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No-till establishment improves the climate benefit of bioenergy crops on marginal grasslands

Leilei Ruan[1,2] | G. Philip Robertson[1,2]

[1] W.K. Kellogg Biological Station, Michigan State Univ., Hickory Corners, MI 49060, USA

[2] Great Lakes Bioenergy Research Center and Dep. of Plant, Soil, and Microbial Sciences, Michigan State Univ., East Lansing, MI 48824, USA

Correspondence
G. Philip Robertson, W.K. Kellogg Biological Station, Michigan State Univ., Hickory Corners, MI 49060 USA.
Email: robert30@msu.edu

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Abstract
Expanding biofuel production is expected to accelerate the conversion of unmanaged marginal lands to meet biomass feedstock needs. Greenhouse gas production during conversion jeopardizes the ensuing climate benefits, but most research to date has focused only on conversion to annual crops and only following tillage. Here we report the global warming impact of converting USDA Conservation Reserve Program (CRP) grasslands to three types of bioenergy crops using no-till (NT) vs. conventional tillage (CT). We established replicated NT and CT plots in three CRP fields planted to continuous corn, switchgrass, or restored prairie. For the 2 yr following an initial soybean year in all fields, we found that, on average, NT conversion reduced nitrous oxide (N_2O) emissions by 50% and CO_2 emissions by 20% compared with CT conversion. Differences were higher in Year 1 than in Year 2 in the continuous corn field, and in the two perennial systems the differences disappeared after Year 1. In all fields net CO_2 emissions (as measured by eddy covariance) were positive for the first 2 yr following CT establishment, but following NT establishment net CO_2 emissions were close to zero or negative, indicating net C sequestration. Overall, NT improved the global warming impact of biofuel crop establishment following CRP conversion by over 20-fold compared with CT (−6.01 Mg CO_2e ha^{-1} yr^{-1} for NT vs. −0.25 Mg CO_2e ha^{-1} yr^{-1} for CT, on average). We also found that Intergovernmental Panel on Climate Change estimates of N_2O emissions (as measured by static chambers) greatly underestimated actual emissions for converted fields regardless of tillage. Policies should encourage adoption of NT for converting marginal grasslands to perennial bioenergy crops to reduce C debt and maximize climate benefits.

Abbreviations: CRP, USDA Conservation Reserve Program; CT, conventional tillage; GHG, greenhouse gas; GWI, global warming impact; IPCC, Intergovernmental Panel on Climate Change; NEE, net ecosystem exchange; NT, no-till; SOM, soil organic matter; UAN, urea ammonium nitrate; WFPS, water-filled pore space.

1 | INTRODUCTION

Expanding the production of cellulosic biofuel crops will correspondingly increase demands for land (Robertson et al., 2017) and, together with incentives for greater corn

(*Zea mays* L.) production, is expected to induce the further conversion of grasslands such as those in the USDA Conservation Reserve Program (CRP) back to crop production (Lark, Salmon, & Gibbs, 2015; Secchi, Gassman, Williams, & Babcock, 2009; Spawn, Lark, & Gibbs, 2019; Wright & Wimberly, 2013).

Conversion of CRP and other uncropped grasslands back to production can lead to carbon (C) loss, as modeled for conversion to annual biofuel crops by Fargione, Hill, Tilman, Polasky, and Hawthorne (2008) and as measured for conversion to no-till (NT) crops by Gelfand et al. (2011). Fargione et al. (2008) estimated a C debt of 134 Mg CO_2 equivalents (CO_2e) ha^{-1} during grassland conversion to corn. Gelfand et al. (2011) reported an initial C debt of 10.6 CO_2e ha^{-1} during the first year conversion of CRP grassland to NT soybeans [*Glycine max* (L.) Merr.], and for the same site Zenone, Gelfand, Chen, Hamilton, and Robertson (2013) reported a 3-yr debt of 18.1 CO_2e ha^{-1} for subsequent conversion to NT corn and 14.2 CO_2e ha^{-1} for subsequent conversion to NT switchgrass (*Panicum virgatum*) and restored prairie.

Still missing, however, are measured greenhouse gas (GHG) costs for converting CRP grasslands using conventional tillage (CT), which is today the most common means for clearing grassland for cultivation. In earlier work (Ruan & Robertson, 2013), we showed that conventional chisel plowing can cause two to three times more C debt than NT during the first year of conversion due to substantial nitrous oxide (N_2O) emissions, accelerated soil organic matter (SOM) decomposition, and foregone C sequestration. Unresolved, however, is the persistence of these effects in subsequent years (i.e., whether the C debt continues to mount or can begin to be repaid).

In addition to SOM decomposition and N_2O release, grassland conversion can affect soil methane (CH_4) oxidation. Aerated soils are a globally important sink for atmospheric CH_4 because of CH_4 oxidation by methanotrophic bacteria (Dalal, Allen, Livesley, & Richards, 2008). Oxidation is substantially reduced by cultivation (Ball, Scott, & Parker, 1999; Del Grosso et al., 2000) but can partially recover on conversion to grassland (Levine, Teal, Robertson, & Schmidt, 2011). Methane oxidation that would have occurred in the future but will not occur upon converting grassland back to cropland might thus be another source of C debt, effectively foregoing CH_4 oxidation.

Choice of biofuel crop can also substantially affect the resulting GHG balance (Robertson et al., 2017). There are well-known differences in environmental impacts between annual grain-based and perennial cellulosic crops (Fargione, Plevin, & Hill, 2010; Farrell et al., 2006), including those related to C debt, net GHG balance, and fertilizer N loss; less is known about to what extent perennial grasses might offset the GHG costs of tillage production.

Core Ideas

- Conversion of former cropland to bioenergy feedstock production creates carbon debt.
- Debt is created by net emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O).
- Debt can be substantially avoided by using no-till to establish biofuel crops.
- IPCC N_2O emission factors greatly underestimate N_2O emissions following grassland conversion.

Here we report the results of experiments to quantify the persistence of tillage-induced GHG costs of biofuel crop establishment. On land converted from CRP grassland the prior year (Gelfand et al., 2011; Ruan & Robertson, 2013; Zenone et al., 2013), we provide a net GHG balance for the subsequent 2 yr under NT vs. CT management. In each of three separate CRP fields planted to either corn, switchgrass, or restored prairie, we established three full factorial tillage experiments to test (in each) the hypothesis that NT can significantly reduce the global warming impact (GWI) of biofuel crop establishment. We established three separate experiments because the fields were not replicated. A fourth field remained in CRP grassland to provide a historical reference. We hypothesized that NT management will substantially lower the net GHG costs associated with crop establishment by reducing N_2O and CO_2 emissions and by avoiding the loss of CH_4 oxidation as compared to CT, regardless of biofuel crop types.

2 | MATERIALS AND METHODS

2.1 | Site description

Four experimental fields (9–21 ha each) were established in the northern part of the U.S. corn belt in southwestern Michigan at the Great Lakes Bioenergy Research Center Marshall Farm at the Kellogg Biological Station Long-term Ecological Research site (42°26′ N, 85°19′ W; 288 m asl). Annual precipitation averages 1,027 mm, with an average snowfall of approximately 1.4 m. Mean annual temperature is 9.9 °C, ranging from a monthly mean of −4.2 °C in January to 22.8 °C in July, with a daily range of −28.9 °C (January) to 43.3 °C (July) (NCDC, 2013).

Soils at the site, developed on glacial outwash (Crum & Collins, 1995) with intermixed loess (Luehmann et al., 2016), are mesic Typic Hapludalfs of three comingled series: Boyer (loamy sand), Kalamazoo (fine-loamy), and Oshtemo (coarse-loamy).

TABLE 1 Soil properties in fields assigned to corn, switchgrass, restored prairie, and reference systems for 0- to 25-cm soil depth

Field assignment	SOC	SON	Bulk density	pH
	g kg^{-1} soil		g cm^{-3}	
Corn	18.3 ± 1.00	1.67 ± 0.09	1.62 ± 0.01	5.8 ± 0.09
Switchgrass	17.1 ± 1.03	1.43 ± 0.09	1.55 ± 0.01	5.8 ± 0.06
Restored prairie	16.1 ± 1.38	1.49 ± 0.12	1.42 ± 0.03	6.1 ± 0.17
Reference	21.2 ± 1.31	1.96 ± 0.12	1.50 ± 0.03	6.1 ± 0.04

Note. SOC, soil organic carbon; SON, soil organic nitrogen. Values are mean ± SE ($n = 10$).

