# Soil Greenhouse Gas Emissions in Response to Corn Stover Removal and Tillage Management Across the US Corn Belt

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**Abstract** In-field measurements of direct soil greenhouse gas (GHG) emissions provide critical data for quantifying the net energy efficiency and economic feasibility of crop residue-based bioenergy production systems. A major challenge to such assessments has been the paucity of field studies addressing the effects of crop residue removal and associated best practices for soil management (i.e., conservation tillage) on soil emissions of carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$). This regional survey summarizes soil GHG emissions from nine maize production systems evaluating different levels of corn stover removal under conventional or conservation tillage management across the US Corn Belt. Cumulative growing season soil emissions of $CO_2$, $N_2O$, and/or $CH_4$ were measured for 2–5 years (2008–2012) at these various sites using a standardized static vented chamber technique as part of the USDA-ARS's Resilient Economic Agricultural Practices (REAP) regional partnership. Cumulative soil GHG emissions during the growing season varied widely across sites, by management, and by year. Overall, corn stover removal decreased soil total $CO_2$ and $N_2O$ emissions by -4 and -7 %, respectively, relative to no removal. No management treatments affected soil $CH_4$ fluxes. When aggregated to total GHG emissions (Mg $CO_2$ eq ha$^{-1}$) across all sites and years, corn stover removal decreased growing season soil emissions by $-5\pm1$ % (mean±se) and ranged from -36 % to 54 % ($n=50$). Lower GHG emissions in stover removal treatments were attributed to decreased C and N inputs into soils, as well as possible microclimatic differences associated with changes in soil cover. High levels of spatial and temporal variabilities in direct GHG emissions highlighted the importance of site-specific management and environmental conditions on the dynamics of GHG emissions from agricultural soils.

**Keywords** Corn stover · Tillage · Residue management · Static vented chamber · Carbon dioxide · Nitrous oxide · Methane

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## Introduction

The US Corn Belt is expected to be a major contributor of crop residues such as corn (*Zea mays* L.) stover for the nation's developing renewable biomass energy industry [26]. The sustainability of a corn stover-based bioenergy feedstock, however, will depend on identifying optimal stover harvest rates and site-specific management practices that maintain or improve soil organic carbon (SOC) levels, minimize the risks of soil erosion or loss in soil productivity, and reduce direct soil emissions of various greenhouse gases (GHGs) such as carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$) [5, 6, 21, 24, 26, 30, 61].

A major challenge to determining optimal site-specific crop, soil, and residue management practices has been the paucity of field studies measuring the effects of stover removal on direct GHG emissions. Removal of corn stover is expected to decrease soil emissions of $CO_2$ and other microbially derived GHGs by reducing the input of easily decomposable labile C [13]. Results from the few empirical studies available addressing crop residue removal effects on soil GHG emissions, however, are inconsistent. In one study, corn stover removal did not alter soil $CO_2$ or $N_2O$ emissions compared with stover retained treatments [25]. In other studies, removing crop residues decreased soil $N_2O$ emissions [13, 46], or residue retention stimulated $N_2O$ emission through new inputs of N in crop biomass [3, 18].

Alternative conservation tillage (ALT) practices (e.g., reduced tillage and no-tillage) are often recommended to ameliorate the potential negative effects of crop residue removal, which may include loss of soil organic carbon (SOC), increased soil compaction, disruption of soil aggregates, and reduced soil health [4, 16, 17, 32, 58, 59]. Although the impacts of tillage on soil GHG emissions has been studied more widely than residue management, field studies also report contrasting results for tillage effects on soil $CO_2$ and $N_2O$ emissions. Soil $CO_2$ emissions under conservation tillage practices have been found to decrease [1, 2, 43], increase [3, 40, 56], or remain unchanged [13] compared with conventional tillage (CON). Similarly, soil $N_2O$ emissions under conservation tillage can also decrease [13, 42], increase [3, 35, 53], or remain unchanged [15, 23, 39, 48].

