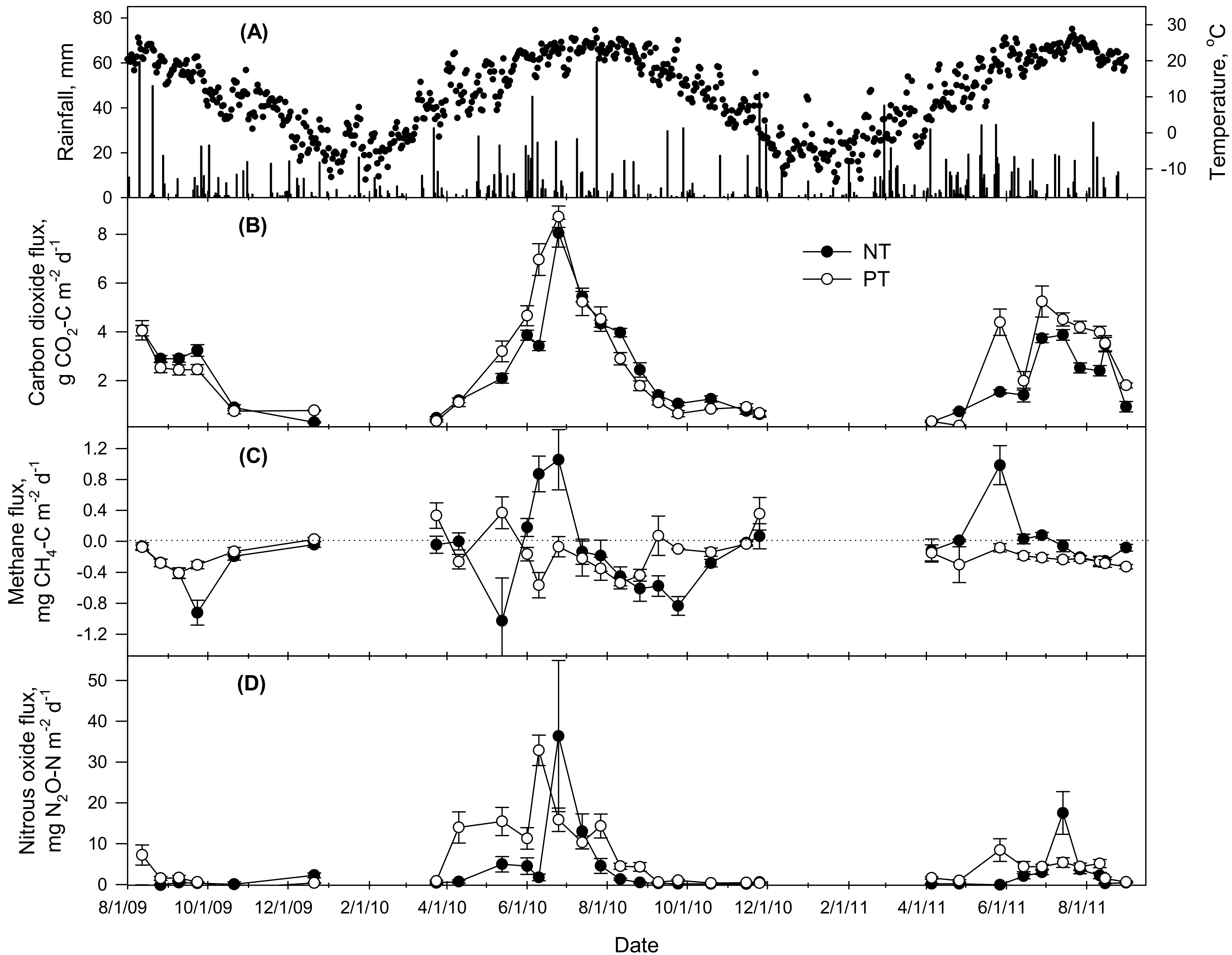
Fig. 8 Relative contribution of carbon dioxide (CO_2) and nitrous oxide (N_2O) to global warming potential (GWP) in relation to no-till (NT) and plow-till (PT) practices. GWP values, expressed in units of Mg CO_2 equivalents ha^{-1} y^{-1}, are reported in brackets. The number in parentheses at the bottom of each bar represents the number of years under no-till.