Before the experiment, each field had been under smooth bromegrass (*Bromus inermis* Leyss.) since 1987, when the fields were enrolled in the USDA CRP program. Prior to this they had been conventionally planted to annual crops for decades (Zenone et al., 2013). In 2009, the bromegrass in three of the fields was killed with glyphosate prior to planting glyphosate-resistant soybeans, which were harvested in the fall. Glyphosate-resistant soybeans are a recommended breakout crop for CRP conversion because they provide the opportunity to thoroughly kill existing CRP grasses with herbicide prior to planting a new crop. The fourth field was reserved as a reference site and remained unconverted. An eddy flux tower was installed in each field in 2008 (Zenone et al., 2013) as part of the Ameriflux network.

Productivity, yields, soil C, and fluxes of CO_2 and N_2O in the three converted fields were statistically indistinguishable during the soybean conversion year prior to the start of our experiments (Gelfand et al., 2011; Zenone et al., 2013). Because of this pre-existing similarity, we attribute among-field gas flux differences to crop and crop management differences but recognize that fields (and therefore crops and soils) are unreplicated, so crop and management differences must be interpreted cautiously. Tillage treatments, on the other hand, were properly replicated within each field, as described below. Table 1 presents initial soil properties for each field.

2.2 | Experimental design and treatments

In spring 2010, each of the three converted fields was randomly assigned to either corn, switchgrass, or restored prairie (an 18-species assemblage dominated by *Elymus canadensis*, *Schizachyrium scoparium*, *Sorghastrum nutans*, *Rudbeckia hirta*, and *R. triloba*). Oats (*Avena sativa* L.) were planted as a first-winter nurse crop into restored prairie and switchgrass fields. We established a randomized, single-factor tillage experiment by creating three paired NT and CT plots (20 m × 5 m) in each field. The remainder of each field was managed without tillage (NT). We also randomly identified four replicate plots to sample in the reference field, for an overall total of 22 plots ([3 converted fields × 2 tillage treatments × 3 replicate plots] + [1 reference field × 4 replicate plots]). The reference field is unconverted CRP land without any agricultural management.

Crop management for corn followed regional best practices for all inputs including fertilizers and pesticides, with rates based on Michigan State University Extension N fertilizer and integrated pest management recommendations for nonirrigated corn. Primary tillage in the three CT plots consisted of chisel plowing (25 cm deep); secondary tillage was performed with a disc harrow. Tillage took place on 28 Apr. 2010 and again on 6 May 2011. The NT plots were left untilled. Corn (Dekalb DK-52) was planted at a density of 69,000 seeds ha^{-1} in 70-cm row widths using a no-till planter on 29 Apr. 2010 and on 12 May 2011. In 2010, liquid urea ammonium nitrate (UAN; 28%) was injected at a rate of 32 kg N ha^{-1} on 29 April and then side-dressed at a rate of 114 kg N ha^{-1} on 9 June. In 2011, 34 kg N ha^{-1} was injected as UAN on 12 May, and then another 137 kg N ha^{-1} was side-dressed on 21 June. In both years, herbicide (Lumax [5.9 L ha^{-1}], Atrazine 4L [0.78 L ha^{-1}], Honcho Plus [2.4 L ha^{-1}], and $(NH_4)_2SO_4$ [0.92 kg ha^{-1}]) was applied 1–2 wk after planting. Corn was harvested in late October 2010 and early November 2011.

In the switchgrass field, CT plots were plowed once on 7 June 2010, and the NT plots were left untilled. Switchgrass with oats was then planted on 8 June 2010. Nitrogen fertilizer (UAN) was applied on 7 July 2011 at a rate of 56 kg N ha^{-1}, as per Michigan State University Extension recommendations. Switchgrass was first harvested in the second year of this experiment, in late October 2011.

In the restored prairie field, CT plots were managed similarly to the switchgrass field, except that a mix of native prairie species with oats was planted rather than switchgrass and no N fertilizer was applied. As for switchgrass, the field was first harvested October 2011.

2.3 | Trace gas fluxes and net greenhouse gas balance

Gas fluxes were determined using a static chamber approach (Ruan & Robertson, 2013). Before sampling, three stainless steel chambers (28 cm diameter × 30 cm high) without lids were permanently installed to a soil depth of 5 cm in each treatment plot of the converted fields, and one chamber was installed in each of the four reference field plots, for a total of 58 chambers. Gas sampling was generally performed once or twice per week during the growing season, with more frequent sampling around tillage, fertilization, and rainfall events, and then every other week thereafter.

During sampling, each chamber was covered with an air-tight lid for 1 h, and its headspace was sampled four times with a 10-ml syringe beginning a few seconds after chamber closure. Gas samples were stored in overpressurized vials to avoid contamination by transferring 10 ml of headspace to 5.6-ml glass vials (Labco Ltd.) that had been pre-flushed with 10 ml of headspace taken immediately prior to the sample. Within 24 h of collection, CO_2 was analyzed using an infrared gas absorption analyzer (LI-820 CO_2 analyzer, LI-COR). At the same time, N_2O and CH_4 were analyzed by gas chromatography (5890 Series II, Hewlett Packard), for which gases were separated on a Porapak Q column (1.8 m, 80/100 mesh) at 80 °C. Nitrous oxide was detected with a ^{63}Ni electron capture detector at 350 °C, and CH_4 was detected with a flame ionization detector at 300 °C.

We interpolated daily gas fluxes between sampling times to estimate annual fluxes of N_2O, CO_2, and CH_4. The GWI was calculated by multiplying fluxes of each gas by its global warming potential (1 for CO_2, 25 for CH_4, and 298 for N_2O; IPCC, 2007) to yield CO_2 equivalents (CO_2e).

To calculate the total GHG balance for each treatment, we incorporated data on the net ecosystem exchange (NEE) of CO_2 measured with eddy covariance towers in the center of each field from Zenone et al. (2013). The eddy-covariance system included an LI-7500 open-path infrared gas analyzer (Li-Cor Biosciences), a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc.), and a CR5000 data logger (Campbell Scientific Inc.). The effective measurement radius of each tower was approximately 200 m, and every 30 min NEE was calculated as the covariance of vertical wind speed and the concentration of CO_2 as described in Zenone et al. (2013). We estimated the NEE for CT treatments as the sum of NEE for NT treatments plus the difference in chamber measurements of CO_2 fluxes between CT and NT treatments as described in Ruan and Robertson (2013). This method assumes that CT and NT treatments in each field captured the same amount of CO_2 via photosynthesis (as indicated by similar yields for CT and NT treatments in each field) and that CO_2 fluxes from plant and herbivore respiration were likewise similar.

We also calculated fossil fuel offset credits (Mg CO_2e ha^{-1} yr^{-1}) as avoided CO_2 emissions due to the displacement of fossil fuel use by biofuels, considering the production, transportation, distribution, combustion, and coproducts allocation (Gelfand et al., 2020; Plevin, 2009). Avoided CO_2e emissions were calculated from life cycle analyses of the difference in CO_2e emissions between petroleum gasoline vs. ethanol from dry corn grain and grass. Then the fossil fuel offset credit was calculated as:

$$\text{Fossil fuel offset credit}\,(\text{Mg}CO_2\text{e ha}^{-1}\,\text{yr}^{-1}) = e\frac{\text{g }CO_2\text{e}}{\text{MJ}} \times f\frac{\text{MJ}}{\text{ha yr}} \times \frac{10^{-6}\text{ Mg}}{1\text{ g}} \quad (1)$$

where e (g CO_2e MJ^{-1} yr^{-1}) is the difference in CO_2e emissions from life cycle analyses of petroleum gasoline and ethanol from dry corn grain or grass. Gasoline releases 94 g CO_2e per MJ of gasoline produced, distributed, and combusted (Farrell et al., 2006; Wang, Han, Dunn, Cai, & Elgowainy, 2012). Net CO_2e emissions per MJ of dry corn grain and grass ethanol were calculated using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Huo, Wang, Bloyd, & Putsche, 2009) with all farming inputs set to 0.

In Equation 2, f is the total ethanol energy equivalent from biomass, estimated from harvested biomass as:

$$f(\text{MJ ha}^{-1}\,\text{yr}^{-1}) = w\frac{\text{Mg dry biomass}}{\text{ha yr}} \times c\frac{\text{L fuel}}{\text{Mg dry biomass}} \times d\frac{\text{MJ energy}}{\text{L fuel}} \quad (2)$$

where w is the harvested dry biomass (Mg ha^{-1} yr^{-1}), c is the conversion factor for cellulosic biomass to ethanol (430 L bioethanol Mg^{-1} dry corn grain and 380 L bioethanol Mg^{-1} dry grass biomass) (Gelfand et al., 2011; Schmer, Vogel, Mitchell, & Perrin, 2008), and d is ethanol energy content (21.1 MJ L^{-1}) (lower heating value) (Gelfand et al., 2011, 2013).