Because of the limited availability of measured soil $N_2O$ emissions under various residue and soil management practices, emissions are often estimated using the revised IPCC 1996 Tier 1 emission factor (EF) that approximates $N_2O$–N emissions as 1.25 % of fertilizer N applied [20]. More recently, this value was revised downwards to 1.00 % [9]. Whether and how stover removal or tillage impact emission factors can be discerned from spatial and temporal variabilities in landscape and weather, however, remains unclear as evidenced by the wide uncertainty range (0.3–3 %) reported for emission factors [9].

A primary goal for using coordinated, replicated field trials is to provide data to verify and improve modeled estimates of sustainable corn stover removal rates and the impacts of residue and soil management practices on direct soil GHG emissions. Currently, the USDA-Agricultural Research Service (ARS) is conducting a multi-location field assessment on the effects of corn stover removal and other management practices at nine maize production systems in five states (Indiana, Iowa, Minnesota, Nebraska, and South Dakota) across the US Corn Belt [50]. This research, which includes the quantification of direct GHG emissions, is part of the USDA-ARS's regional research partnership for Resilient Economic Agricultural Practices (REAP, formerly the Renewable Energy Assessment Project; http://www.ars.usda.gov/research/programs/programs.htm?np_code=202&docid=15193) and a broad integrated study funded through USDA and DOE [29, 60]. The objective of this report is to provide a regional summary of how corn stover removal under conventional tillage (CON) or alternative conservation tillage (ALT) affects direct GHG emissions during the growing season in the US Corn Belt.

## Materials and Methods

### Site Descriptions

The nine study sites (Sites 1–9) used in this report span five states in the central USA (Table 1; Fig. 1). Three corn stover removal levels were tested, with all sites testing at least two levels: low residue removal (LRR), medium residue removal (MRR), or high residue removal (HRR). The LRR treatment consists of grain harvest only, with all stalks, leaves, and cobs remaining on the soil surface (equivalent to no removal of non-grain biomass). The MRR and HRR rates consist of differences in stalk cutting height (30 vs 10 cm, respectively) or harvesting stover from half or all rows within a treatment for a uniform cutting height, respectively. Although stover removal methods and equipment vary from site to site, approximately 15–40 % of the total stover produced is removed in MRR, and >40 % (up to 75 %) of the total stover biomass is removed in HRR at partnership sites measuring GHGs [29]. Other management practices (e.g., crop rotation; N fertilizer type and rate; irrigation; biochar application; and cover crops) and management timing vary by site, as appropriate to local soil and climate conditions (Table 2). Additional site-specific management records and environmental conditions are available online through the USDA-ARS REAP database (available at: http://nrrc.ars.usda.gov/reappb/#/Home) and GRACEnet database (available at: http://nrrc.ars.usda.gov/slgracenet/#/Home) [11]. Although experimental designs and treatments vary by location depending on site-specific research questions, all sites evaluate at least two levels of corn residue removal. Results presented here are limited to comparing cumulative growing season GHG emissions in LRR and MRR and/or HRR treatments under conventional tillage (CON) practices ($n=4$ sites) or alternative conservation tillage (ALT) practices ($n=9$ sites). Specific tillage types for CON or ALT practices are defined by common producer practices at each location (Table 2). CON practices consisted of disk tillage at Site 6, chisel plow at Sites 2 and 5, and moldboard plow at Site 3. ALT practices consisted of strip tillage at Site 3 and no-tillage at all other sites.

**Table 1** Location and selected soil information (0–15 cm) for the Resilient Economic Agricultural Practices (REAP) regional partnership sites

| Site(s) | Location | Latitude (°N) | Longitude (°W) | MAT (°C) | MAP (mm) | Texture class/classes[a] | Soil pH (1:1) | SOM[b] (g kg$^{-1}$) | Dominant soil series |
|---|---|---|---|---|---|---|---|---|---|
| 1, 2 | Morris, MN | 45.7 | 95.8 | 5.8 | 645 | CL | 6.0–6.3 | ~50 | Barnes-Aastad |
| 3 | Rosemount, MN | 44.3 | 96.8 | 6.4 | 879 | SiL | 5.8–6.0 | 40–50 | Waukegan |
| 4 | Brookings, SD | 44.7 | 93.1 | 6.2 | 579 | SiCL | 6.3–7.3 | 50+ | Kranzburg-Brookings |
| 5 | Ames, IA | 42.0 | 93.6 | 9.2 | 865 | L, CL, SiCL | 6.5 | 30–50 | Clarion-Nicollet-Webster |
| 6 | Ithaca, NE | 41.2 | 96.5 | 10.5 | 766 | SiL | 7.6–7.7 | 30–40 | Tomek-Filbert |
| 7 | Ithaca, NE | 41.2 | 96.5 | 10.5 | 766 | SiL | 5.2–6.9 | 30–50 | Tomek-Yutan |
| 8 | Clay Center NE | 40.5 | 98.1 | 10.1 | 721 | SiL | 6.0–6.7 | 30–40 | Hastings |
| 9 | West Lafayette, IN | 40.5 | 87.0 | 10.3 | 946 | SiL | 5.8 | 30–40 | Octagon-Throckmorton |