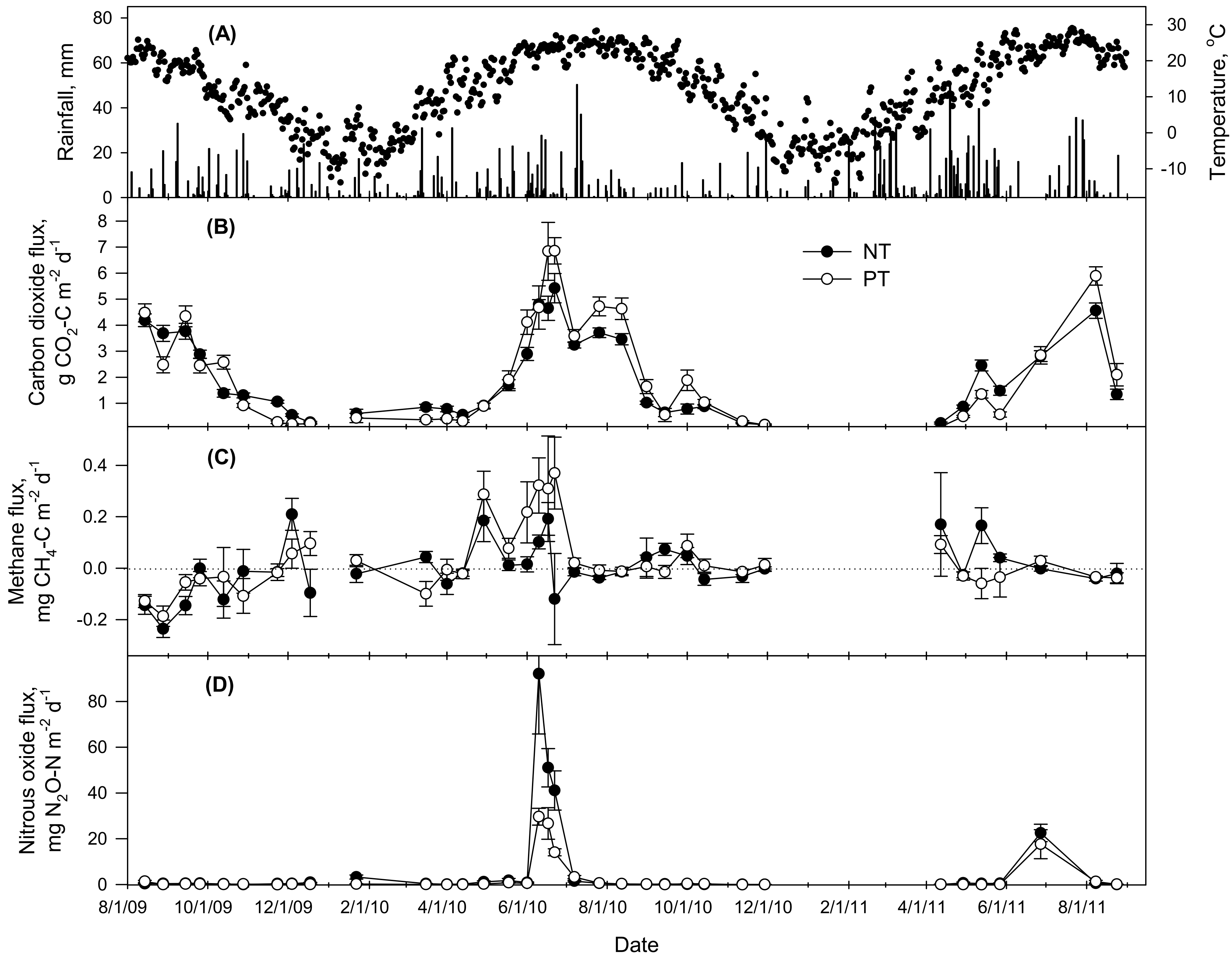


Rainfall, mm
Temperature, °C
Carbon dioxide flux, g CO_2-C m^{-2} d^{-1}
Methane flux, mg CH_4-C m^{-2} d^{-1}
Nitrous oxide flux, mg N_2O-N m^{-2} d^{-1}
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11
Date