The net GHG balance was then calculated as the CO_2e sum of directly measured field GHG fluxes and indirectly calculated agricultural inputs (Supplemental Table S1) less C offset credits.

2.4 | Weather and soil sampling

Air temperature and precipitation were measured at the Kellogg Biological Station Long-term Ecological Research weather station (https://lter.kbs.msu.edu/datatables/7) approximately 5 km from the study site. At each gas sampling event we measured soil temperature, gravimetric water content, and ammonium (NH_4^+) and nitrate (NO_3^-) concentrations. Soil gravimetric water content (g water g^{-1} dry soil) for the 0- to 25-cm soil layer was determined by oven-drying soils for 48 h. For measuring NH_4^+ and NO_3^-, three 2.5-cm-diameter cores (0–25 cm depth) randomly collected within each treatment plot were composited and passed through a 4-mm sieve. Three 10-g subsamples were then each extracted with 100 ml of 1 M KCl. Filtrates from soil extracts were analyzed on a Flow Solution IV colorimetric analyzer (OI Analytical).

Soil bulk density (BD) (0–25 cm depth) was measured three times each in 2010 and 2011 using a fixed-volume core (123 cm^3) for each treatment plot. Percentage of water-filled pore space (WFPS) was then calculated as

$$\text{WFPS\%} = \frac{\text{Gravimetric water content } (\%,\ g/g)\ \times BD\ (g\ cm^{-3})}{[\text{water density } (1\ g\ cm^{-3})\ \times soil \text{ porosity } (\%)] \times 100\%} \tag{3}$$

where soil porosity = 1 − BD (g cm^{-3})/particle density (g cm^{-3}). Particle density was assumed to be 2.65 g cm^{-3}.

2.5 | Data analysis

Treatment differences were analyzed using one-way ANOVA in SAS 9.2 (SAS Institute, 2009). To avoid pseudoreplication bias, differences were compared separately for each field for significance using *t*-tests at the $\alpha = .05$ significance level. Crop differences cannot be statistically tested with this experimental design because fields were not replicated. Multiple linear regressions (stepwise) between daily gas fluxes and influencing factors were performed in PROC REG and nonlinear regressions in PROC NLIN. Normality of the residuals and homogeneity of variance assumptions were checked using stem-and-leaf box and normal probability plots of the residuals and Levene's test. Data were not transformed prior to analysis.

3 | RESULTS

3.1 | Weather, soil nitrous oxide fluxes, and inorganic nitrogen

3.1.1 | Weather

Daily air temperature and precipitation are shown in Figure 1. Mean daily air temperature was 17.6 and 16.3 °C for the study period of late April to late November in 2010 and 2011, respectively (range, −1 to 29.9 °C). This compares with a long-term (1981–2010) average of 16.6 °C for May–November (NCDC, 2013). Cumulative precipitation was 626 and 723 mm in 2010 and 2011, respectively, as compared to the long-term (1981–2010) average of 686 mm for May–November (NCDC, 2013).

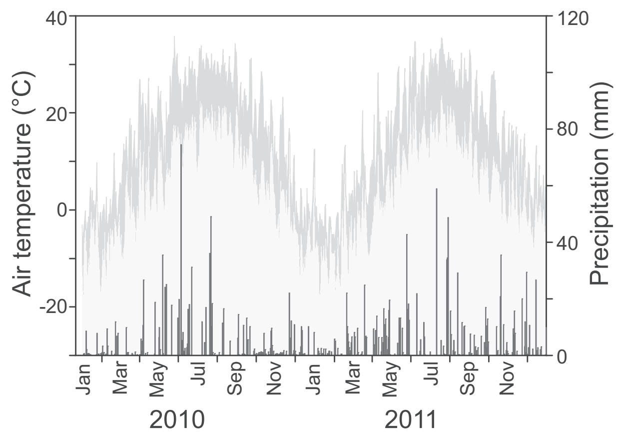

FIGURE 1 Air temperature (°C, minimum–maximum; continuous band) and precipitation (mm; vertical bars) in 2010 and 2011.

3.1.2 | Nitrous oxide fluxes in the corn field experiment

In CT corn during 2010, N_2O fluxes increased immediately after tillage on 28 April, when fluxes were 56.6 ± 13.7 (mean ± SE) g N_2O–N ha^{-1} d^{-1}, as compared to 3.05 ± 0.79 g N_2O–N ha^{-1} d^{-1} in NT corn (Figure 2a). For the 42 d between plowing and side-dress N application, average daily N_2O fluxes were substantially higher in CT vs. NT (105 ± 20.7 vs. 21.5 ± 7.3 g N_2O–N ha^{-1} d^{-1}, respectively; $P < .05$). After side-dressing, N_2O fluxes remained high for approximately 15 d in both CT and NT treatments (63.2 ± 7.34 and 67.0 ± 7.40 g N_2O–N ha^{-1} d^{-1}, respectively). Additional peaks occurred on 14 May, 3 June, and 16 June after rainfall events had elevated soil moisture to >50% WFPS (Supplemental Figure S2). After mid-July, N_2O fluxes were low in both CT and NT treatments, regardless of WFPS.

In 2011, soil N_2O fluxes also increased immediately after tillage to 19.7 ± 3.79 g N_2O–N ha^{-1} d^{-1} on 6 May, as compared to 1.16 ± 0.41 g N_2O–N ha^{-1} d^{-1} in the NT treatment. Following N fertilizer added at planting on 12 May, by 16 May N_2O fluxes increased to 62.1 ± 5.0 and 61.2 ± 25.1 g N_2O–N ha^{-1} d^{-1}, respectively, in the CT and NT treatments. After side-dressing on 21 June, N_2O fluxes increased again to 219 ± 31.9 and 232 ± 49.7 g N_2O–N ha^{-1} d^{-1}, respectively. Additional peaks occurred in both treatments on 12 July, 3 August, and 18 August after rainfall events elevated soil moisture to >60% WFPS.