[a] *C* clay, *L* loam, *Si* silt

[b] *SOM* soil organic matter

## Gas Sampling and Analyses

Greenhouse gas emissions were measured and calculated at all sites using sampling designs and data processing protocols standardized by the USDA-ARS's Greenhouse Reduction through Agricultural Carbon Enhancement Network (GRACEnet) [19, 41]. Gas measurements were taken with static vented chambers using a stratified sampling design in which gases were sampled with syringes and injected into evacuated vials at three or four evenly spaced time-points over 30 min (0, 15, 30 min; or 0, 10, 20, 30 min). At Sites 1 and 2, sampling occurred at four time points within 30 min recording the time interval [11, 28]. Minimum sample collection at all sites involved sampling every 7 to 14 days during the growing season; a subset of sites also measures GHGs monthly during the non-growing season. To account for diurnal variability, gas samples were usually collected between at times of the day closely corresponding to the daily average temperature (mid-morning and early evening) [41].

At each site, three to six chamber replicates were measured per treatment combination. Concentrations of $CO_2$, $N_2O$, and/or $CH_4$ in air samples from the sampling chamber headspace
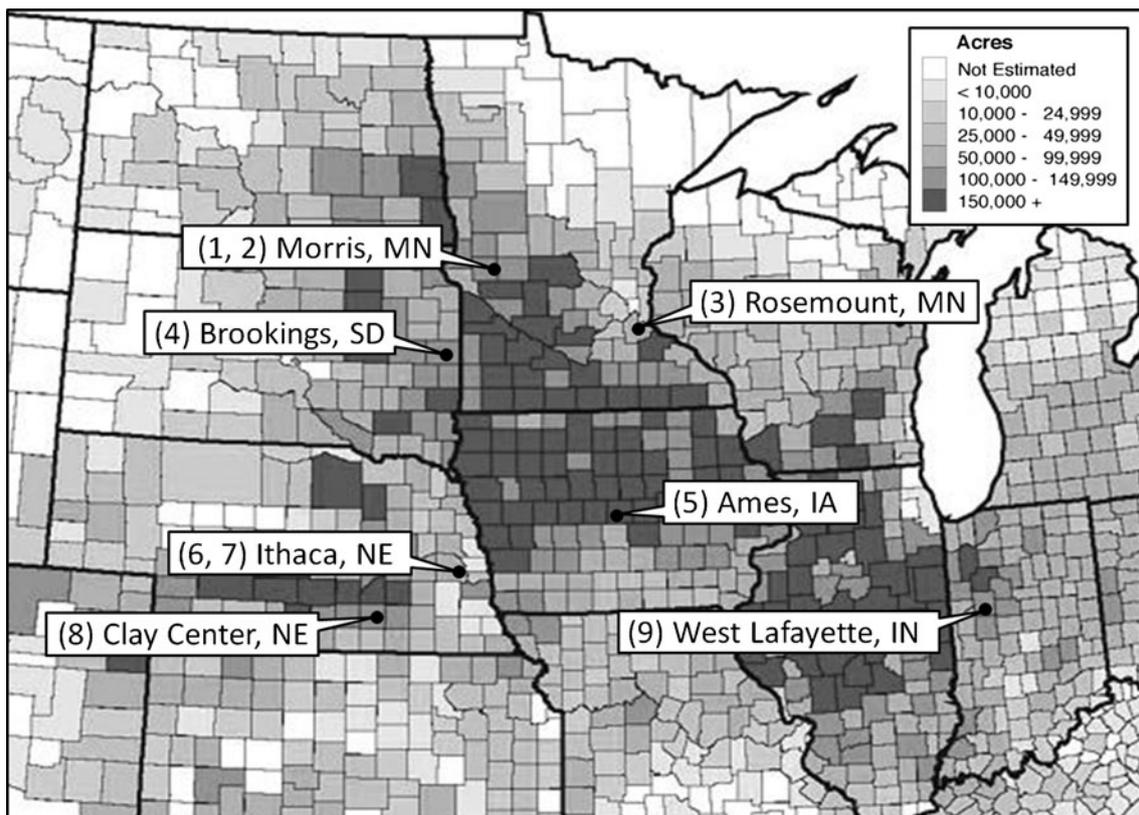