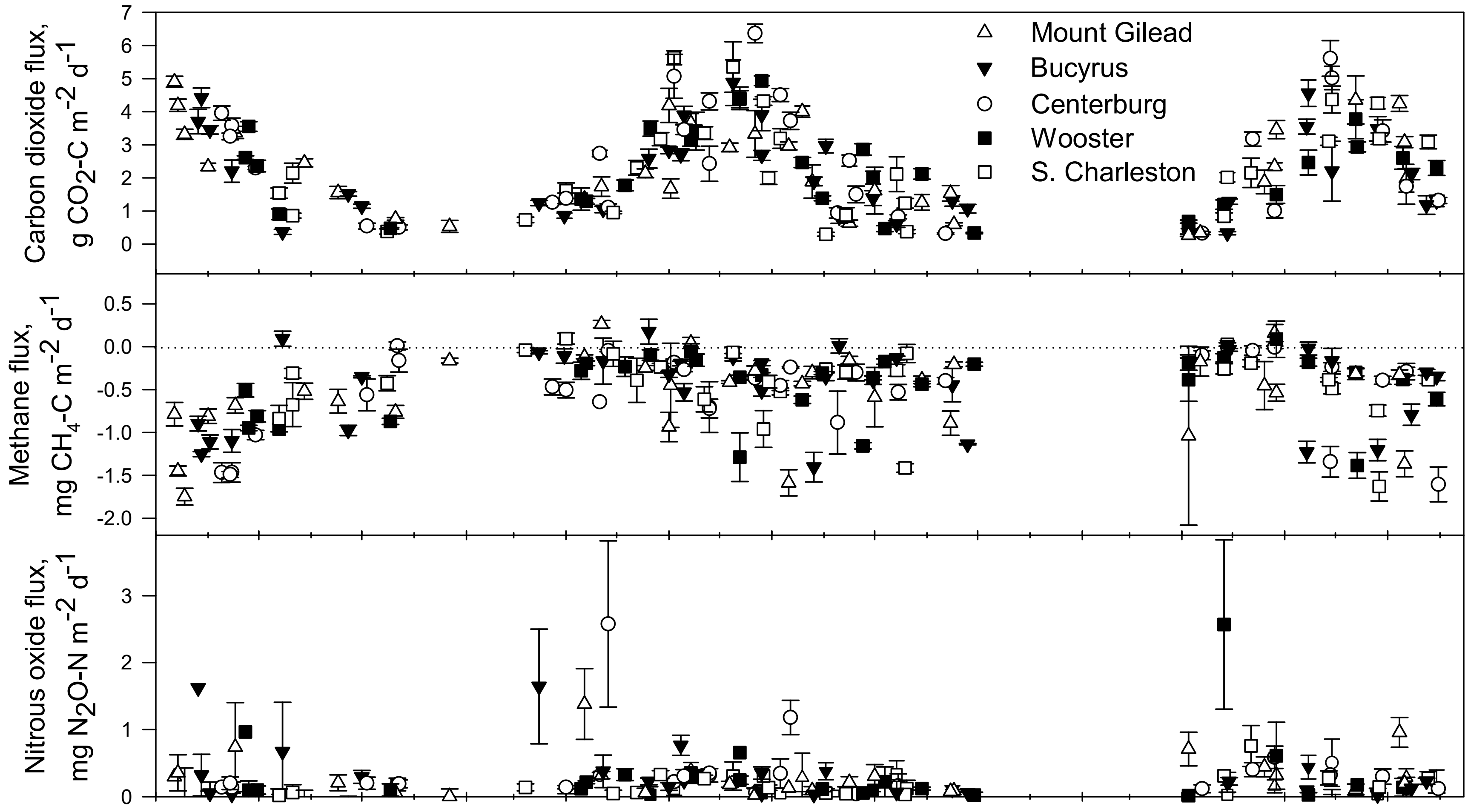

(A)
Rainfall, mm
Temperature, °C
(B)
Carbon dioxide flux, g CO2-C m-2 d-1
NT
PT
(C)
Methane flux, mg CH4-C m-2 d-1
(D)
Nitrous oxide flux, mg N2O-N m-2 d-1
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11
Date


(A)
Rainfall, mm
Temperature, °C
(B)
Carbon dioxide flux, g CO2-C m-2 d-1
NT
PT
(C)
Methane flux, mg CH4-C m-2 d-1
(D)
Nitrous oxide flux, mg N2O-N m-2 d-1
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11
Date