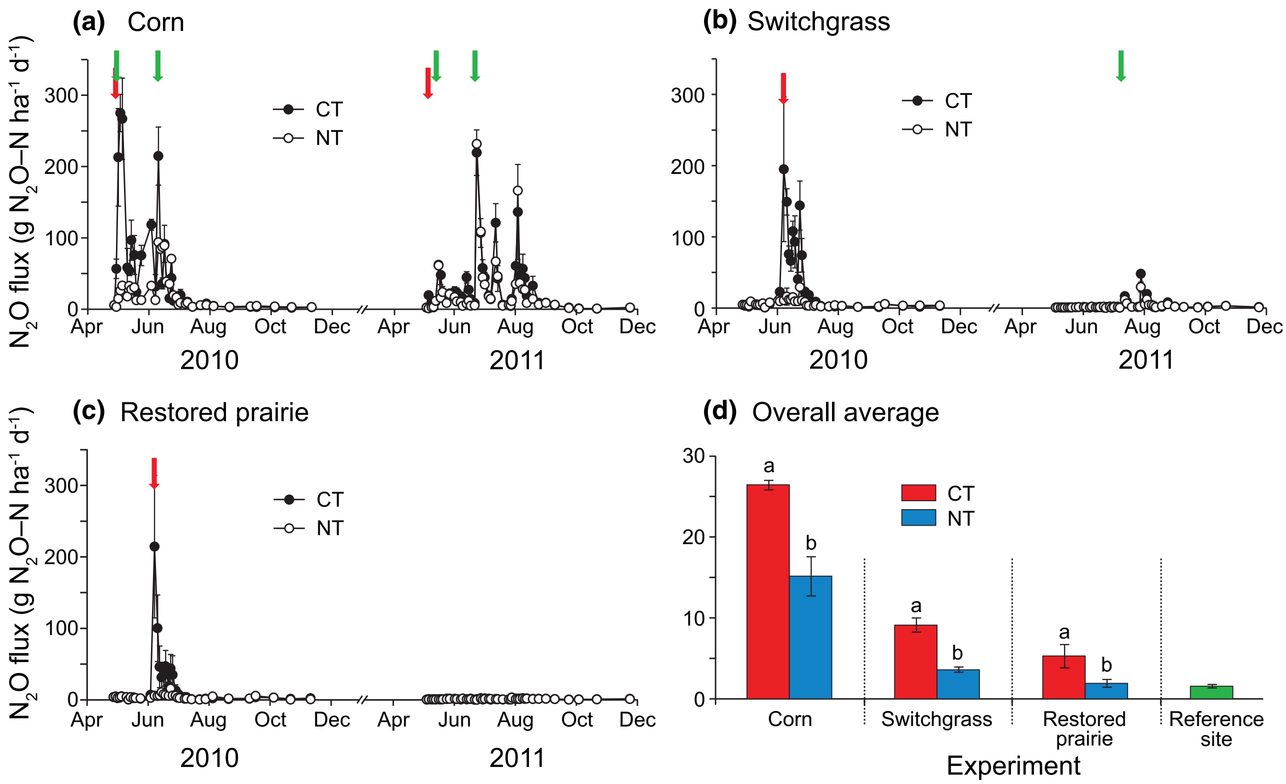

FIGURE 2 Daily N_2O fluxes by treatment (conventional till [CT] vs. no-till [NT]) in (a) corn, (b) switchgrass, and (c) restored prairie fields in 2010 and 2011. Error bars represent SEM of N_2O emissions based on three replicate plots in each field. (d) Average N_2O fluxes for CT and NT in corn, switchgrass, and restored prairie fields (three replicate plots) and an unconverted USDA Conservation Reserve Program reference field (four replicate plots). Treatments marked with different letters within each individual field are significantly different from one another ($P < .05$). Dates of tillage are indicated by red arrows; dates of N fertilization are shown by green arrows.

3.1.3 | Nitrous oxide fluxes in the switchgrass and restored prairie field experiments

In switchgrass and restored prairie fields during 2010, soil N_2O fluxes were low in April and May in both CT and NT treatments. In CT plots, N_2O fluxes increased immediately after tillage on 7 June to 195 ± 102 and 241 ± 98.8 g N_2O–N ha^{-1} d^{-1} in switchgrass and restored prairie fields, respectively, as compared to 10.8 ± 5.8 and 5.9 ± 2.1 g N_2O–N ha^{-1} d^{-1} in the respective NT plots (Figure 2b,c). Tillage-induced fluxes lasted for 20–30 d. Other large fluxes occurred only in the CT treatments on 16 June and 23 June after rainfall events.

Tillage did not occur in the switchgrass and restored prairie fields in 2011. In the switchgrass field, fluxes in both CT and NT treatments responded to the 7 July fertilizer application and on 28 July reached 48.0, 4.91, and 29.5 6.9 g N_2O–N ha^{-1} d^{-1} in CT and NT treatments, respectively. Two additional peaks occurred in both treatments on 3 and 24 August after rainfall events. Nitrous oxide fluxes diminished and stayed low after September (Figure 2b). The restored prairie field was not fertilized, and N_2O fluxes remained low (<6.43 g N_2O–N ha^{-1} d^{-1}) in both CT and NT treatments throughout the year (Figure 2c).

Nitrous oxide fluxes from the reference field were low in both 2010 and 2011 (<8.21 g N_2O–N ha^{-1} d^{-1}) regardless of rainfall events.

3.1.4 | Nitrous oxide flux differences

Overall, for the 2-yr study period, mean daily N_2O emissions in CT were 1.75, 2.67, and 2.51 times those of NT in corn, restored prairie, and switchgrass fields, respectively (Figure 2d). Among fields, N_2O emissions in the corn field were higher than those in the restored prairie, switchgrass, and reference fields (Figure 2d). Conventional tillage switchgrass emitted more N_2O than did CT restored prairie, but the NT difference was negligible. Emissions from the reference field were lower than emissions from converted fields regardless of tillage treatments: 26.4 ± 0.57 in CT corn, 9.17 ± 0.85 in CT switchgrass, and 5.30 ± 1.46 in CT restored prairie fields vs. 15.1 ± 2.38 in NT corn, 3.65 ± 0.31 in NT switchgrass, and 1.98 ± 0 .50 in NT

TABLE 2 Average soil inorganic nitrogen by tillage treatment during April–December in 2010 and 2011 in corn, switchgrass, restored prairie, and reference fields for the 0- to 25-cm soil depth

Field assignment	Tillage[a]	Inorganic N[b] 2010	Inorganic N[b] 2011
		–mg kg^{-1}–	
Corn	CT	15.7 ± 1.34a	33.9 ± 7.38a
	NT	9.14 ± 0.90b	16.1 ± 3.22b
Switchgrass	CT	7.96 ± 0.15a	6.35 ± 0.38a
	NT	6.33 ± 0.06b	6.45 ± 0.10a
Restored prairie	CT	8.90 ± 0.54a	5.30 ± 0.14a
	NT	7.26 ± 0.09b	5.46 ± 0.28a
Reference	–	4.93 ± 0.15	5.51 ± 0.16

[a]CT, conventional tillage; NT, no-till.
[b]Values are mean ± SE ($n = 3$). Treatments marked with different letters within each field assignment are significantly different from one another ($\alpha = .05$).

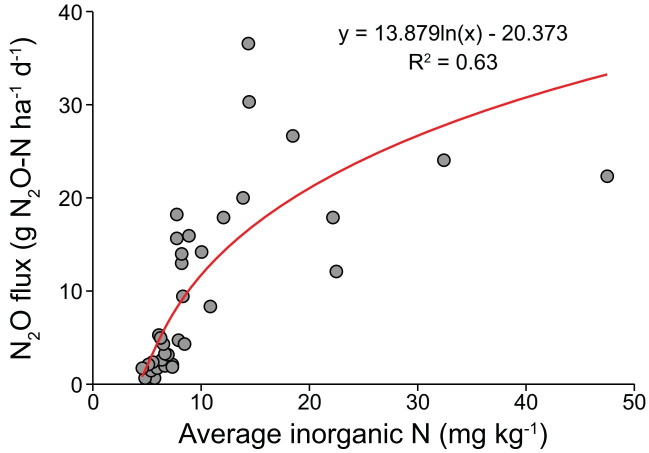

FIGURE 3 Relationships of average daily N_2O emission rates across all treatments ($n = 44$) to soil inorganic nitrogen (0–25 cm depth) in 2010 and 2011. See Supplemental Figure S3 for individual N species relationships.

restored prairie fields vs. 1.66 ± 0.20 g N_2O–N ha^{-1} d^{-1} in the reference field (Figure 2d; Supplemental Table S2).

3.1.5 | Nitrous oxide fluxes in relation to soil inorganic nitrogen content

As noted in Table 2 and Supplemental Figure S1, in 2010, average soil inorganic N contents were significantly higher in CT than in NT treatments ($P < .05$) in all three converted fields, whereas in 2011, soil inorganic N differences were significant only in the corn field.

Average daily N_2O fluxes in each year were strongly correlated with soil inorganic N across all treatments ($R^2 = .63$; $P < .01$) (Figure 3). In contrast, average daily soil moisture (%WFPS) in each year was not correlated with daily N_2O fluxes (data not shown).

3.2 | Soil carbon dioxide fluxes

3.2.1 | Carbon dioxide fluxes in response to tillage

Across all fields in 2010 and 2011, chamber-based soil CO_2 fluxes generally demonstrated a seasonal trend, with higher emissions from June to August and lower emissions before May and after October (Figure 4), coincident with the seasonal trend in air temperatures (Figure 1). In 2010, immediately after CT tillage on 28 April in the corn field and 7 June in switchgrass and restored prairie fields, soil CO_2 fluxes increased to 97.4 ± 16.6, 86.6 ± 2.0, and 105.1 ± 2.8 kg CO_2–C ha^{-1} d^{-1}, respectively, as compared to respective NT fluxes of 27.0 ± 3.3, 32.7 ± 0.9, and 49.1 ± 6.5 kg CO_2–C ha^{-1} d^{-1} (Figure 4). Tillage-induced CO_2 fluxes persisted for approximately 30–40 d.

In 2011, tillage-induced fluxes in the corn field persisted only for approximately 7 d (average, 58.6 ± 7.27 kg CO_2–C ha^{-1} d^{-1} under CT vs. 30.0 ± 2.07 kg CO_2–C ha^{-1} d^{-1} under NT). There were no residual tillage effects on CO_2 emissions in the switchgrass or restored prairie fields in 2011 (Figure 4b, c).