**Fig. 1** Map of research site locations across the US Corn Belt. Shading indicates acreage in corn production by county [49]

**Table 2** Selected management information for the Resilient Economic Agricultural Practices (REAP) regional partnership sites

| Site | Location | Crop[a] | N rate[b] | Tillage[c] | Residue removal[d] | Tillage start[e] | RR start[f] | Years sampled | Growing season period sampled[g] | Other[h] |
|------|----------|---------|-----------|------------|--------------------|-----------------|-------------|---------------|-----------------------------------|----------|
| 1 | Morris, MN | CS | 105 | ALT | LRR, HRR | 1995 | 2002 | 2008–2010 | May 13–October 30 | NI |
| 2 | Morris, MN | CS | 105 | ALT, CON | LRR, HRR | 2005 | 2005 | 2008–2010 | May 13–October 30 | NI |
| 3 | Rosemount, MN | CC | 146 | ALT, CON | LRR, MRR, HRR | 1991 | 2007 | 2010–2012 | May 22–September 15 | NI |
| 4 | Brookings, SD | CS | 133 | ALT | LRR, MRR | 2000 | 2000 | 2008–2012 | May 26–September 20 | NI |
| 5 | Ames, IA | CC | 224 | ALT, CON | LRR, MRR, HRR | 2007 | 2007 | 2010–2012 | April 19–October 2 | NI |
| 6 | Ithaca, NE | CC | 202 | ALT, CON | LRR, HRR | 2001 | 2001 | 2011–2012 | April 19–September 18 | IR |
| 7 | Ithaca, NE | CC | 120 | ALT | LRR, HRR | 1999 | 2000 | 2010–2012 | May 7–September 18 | NI |
| 8 | Clay Center, NE | CC | 200 | ALT | LRR, HRR | 2010 | 2010 | 2011–2012 | May 1–September 25 | IR |
| 9 | West Lafayette, IN | CC | 224 | ALT | LRR, MRR, HRR | 2004 | 2004 | 2008–2009 | May 1–October 1 | NI |

[a] *CS* corn soybean rotation, *CC* continuous corn

[b] kg N ha$^{-1}$ y$^{-1}$; Site 5 (2010: 213, 238, 253 kg N ha$^{-1}$ y$^{-1}$ for LRR, MRR, HRR, respectively; 2011–2012: all 224 kg N ha$^{-1}$ y$^{-1}$)

[c] *ALT* conservation tillage (strip-till at Site 3, no-till at all other sites), *CON* conventional tillage (moldboard plow at Site 3; chisel plow at Sites 2, 5; disk tillage at Site 6)

[d] *LRR* low residue removal, *MRR* medium residue removal, *HRR* high residue removal

[e] Year tillage treatments initiated; for Site 1, ALT treatment started in 1995 and CON started in 2002

[f] Year residue removal treatments initiated

[g] Average dates for sampling period during the growing season

[h] *IR* irrigated, *NI* non-irrigated; for 2011 and 2012, respectively, Site 6 irrigated with 125,200 mm; Site 8 with 38,166 mm

were measured within 10 days of sample collection using a gas chromatograph equipped with a thermal conductivity detector ($CO_2$), electron capture detector ($N_2O$), and flame ionization detector ($CH_4$). Soil gas emission rates were calculated as the change in headspace gas concentration over time within the enclosed chamber volume. Cumulative GHG emissions were estimated by linear interpolation of flux rates between sampling dates then summing daily rates over each growing season (i.e., trapezoidal integration method). Regional responses to corn residue removal and tillage practices are reported here as treatment means±standard errors across all sites.