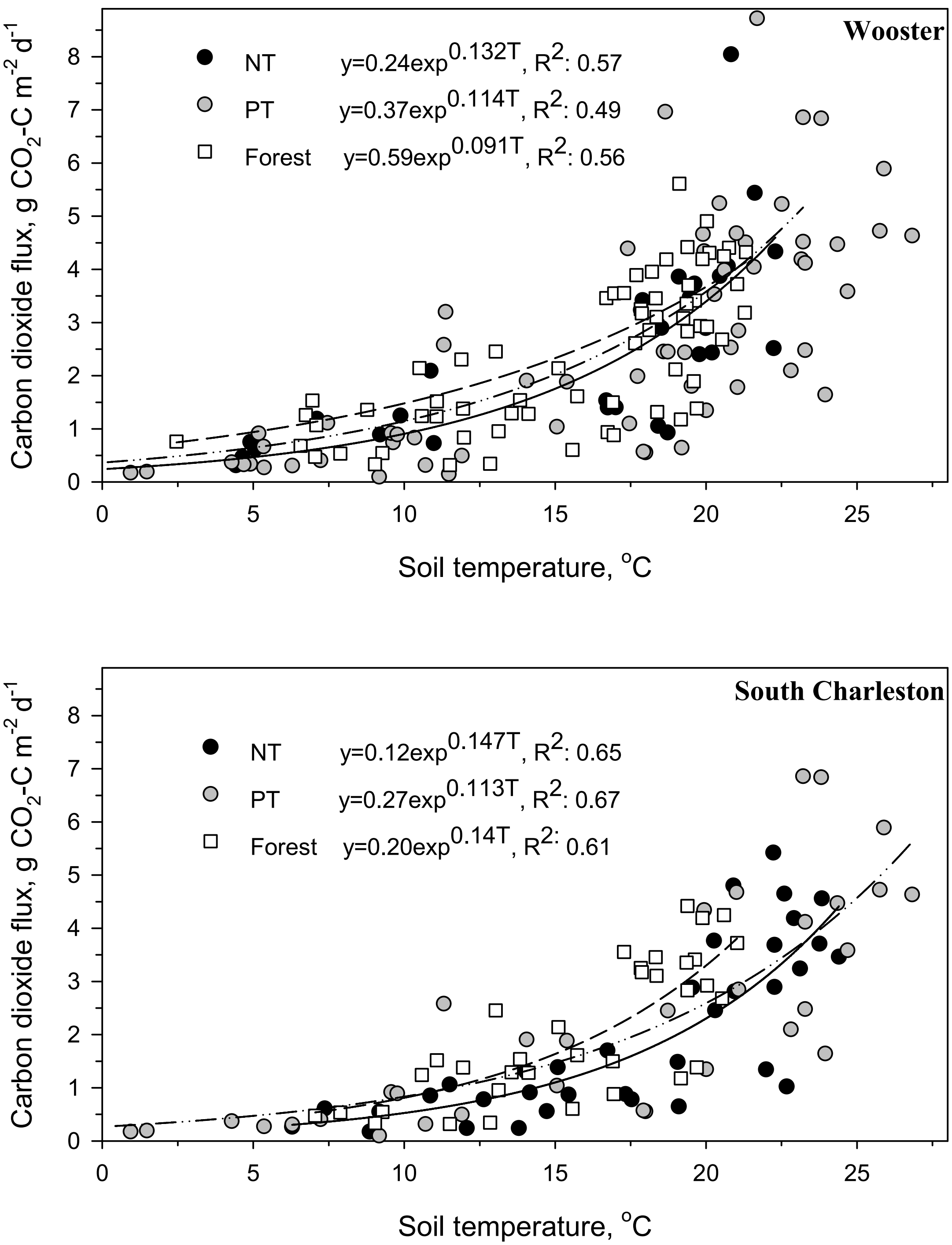

(A)
Rainfall, mm
Temperature, °C
(B)
Carbon dioxide flux, g CO2-C m-2 d-1
NT
PT
(C)
Methane flux, mg CH4-C m-2 d-1
(D)
Nitrous oxide flux, mg N2O-N m-2 d-1
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11
Date