3.2.2 | Carbon dioxide flux differences

Over the 2-yr study period, all converted fields released more soil CO_2 than the reference field (Figure 4d). Soil CO_2 emissions under CT corn were higher than those in CT switchgrass and restored prairie, but no differences were apparent under NT among fields. Mean soil CO_2 fluxes in the CT treatment increased by 23.1, 12.2, and 13.8% in the corn, switchgrass, and restored prairie fields, respectively, as compared to the NT treatment (48.4 ± 1.3 vs. 39.3 ± 0.7 kg CO_2–C ha^{-1} d^{-1} in the corn field, 43.7 ± 0.9 vs. 39.0 ± 0.4 kg CO_2–C ha^{-1} d^{-1} in the switchgrass field, and 44.7 ± 1.5 vs. 39.3 ± 1.4 kg CO_2–C ha^{-1} d^{-1} in the restored prairie field). Across all converted fields, CT fluxes were 29–43% higher, and NT fluxes averaged approximately 15% higher than those in the reference field (33.9 ± 1.42 kg CO_2–C ha^{-1} d^{-1}; $p < .05$).

3.2.3 | Carbon dioxide fluxes in relation to soil temperature and moisture

Daily soil CO_2 fluxes were positively correlated with soil temperature: soil CO_2 fluxes $= 15.9 \times e^{0.06 \times \text{soil temperature}}$

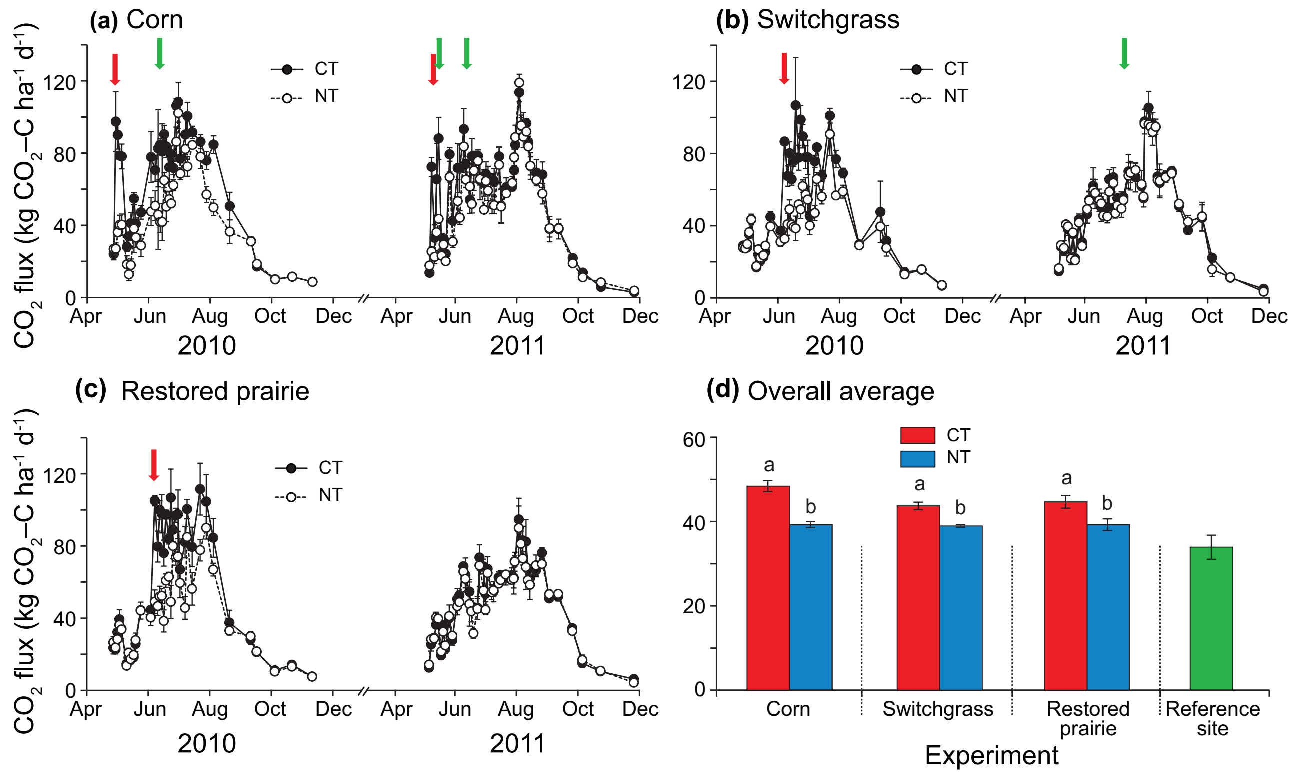

FIGURE 4 Daily CO_2 fluxes by treatment (conventional till [CT] vs. no-till [NT]) in (a) corn, (b) switchgrass, and (c) restored prairie fields in 2010 and 2011. Error bars represent SEM of CO_2 emissions based on three replicate plots in each field. (d) Average CO_2 fluxes for CT and NT in corn, switchgrass, and restored prairie fields (three replicate plots) and an unconverted Conservation Reserve Program reference field (four replicate plots). Treatments marked with different letters within each individual field are significantly different from one another ($P < .05$). Dates of tillage are indicated by red arrows; dates of N fertilization are indicated by green arrows.

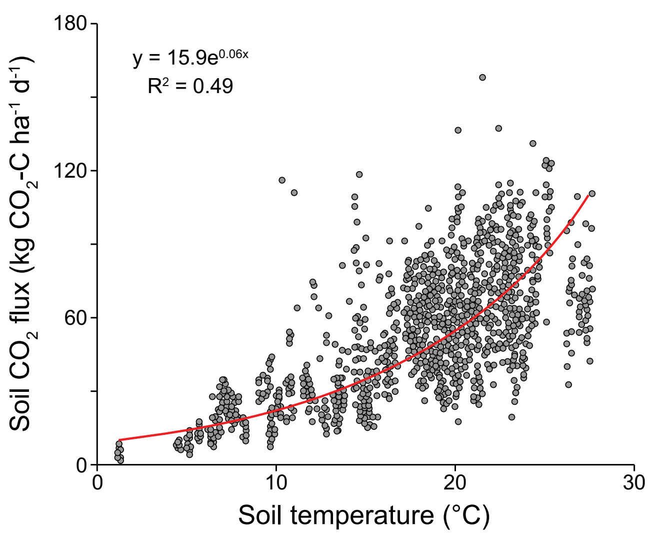

FIGURE 5 Relationships of daily CO_2 fluxes across all treatments (n = 1,528) to soil temperature (0–25 cm) in 2010 and 2011.

($R^2 = 0.49$; $P < .001$) (Figure 5). We found no significant relationship between daily CO_2 fluxes and soil moisture (%WFPS) or inorganic N.

3.3 | Soil methane fluxes

During 2010 and 2011, all fields exhibited both positive and negative daily CH_4 fluxes without consistent seasonal patterns or significant treatment effects. Fluxes were generally low, with most rates ranging from −4.13 to 4.27 g CH_4–C d^{-1} ha^{-1} (Figure 6a–c). Average daily CH_4 fluxes were negative in all treatments, indicating net CH_4 oxidation or uptake (Figure 6d). Mean CH_4 oxidation rates under NT were greater by 132% in corn fields and 45.9% in restored prairie fields, as compared to those under CT (−0.72 ± 0.11 vs. −0.31 ± 0.17 g CH_4–C d^{-1} ha^{-1} in corn fields; −1.38 ± 0.20 vs. −0.94 ± 0.44 g CH_4–C d^{-1} ha^{-1} in restored prairie fields), but the differences were not statistically significant ($P > .10$). No measured soil or environmental factor was found to correlate significantly with CH_4 fluxes.