Growing season dates and length varied across sites depending on geographic location and climate conditions. The growing season for each site was approximated as the period between corn planting and grain harvest (Table 2). For sites using corn-soybean (*Glycine max* (L.) Merr) rotations (Sites 1, 2 and 4), both crop phases were present each year of the study; only GHG measurements from the corn phase, however, were used in this survey to maintain consistency with measurements taken from continuous corn sites (Sites 3 and 5–9).

To account for site-specific management, the effect (%) of corn stover removal (MRR and HRR) was calculated relative to no removal (LRR) at each location by tillage treatment for each growing season (Eq. 1)

$$\frac{(MRR \ or \ HRR) - LRR}{LRR} * 100 \qquad (1)$$

Positive values indicate that residue removal increased GHG emissions relative to no stover removal, and negative values indicate decreased emissions relative to no stover removal. Emission factors (EF, %) for $N_2O$–N were also calculated to account for site-specific management during the growing season. For each site, an EF was calculated as the percent of N added as fertilizer which was lost as measured $N_2O$–N over the growing season. Background $N_2O$ emissions were not subtracted because such emissions in intensively managed soils are likely derived from fertilizer N or crop residues remaining from the previous season; thus, background emissions are included as an agriculturally derived component [9, 54]. Values are reported as means±standard errors.

Weather data from the National Climate Data Center's Climate Data Online archive (http://www.ncdc.noaa.gov/cdo-web/) or from on-site weather stations were used to calculate the average daily minimum and maximum air temperatures and the total precipitation received (mm) during the growing season for each site and each year. For irrigated sites, irrigation amounts were added to precipitation received to account for the total water inputs each growing season.

### Statistical Analyses

Each site reported mean growing season soil GHG emissions for multiple years (2008–2012), though not all sites reported data for all years or all tillage and residue removal treatment combinations (Table 2). A total of 87, 69, and 51 site-year

observations were reported for mean cumulative growing season $CO_2$, $N_2O$, and $CH_4$ emissions across all tillage and residue removal treatments (kg C or N $ha^{-1}$ growing season$^{-1}$), respectively. Total growing season GHG emissions was calculated as $CO_2$-equivalents (Mg $CO_2$eq $ha^{-1}$ growing season$^{-1}$) using 100-year global warming potentials for each GHG ($CO_2=1$, $N_2O=298$, and $CH_4=25$) [22].

Because not all stover removal-by-tillage treatments were represented at each site for all years (e.g., unbalanced experimental design), a generalized linear mixed effects analysis of variance (ANOVA) was used to assess the fixed effects of tillage (CON and ALT), residue removal (LRR, MRR and HRR), and their interaction on cumulative growing season $CO_2$, $N_2O$, $CH_4$, and the total GHG emissions (PROC GLIMMIX; SAS v9.3; SAS, Inc., Cary, NC). Site, year, and their interaction were identified as random factors. Data were tested for normality using the Shapiro–Wilk statistic and transformed when necessary. For the limited data available from irrigated systems, the main and interaction effects of irrigation did not affect cumulative growing season GHG emissions (data not shown), so data were analyzed for tillage and stover removal effects only as described above. Post-hoc multiple comparisons between fixed treatment means or differences from zero were tested using least squares means (LSMEANS).

Linear regressions for LRR and MRR+HRR (hereafter 'RR') were used to evaluate potential correlations between soil GHG emissions and (1) average minimum and maximum air temperatures during the growing season (°C) and (2) the total growing season precipitation received (mm). Irrigation amounts at Sites 6 and 8 were included in growing season precipitation to represent the total water inputs in those systems. Similarly, correlations between $N_2O$ emission factors and air temperatures, growing season precipitation, and N fertilizer rate applied (kg N $ha^{-1}$ $y^{-1}$) were also evaluated.