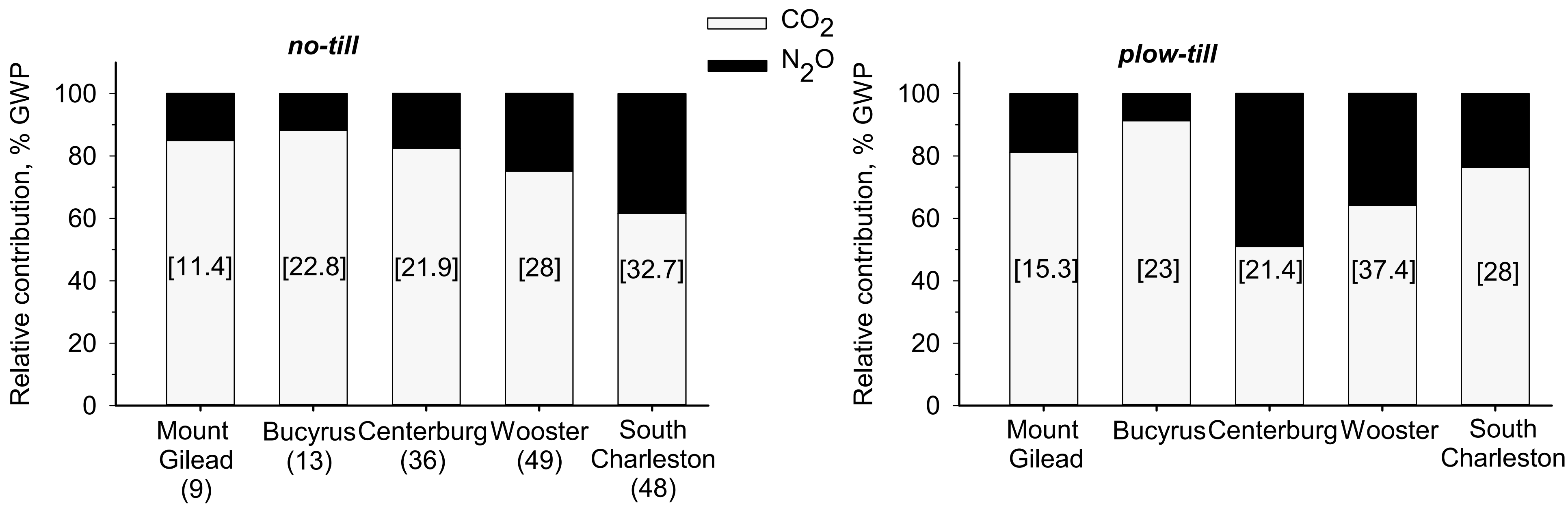


(A)
(B)
(C)
(D)
Rainfall, mm
Temperature, °C
Carbon dioxide flux, g CO$_2$-C m^{-2} d^{-1}
Methane flux, mg CH$_4$-C m^{-2} d^{-1}
Nitrous oxide flux, mg N$_2$O-N m^{-2} d^{-1}
NT
PT
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11
Date



Carbon dioxide flux, g CO_2-C m^{-2} d^{-1}
Methane flux, mg CH_4-C m^{-2} d^{-1}
Nitrous oxide flux, mg N_2O-N m^{-2} d^{-1}
Mount Gilead
Bucyrus
Centerburg
Wooster
S. Charleston
8/1/09
10/1/09
12/1/09
2/1/10
4/1/10
6/1/10
8/1/10
10/1/10
12/1/10
2/1/11
4/1/11
6/1/11
8/1/11


Wooster
NT y=0.24exp^0.132T, R^2: 0.57
PT y=0.37exp^0.114T, R^2: 0.49
Forest y=0.59exp^0.091T, R^2: 0.56
Carbon dioxide flux, g CO2-C m-2 d-1
Soil temperature, °C
South Charleston
NT y=0.12exp^0.147T, R^2: 0.65
PT y=0.27exp^0.113T, R^2: 0.67
Forest y=0.20exp^0.14T, R^2: 0.61
Carbon dioxide flux, g CO2-C m-2 d-1
Soil temperature, °C



CO2
N2O
no-till
plow-till
Relative contribution, % GWP
0
20
40
60
80
100
[11.4]
[22.8]
[21.9]
[28]
[32.7]
Mount Gilead (9)
Bucyrus (13)
Centerburg (36)
Wooster (49)
South Charleston (48)
[15.3]
[23]
[21.4]
[37.4]
[28]
Mount Gilead
Bucyrus
Centerburg
Wooster
South Charleston

Table 1

Location, tillage type and crop rotation at the study sites in Ohio (USA).