3.4 | Biomass yields

Over the 2-yr study period, no significant differences in mean annual dry biomass yields (grain for corn,

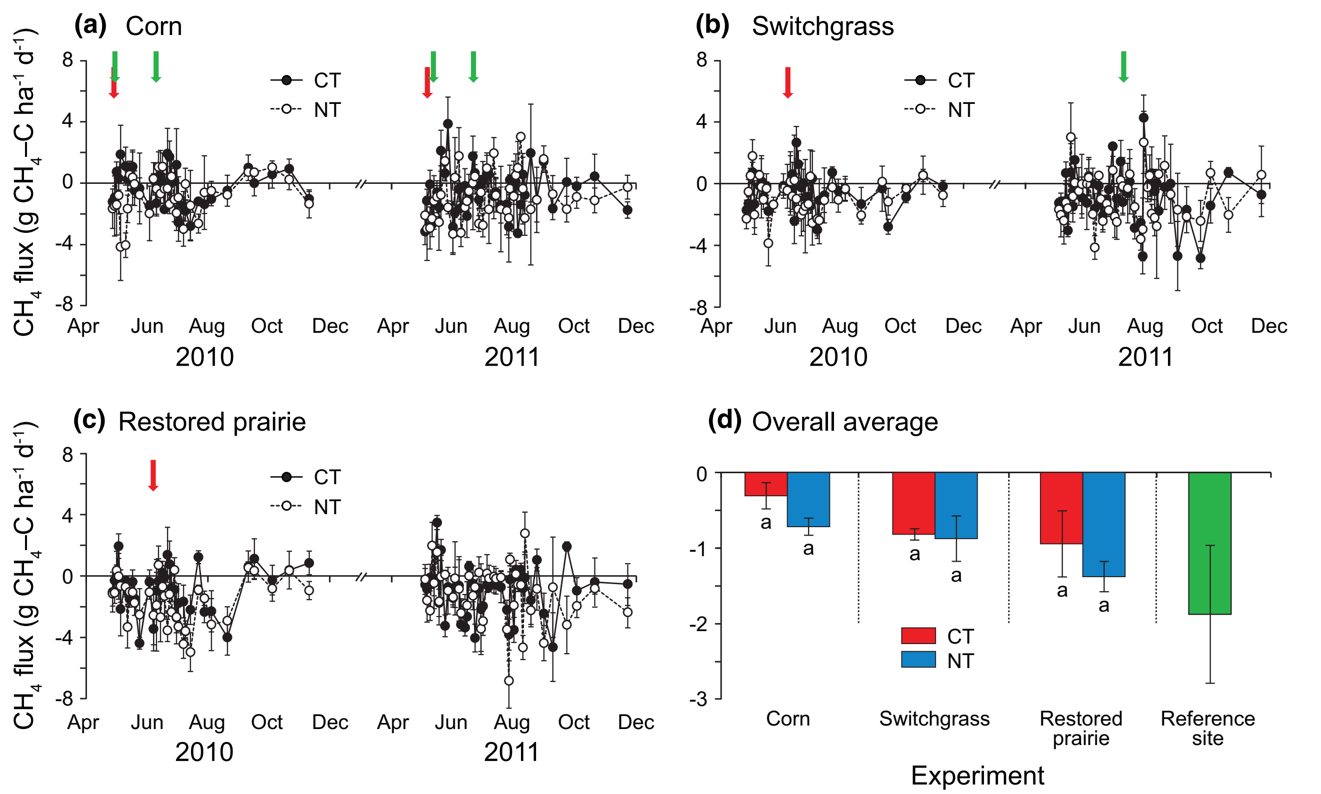

FIGURE 6 Daily CH_4 fluxes by treatment (conventional tillage [CT] vs. no-till [NT]) in (a) corn, (b) switchgrass, and (c) restored prairie fields in 2010 and 2011. Negative values indicate CH_4 uptake from the atmosphere (CH_4 oxidation). Error bars represent SEM of CH_4 emissions based on three replicate plots in each field. (d) Average CH_4 fluxes for CT and NT in corn, switchgrass, and restored prairie fields (three replicate plots) and an unconverted Conservation Reserve Program reference field (four replicate plots). Treatments marked with different letters within each individual field are significantly different from one another ($P < .05$). Dates of tillage are indicated by red arrows; dates of fertilization are indicated by green arrows.

aboveground biomass for switchgrass, and restored prairie) were found between CT and NT treatments in any of the three converted fields (respectively, 11.5 ± 0.4 vs. 11.3 ± 0.6 Mg ha^{-1} for corn fields, 5.74 ± 0.24 vs. 6.38 ± 0.22 Mg ha^{-1} for switchgrass, and 4.72 ± 0.67 vs. 5.73 ± 0.63 Mg ha^{-1} for restored prairie fields; $p > .05$ for all) (Figure 7).

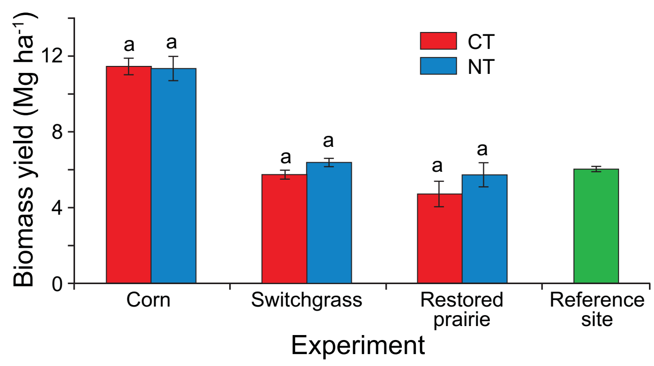

FIGURE 7 Mean dry aboveground biomass yield (grain yield for corn) under conventional tillage (CT) and no-till (NT) in 2010 and 2011 (Mg ha^{-1}). Error bars represent SE based on three replicate plots. Treatments marked with different letters within each individual field are significantly different from one another ($P < .05$).

3.5 | Global warming impact

The mean annual NEE values of CO_2 (May–December) for CT treatments in the corn, switchgrass, and restored prairie fields all exhibited net C emissions from soil (3.91 ± 0.49, 0.50 ± 0.87, and 4.57 ± 0.19 Mg CO_2e ha^{-1}, respectively) (Figure 8). In contrast, mean NEE values for NT corn, switchgrass, and restored prairie fields exhibited negative (net C uptake) or very low positive values (−2.76, −2.94, and 0.51 Mg CO_2e ha^{-1}, respectively).

The GWI of N_2O emissions was higher in corn fields (2.48 ± 0.05 Mg CO_2e ha^{-1} under CT and 1.43 ± 0.22 Mg CO_2e ha^{-1} under NT), switchgrass fields (0.85 ± 0.08 Mg CO_2e ha^{-1} under CT and 0.34 ± 0.14 Mg CO_2e ha^{-1} under NT), and restored prairie fields (0.49 ± 0.14 Mg CO_2e ha^{-1} under CT and 0.18 ± 0.05 Mg CO_2e ha^{-1} under NT) than in reference fields (0.16 ± 0.02 Mg CO_2e ha^{-1}) (Figure 8a).

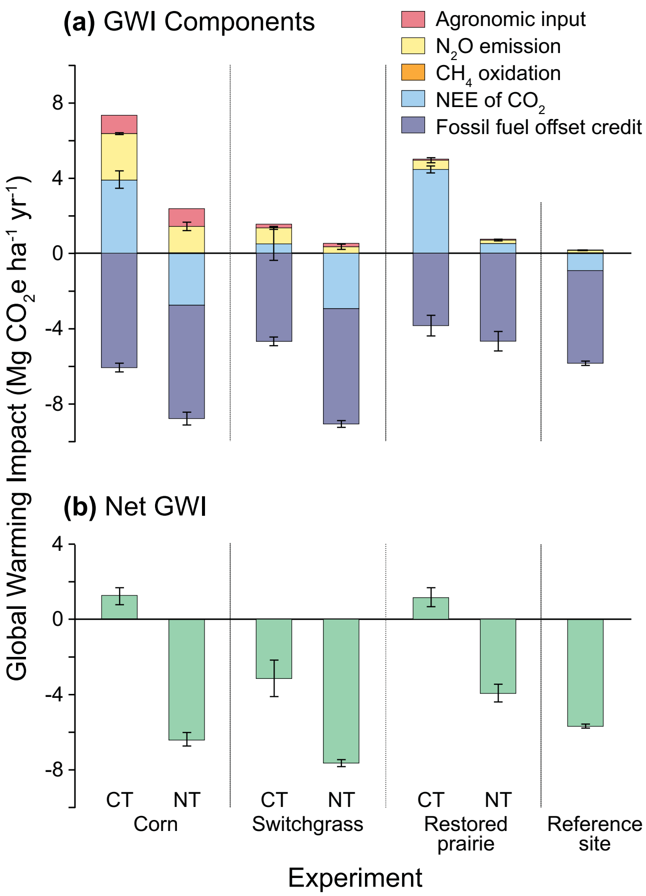

FIGURE 8 Annual global warming impact (GWI) of biofuel crop production by treatment (conventional tillage [CT] vs. no-till [NT]) in corn, switchgrass, and restored prairie fields and the reference field in CO_2 equivalents (CO_2e). (a) Detailed GWI balance showing the contribution of different components. (b) Net GWI balance. See Supplemental Table S1 for GWI of individual agriculture inputs. Values for N_2O and CH_4 represent mean in situ measurements in 2010 and 2011. The CH_4 oxidation rates (CH_4 flux in Figure 6) are negligible and not visible in graph. Error bars represent SEs based on three replicate plots (no error bars for agricultural inputs)

Methane oxidation contributions to the GHG balance across all fields were negligible, on the order of −0.002 ± 0.001 to −0.01 ± 0.006 Mg CO_2e ha^{-1} (Figure 8a). The CO_2e emissions from agricultural inputs (Supplemental Table S1) were similar between CT and NT treatments and higher in corn fields than in restored prairie and switchgrass fields (Figure 8a).

Fossil fuel offset credits of 58.6 and 102.0 g CO_2e MJ^{-1} were calculated for avoided fossil fuel C emissions due to the use of biofuels from dry corn grain and grass, respectively. This results in fossil fuel offset credits for corn of −6.09 ± 0.23 under CT and −6.03 ± 0.34 Mg CO_2e ha^{-1} yr^{-1} under NT, for switchgrass credits of −4.69 ± 0.19 under CT and −5.22 ± 0.18 Mg CO_2e ha^{-1} yr^{-1} under NT, for restored prairie credits of −3.85 ± 0.55 under CT and −4.68 ± 0.52 Mg CO_2e ha^{-1} yr^{-1} under NT, and for the reference field credits of −4.93 ± 0.12 Mg CO_2e ha^{-1} yr^{-1} (when the reference field harvested for biofuel production). Fossil fuel offset credits did not differ by tillage treatment in any field (Figure 8a).

In general, annual net GWIs under CT were substantially higher than those under NT in corn, switchgrass, and restored prairie (for the corn field 1.26 ± 0.45 under CT vs. −6.42 ± 0.36 Mg CO_2e ha^{-1} yr^{-1} under NT, for the switchgrass field −3.15 ± 0.97 under CT vs. −7.65 ± 0.19 Mg CO_2e ha^{-1} yr^{-1} under NT, and for the restored prairie field 1.14 ± 0.50 under CT vs. −3.94 ± 0.47 Mg CO_2e ha^{-1} yr^{-1} under NT) (Figure 8b). Conventional tillage treatments in both the corn and restored prairie fields had positive GWIs, and all GWIs under CT were higher than those from the reference field (−5.69 ± 0.11 Mg CO_2e ha^{-1} yr^{-1}). Global warming impacts under NT in the corn field were not different from the reference field. In contrast, GWIs for NT in the restored prairie field were significantly lower than for the reference field, but GWIs for NT in the switchgrass field were higher than for the reference field ($P < .05$) (Figure 8b).

4 | DISCUSSION

Our results support the hypothesis that NT can mitigate the effects of CRP land conversion by CT and in particular can mitigate the effects of conversion on N_2O and CO_2 emissions. On average, NT management reduced global warming impacts by >20-fold compared with CT: averaged across all fields, −6.01 Mg CO_2e ha^{-1} yr^{-1} for NT conversion vs. −0.25 Mg CO_2e ha^{-1} yr^{-1} for CT conversion. The beneficial effect of NT was especially pronounced in the field converted to corn, where the GHG cost was approximately six times greater for CT than for NT conversion (1.26 ± 0.45 vs. −6.42 ± 0.36 Mg CO_2e ha^{-1}). Even for the fields converted to perennial cellulosic crops, however, the benefit was substantial in that NT conversion provided one to four times greater mitigation than did CT conversion.

The main reasons for the NT benefit were lower N_2O and CO_2 emissions because differences in CH_4 oxidation and farming costs were very low. Nitrous oxide emissions in CT treatments in corn, switchgrass, and restored prairie fields were 1.75, 2.51, and 2.67 times those in NT treatments, respectively. Differences were higher in Year 1 than in Year 2 in the corn field and disappeared in Year 2 for the restored prairie and switchgrass fields, where tillage had stopped after Year 1. Carbon dioxide emissions from soil were always lower and NEE was always negative or only slightly positive under NT: in all converted fields NT crops were either a net C sink (corn and switchgrass fields), or net C loss was minor (restored prairie field). In contrast, in all fields CT crops expressed net C loss, as shown by a positive NEE of CO_2.

In the comparisons that follow, it is important to keep in mind that fields are not replicated, preventing statistical inference about crop differences. Thus, the trends noted regarding continuous corn vs. switchgrass vs. restored prairie are suggestive rather than conclusive. Conclusions regarding tillage effects within fields, however, are statistically robust as noted.

4.1 | Nitrous oxide fluxes

During the first year, N_2O emissions under CT management in all converted fields increased substantially compared with those under NT management (Figure 2d). Especially for the first 30 d after tillage, N_2O emissions under CT were five to seven times those under NT. Similar results have been reported based on shorter-term studies (Nikièma, Rothstein, Min, & Kapp, 2011; Ruan & Robertson, 2013).

The likely reason for the N_2O pulse is enhanced SOM decomposition under CT, which increased the availability of inorganic N (NH_4^+ and NO_3^-) (Table 2), stimulating nitrification and denitrification and thus N_2O production (Grandy & Robertson, 2006a; Piva et al., 2012; Reinsch, Loges, Kluß, & Taube, 2018). In Year 2 we found fewer differences in N_2O emissions between CT and NT, consistent with long-cultivated soils (Gelfand, Shcherbak, Millar, Kravchenko, & Robertson, 2016; Huang et al., 2018; Mei et al., 2018; van Kessel et al., 2013). In the corn field experiment, N_2O emissions under CT were 2.3 times those under NT in Year 1 (31.3 ± 2.94 g N_2O–N ha^{-1} d^{-1} in CT vs. 13.4 ± 2.49 in NT) but only 1.3 times greater in Year 2 (21.6 ± 1.81 g N_2O–N ha^{-1} d^{-1} in CT vs. 16.8 ± 2.34 in NT). In switchgrass and restored prairie fields, the NT vs. CT differences in Year 1 disappeared in Year 2 (Supplemental Table S2). This is likely because the pulse of substrate that occurred upon tillage in Year 1 had diminished by Year 2. Based on CT vs. NT differences in long-term cropping systems, we expect N_2O emission differences between CT and NT corn will eventually diminish (van Kessel et al., 2013) and perhaps reverse (Gelfand et al., 2016).

Over the study period, that corn in both NT and CT treatments produced more N_2O than the reference grassland can be attributed to its higher available soil N (Table 2), which is a significant predictor of N_2O fluxes (Figure 3).

4.2 | Nitrous oxide emission factors used by life cycle assessments

Biofuel life cycle assessment analyses (Plevin, 2009) typically use the Intergovernmental Panel on Climate Change (IPCC) Tier 1 emission factor (IPCC, 2006) to estimate direct N_2O emissions. Tier 1 methodologies apply a constant emission factor of 1% of fertilizer inputs to estimate direct N_2O emission in crops without residue return, without regard for tillage or other management factors. Thus, emission factor–estimated N_2O emissions for the corn field would be the same for CT as for NT (in this study, 1.59 kg N_2O–N ha^{-1} yr^{-1} on average). For our switchgrass field, emission factor-estimated N_2O would be 0.28 kg N_2O–N ha^{-1} yr^{-1} and for the restored prairie field would be 0 kg N_2O–N ha^{-1} yr^{-1} because restored prairie was unfertilized. In all cases, life cycle analysis based on the emission factor approach would have substantially underestimated the actual contribution of N_2O emissions to the overall GHG balance, which ranged from 5.29 kg N_2O–N ha^{-1} yr^{-1} for CT in the corn field to 1.05 kg N_2O–N ha^{-1} yr^{-1} for conventional tillage in the (unfertilized) restored prairie field.

We used fluxes from unfertilized corn in a nearby fertilizer N_2O response experiment (McSwiney & Robertson, 2005) to calculate emission factors for our corn field. Emission factors were 4.2 and 1.6% for CT and NT management, respectively, for Year 1 and 2.4 and 1.8%, respectively, for Year 2. Thus, during Year 1, over four times more N_2O under CT was released than estimated by the IPCC's 1% emission factor.

The constant emission factor approach is known to substantially underestimate fluxes as N fertilizer inputs exceed crop N needs (Hoben, Gehl, Millar, Grace, & Robertson, 2011; Millar et al., 2018; Shcherbak, Millar, & Robertson, 2014), and it appears equally unsuited for converted lands insofar because it fails to account for the large amount of available N provided by rapidly decomposing SOM (Grandy & Robertson, 2006a; Haas, Evans, & Miles, 1957; Huggins et al., 1998). Thus, using N fertilizer rates to estimate N_2O emissions following biofuel crop establishment may substantially underestimate the importance of N_2O emissions to the overall GHG balance of conversion; this holds important implications for life cycle analyses that estimate rather than measure N_2O fluxes.