Location	Geographical coordinates	Dominant soil series†	Tillage‡	Crop grown during cropping season		
				2009	2010	2011
Mount Gilead	40°47'59"N, 83° 4'32"W	Tiro, Blount	NT	Corn	Soybean	Corn
	40°44'40"N, 83° 4'30"W	Tiro	PT	Corn	Soybean	Corn
Bucyrus	40°36'4"N, 82°43'21"W	Bennington, Condit	NT	Soybean	Corn	Soybean
	40°36'8"N, 82°41'47"W	Bennington, Condit	PT	Soybean	Corn	Soybean
Centerburg	40°18'21"N, 82°44'27"W	Centerburg, Bennington	NT	Soybean	Corn	Soybean
	40°14'42"N, 82°44'6"W	Bennington	PT	Soybean	Corn	Soybean
Wooster	40°45′48″N, 81°54′20″W	Wooster, Canfield	NT	Corn	Corn	Corn
	40°45′48″N, 81°54′20″W	Wooster, Canfield	PT	Corn	Corn	Corn
South Charleston	39°51'48"N, 83°40'20"W	Crosby	NT	Corn	Corn	Corn
	39°51'48"N, 83°40'20"W	Crosby	PT	Corn	Corn	Corn

†Soil series: Bennington (Aeric Epiaqualfs, SPD), Blount (Aeric Epiaqualfs, SPD), Canfield (Aquic Fragiudalfs, MWD), Centerburg (Aquic Hapludalfs, MWD), Condit (Typic Epiaqualfs, PD), Crosby (Aeric Epiaqualfs, SPD), Tiro (Aeric Epiaqualfs, SPD), Wooster (Oxyaquic Fragiudalfs, WD). Abbreviations: PD = poorly drained, SPD = somewhat poorly drained, WD = well drained, MWD = moderately well drained.

‡NT= no-till; PT= plow till.

Table 2
Properties of soils (0-20 cm) at the study sites. Each value is the average of 9 measurements.

Location	Management	pH	Bulk density, Mg m^{-3}	Silt, %	Clay, %	Organic C, g C kg^{-1}	Total N, g N kg^{-1}	C/N ratio
Mount Gilead	PT[†]	7.4	1.72	56	22	14.7	1.7	8.5
	NT (9) [‡]	7.6	1.61	64	22	24.6	2.0	12.1
	F	5.5	1.15	53	29	37.7	2.6	14.6
Bucyrus	PT	5.2	1.71	52	26	9.5	1.9	5.1
	NT (13)	5.9	1.61	63	20	18.4	1.6	11.5
	F	4.8	1.1	64	18	32.6	2.0	16.2
Centerburg	PT	5.3	1.46	40	29	14.9	1.6	9.5
	NT (36)	6.2	1.54	38	23	24.6	1.9	13.1
	F	5.8	1.24	47	24	30.2	2.2	13.7
Wooster	PT	5.8	1.63	56	20	13.8	1.7	8.2
	NT (48)	7.0	1.59	59	22	15.7	1.8	9.0
	F	5.3	1.53	59	18	21.1	2.1	10.3
South Charleston	PT	7.0	1.53	45	30	10.8	1.6	6.7
	NT (49)	6.2	1.58	49	23	17.6	1.7	10.4
	F	6.1	0.94	59	20	48.6	2.2	21.8

[†] PT = plow-till, NT= no-till; F= adjacent secondary-growth forest.
[‡]Value in parentheses represents the number of years under no-till at the time of soil sampling.

Table 3

Soil moisture and mineral nitrogen (0-30 cm) at the study sites. Values are means ± standard deviations of 5-7 sampling occasions during the 2-year study.