4.3 | Carbon dioxide fluxes

Our results showed significantly higher soil CO_2 emissions under CT than NT for all fields over the study period (Figure 4d). Tillage destroys soil aggregates and exposes soil C previously protected against decomposition (Six, Elliott, & Paustian, 1999) and thus results in increased soil CO_2 emissions following tillage. Similar results have been observed by others (Almaraz et al., 2009; Grandy & Robertson, 2006b; Ruan & Robertson, 2013). In Year 2 we found smaller differences between CT and NT CO_2 emissions in the corn field, and no difference was detected in the restored prairie and switchgrass fields. Other studies have also shown bigger differences in soil CO_2 emissions between CT and NT in the first year than in subsequent years (e.g., Almaraz et al., 2009). Most likely soil active C is lost quickly from the top 25 cm after tillage during the first year so that less easily decomposed C was left for the second year.

Soil CO_2 fluxes can also be affected by environmental factors, such as soil temperature and moisture (Almaraz et al., 2009; Reichstein & Beer, 2008). Our results show an exponential increase in soil CO_2 fluxes with increasing soil temperature, consistent with reports by others (e.g., Reichstein & Beer, 2008; Ruan & Robertson, 2013). There was no significant correlation between CO_2 and %WFPS, however.

The positive NEE of CO_2 for all CT treatments indicates net C loss to the atmosphere. The NEE of CO_2 for CT in the restored prairie field was even higher than for CT in the corn field. If generalizable, one reason could be that corn grain production was approximately 2.2 times that of biomass production in the restored prairie field (Figure 7), and higher C uptake from photosynthesis and return as harvest residue and roots can offset some of the C loss from intensive tillage. In contrast to CT in the restored prairie field, CT in the switchgrass field received the same tillage management, but C loss under CT was only 11% of that in the restored prairie. This may be because of higher root production in switchgrass than in restored prairie, which would mean more C uptake in switchgrass (Zenone et al., 2013).

In contrast, NT crops in both corn and switchgrass fields were a net C sink (−2.76 and −2.95 Mg CO_2e ha^{-1}, respectively). Although some C was lost under NT in the restored prairie field, losses were 88% less than those under CT. A net loss means that C released from soil C decomposition exceeds C uptake from photosynthesis. Because total photosynthesis is unaffected by tillage (biomass production was the same under both CT and NT for all crops), lower or more negative NEE indicates less soil C loss. Therefore, NT protected soil C so that less C was released under NT management. In addition, NT plots in both corn and switchgrass fields showed even higher C uptake than did the unconverted CRP reference field (−0.92 Mg CO_2e ha^{-1}).

It is well known from the primary literature that NT attenuates the oxidation of soil organic C to CO_2 that otherwise occurs with tillage. Scores of studies have shown that, in most soils worldwide, decomposition is slower with NT management than with CT management (Dick et al., 1998; Holland & Coleman, 1986; Ogle, Breidt, & Paustian, 2005; Six et al., 1999; West & Marland, 2002; West & Post, 2002). Thus, in principle, reduced CO_2 loss with NT is not surprising and is consistent with studies in annual cropping systems worldwide.

4.4 | Methane oxidation

Well-aerated soils can be a small but significant (Robertson, 2004) sink for atmospheric CH_4, and previous work has shown that both tillage (Ball et al., 1999; Six et al., 2004; Ussiri, Lal, & Jarecki, 2009) and N fertilization (Chu, Hosen, & Yagi, 2007; Gulledge & Schimel, 1998; Suwanwaree & Robertson, 2005) can affect soil CH_4 oxidation rates. In this study all fields, both converted and reference, were net sinks for CH_4 (Figure 6d). Our recorded daily CH_4 fluxes for converted fields (ranging from −0.31 ± 0.17 to −1.37 ± 0.20 g CH_4–C ha^{-1} d^{-1}) were close to the average CH_4 oxidation rates of −1.80 ± 0.06 g CH_4–C ha^{-1} d^{-1} at nearby crop sites (Robertson, Paul, & Harwood, 2000; Suwanwaree & Robertson, 2005). However, we found no significant differences in CH_4 oxidation rates among treatments within fields, although oxidation rates under NT were numerically and consistently higher than those under CT for the corn field (1.4 times higher overall) and restored prairie field (36% higher). Regardless of tillage, the corn field expressed oxidation rates that were only 33–38% of those in the restored prairie and switchgrass fields.

Overall, CH_4 fluxes were negligible compared with N_2O and CO_2 fluxes, consistent with findings elsewhere and nearby (Gelfand et al., 2011, 2013; Ruan & Robertson, 2013; Schmer et al., 2008; Walter, Don, & Flessa, 2015).

4.5 | Global warming impact

Negative GWIs (Figure 8b) indicate net climate change mitigation, and mitigation here includes fossil fuel offset credits based on the use of biofuel in place of gasoline. During the first 2 yr of biofuel crop establishment, our results show that by reducing N_2O and whole-ecosystem C loss, NT practices, with an average GWI of −6.01 Mg CO_2e ha^{-1} yr^{-1} across all fields, can substantially improve the GWI of grassland conversion compared with CT, with its average GWI of only −0.25 Mg CO_2e ha^{-1} yr^{-1}.

Regardless of tillage management (i.e., CT or NT) and regardless of crop, N_2O emissions are as important as soil C loss during grassland conversion. Across all cropped fields, N_2O emissions as CO_2e were approximately 30% of the net ecosystem C lost as CO_2e.

The net GWI of NT in the corn field was numerically similar to the net GWI of the unconverted CRP reference field assuming its harvest for bioenergy. The net GWI of NT in the switchgrass field was numerically even lower than that in the reference field. Although our experimental design prevents a statistical comparison, the trend corroborates earlier suggestions (Gelfand et al., 2011; Ruan & Robertson, 2013) that NT conversion to switchgrass can be of greater climate benefit than the direct use of existing but lower-productivity CRP grasslands. In other words, the higher productivity and therefore higher fossil fuel offset of switchgrass appears to quickly compensate for its establishment costs.

The relative importance of different GWI components in this study is similar to other annual and perennial cropping systems but for this study's exaggerated importance of soil N_2O fluxes and C loss following conversion. In most systems (Gelfand & Robertson, 2015; Guardia et al., 2019; Robertson & Grace, 2004), including nearby annual and perennial cropping systems (Gelfand et al., 2013; McGill, Hamilton, Millar, & Robertson, 2018; Ruan, Bhardwaj, Hamilton, & Robertson, 2016), N_2O fluxes and agronomic inputs—especially N fertilizer production—contribute the most to a system's GWI, with soil C change representing a net sink or source depending on time since agricultural conversion and tillage and residue management. Irrigation and liming can likewise represent sinks or sources of GWI, depending on context (Hamilton, Kurzman, Arango, Jin, & Robertson, 2007; McGill et al., 2018; Mosier, Halvorson, Peterson, Robertson, & Sherrod, 2005).

At least two additional GWI components were not evaluated in this study: (a) off-site or indirect N_2O emissions that arise from differential rates of NO_3^- leaching and (b) albedo differences that can lead to differential rates of atmospheric warming above cropping systems. In nearby cropping systems, less NO_3^- is leached from NT than CT systems (Syswerda, Basso, Hamilton, Tausig, & Robertson, 2012), which, if also true here, would further exacerbate CT C debt because more indirect N_2O would be emitted from streams receiving CT groundwater. Likewise, surface residues in NT systems have greater surface reflectance than the bare soil of CT systems, leading to atmospheric cooling (Davin, Seneviratne, Ciais, Olioso, & Wang, 2014) that will also speed the recovery of C debt in NT relative to CT systems. Although the albedo difference will disappear in perennial crops once the crop canopy closes, it will persist in the corn system.

That NT practices regardless of crop type can substantially reduce the GHG impact of CRP grassland conversion suggests that conversion, when it occurs, should be conducted without tillage. Under CT, the C debt of corn and restored prairie fields continued to increase even 2 yr after conversion. In contrast, under NT the C debt began to be repaid. To reap the full and immediate climate benefits of biofuels, policies should be designed to encourage adoption of NT conversion practices.

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DATA AVAILABILITY STATEMENT

All data reported here are openly available at https://doi.org/10.5061/dryad.cfxpnvx2v.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

G. Philip Robertson https://orcid.org/0000-0001-9771-9895

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SUPPORTING INFORMATION

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