Location	Land-use/tillage	Soil moisture (g water g^{-1} soil)	Ammonium (mg N kg^{-1} soil)	Nitrate (mg N kg^{-1} soil)
Mount Gilead	PT†	0.22±0.04	3.6±2.6	9±9.4
	NT-9†	0.21±0.03	3.3±2.1	7.1±7
	F	0.29±0.10	4.2±2.4	7.9±17.3
Bucyrus	PT	0.23±0.03	3.1±2	4.4±3.3
	NT-13	0.23±0.02	3.2±2.6	6.2±4.7
	F	0.25±0.05	4.1±3.5	5±10.1
Centerburg	PT	0.21±0.07	8.1±15.7	10.7±8.9
	NT-36	0.23±0.04	4.7±4.6	6.7±3.8
	F	0.30±0.13	4.9±4.8 [8.9] §	9.1±9.4 [12.1]
Wooster	PT	0.21±0.05	2.8±1.6	17.4±10.9
	NT-48	0.23±0.05	3.1±1.9	9.2±5.5
	F	0.23±0.05	3.6±2.1	3.9±4
South Charleston	PT	0.18±0.03	8.4±11	12.6±15.4
	NT-49	0.22±0.06	6.5±6.8	11.5±12.6
	F	0.39±0.04	7±6.1 [9.57]	8.3±9.9 [9.41]

† PT = plow-till, NT= no-till; F= adjacent secondary-growth forest.
‡Value in parentheses represents the number of years under no-till at the beginning of the study.
§Elevated concentration on mineral N (as high as 42 mg N kg^{-1} soil) was measured in the forested area at the Centerburg and South Charleston sites in late June 2010 and 2011. These results were interpreted to represent the transport of N-laden runoff from recently-fertilized agricultural fields into the forested area. Values in parentheses are the mean concentration of mineral N with these extreme values included.

Table 4

Annual flux of greenhouse gases in agricultural fields under no-tillage (NT) and conventional tillage (PT) during the corn and soybean phases of the rotation. Each value is the mean of 12 chambers with standard error in parentheses.

Location	Tillage	Carbon dioxide ($Mg\ CO_2$-$C\ ha^{-1}$)		Methane ($kg\ CH_4$-$C\ ha^{-1}$)		Nitrous oxide ($kg\ N_2O$-$N\ ha^{-1}$)	
		Soybean crop	Corn crop	Soybean crop	Corn crop	Soybean crop	Corn crop
Mount Gilead	PT	4.52 (0.35)	2.46 (0.15)	-0.050 (0.05)	-0.036 (0.02)	1.85 (0.35)	3.57 (0.33)
	NT (9) †	2.90 (0.17)	2.40 (0.16)	-0.070 (0.10)	-0.076 (0.02)	1.82 (0.22)	1.70 (0.28)
Bucyrus	PT	3.35 (0.15)	8.25 (0.47)	+0.018 (0.01)	-0.065 (0.05)	1.58 (0.08)	2.09 (0.19)
	NT (13)	6.38 (0.45)	4.67 (0.21)	+0.056 (0.02)	-0.019 (0.05)	1.89 (0.18)	3.43 (0.31)
Centerburg	PT	2.72 (0.19)	2.87 (0.12)	-0.102 (0.03)	-0.028 (0.04)	5.53 (0.51)	18.4 (2.12)
	NT (36)	5.07 (0.20)	4.70 (0.24)	-0.142 (0.02)	-0.144 (0.07)	1.13 (0.06)	7.43 (0.95)
Wooster‡	PT		6.53 (0.78)		-0.439 (0.11)		13.8 (2.89)
	NT (48)		5.73 (0.70)		-0.406 (0.17)		7.14 (1.23)
South Charleston	PT		5.84 (0.64)		+0.033 (0.04)		6.79 (1.71)
	NT (49)		5.49 (0.47)		-0.013 (0.02)		12.9 (1.73)

† Value in parentheses represents the number of years under no-till at the beginning of the study.
‡ The study sites in Wooster and South Charleston are in continuous corn.

Table 5

Annual flux of greenhouse gases in secondary-growth forests in Central Ohio. Values are mean of 6 chambers with standard error in parentheses.

Location	Carbon dioxide	Methane	Nitrous oxide
	($Mg\ CO_2$-C ha^{-1})	($kg\ CH_4$-C ha^{-1})	($kg\ N_2O$-N ha^{-1})
Mount Gilead	4.41 (0.86)	-0.47 (0.1)	0.56 (0.18)
Bucyrus	6.40 (0.69)	-0.90 (0.08)	0.22 (0.08)
Centerburg	4.86 (0.26)	-0.91 (0.09)	1.05 (0.14)
Wooster	6.67 (0.83)	-2.36 (0.36)	0.38 (0.20)
South Charleston	5.83 (0.55)	-1.14 (0.12)	0.92 (0.31)