High variability in soil emissions due to geographic location and site-specific weather conditions decreases the statistical power to detect treatment effects. Thus, the probability of type I errors was countered against the increasing probability of type II errors (i.e., accepting the null hypothesis when false, or failing to declare a real difference as significant) by considering effects significant when $P \leq 0.10$ [62].

## Results

Cumulative growing season soil GHG emissions varied widely across sites, by management, and by year. Across all sites, management, and years, mean cumulative growing season soil emissions were 3.4±0.2 Mg $CO_2$–C $ha^{-1}$ ($n=87$), 1.6±0.1 kg $N_2O$–N $ha^{-1}$ ($n=69$), and –0.12±0.04 kg $CH_4$–C $ha^{-1}$ ($n=51$) (Fig. 2a–c). For each $CO_2$ and $N_2O$, growing season emissions contributed 76±1 % ($n=63$) and 66±3 % ($n=45$),

respectively, to total annual emissions of each GHG (Mg C $ha^{-1}$ or kg N $ha^{-1}$, respectively) (Sites 1, 2, and 4–8). Growing season soil $CH_4$ fluxes were highly variable and negligible in comparison with $CO_2$ and $N_2O$ emissions; results and discussion focus on $CO_2$ and $N_2O$ hereafter. Of the total GHG emitted during the growing season (Mg $CO_2$eq $ha^{-1}$), soil emissions of $CO_2$ contributed 93±1 % and $N_2O$ contributed 7±1 %. The mean growing season total GHG emissions ($CO_2$, $N_2O$, $CH_4$) was 12.9±0.7 Mg $CO_2$eq $ha^{-1}$ for all sites, management, and years (Fig. 2d).

Tillage Effects

Cumulative growing season $CO_2$ emissions were 12±4 % higher in CON soils (3.7±0.3 Mg $CO_2$–C $ha^{-1}$, $n=28$) relative to ALT soils (3.2±0.2 Mg $CO_2$–C $ha^{-1}$, $n=59$) ($P_{tillage}=0.0212$; Sites 2, 3, 5, 6) (Fig. 2a). Although there was no main effect of tillage on soil $N_2O$ emissions (kg $N_2O$–N $ha^{-1}$), cumulative growing season $N_2O$ emissions tended to be lower in CON than ALT (Fig. 2b). A marginal interaction between tillage and stover removal, however, showed that stover removal affected cumulative growing season $N_2O$ emitted in ALT soils only (see next section).

Stover Removal Effects

Cumulative growing season $CO_2$ emissions (Mg $CO_2$–C $ha^{-1}$) were 4±3 % lower when corn stover was removed (MRR and HRR) compared with no removal (LRR) ($P_{residue}=0.0967$; Table 3; Fig. 2a). Stover removal-by-tillage interaction was not significant for cumulative growing season $CO_2$ emissions. In 2010 only, the effect (% change) of residue removal (MRR and HRR) relative to no removal (LRR) treatments was lower than zero (i.e., zero=no effect) (CON −17±6 %; ALT −13±7 %; $P<0.10$; Fig. 3a). In contrast during 2012, stover removal resulted in higher $CO_2$ emissions from CON soils (+26±15 %; $P<0.10$; Fig. 3a). Soil $CH_4$ fluxes were not different from zero in LRR and MRR treatments, and HRR soils were minor $CH_4$ sinks (Fig. 2c). Residue removal effects on the total GHG emissions (Mg $CO_2$eq $ha^{-1}$) paralleled those observed for $CO_2$ emissions (Fig. 2d, 3c).

Cumulative growing season $N_2O$ emissions (kg $N_2O$–N $ha^{-1}$) tended to be lower in ALT soils when stover was removed ($P_{tillage*residue}=0.1207$) but had more variable effects in CON soils (Fig. 2b, 3b; Table 3). The average removal effect (% change from LRR) in ALT soils was -15±5 % and was significantly lower than zero in 2009 and 2012 (Fig. 3b). In contrast, residue removal effects were significantly higher than zero for CON soils in 2011 and 2012 (Fig. 3b). In CON soils, the emission factor for growing season $N_2O$ emitted relative to N fertilizer applied ranged from 0.12 to 2.26 % (1.00±0.18 %). For ALT soils, cumulative growing season $N_2O$ emissions with residue removal (MRR, HRR; 1.5±
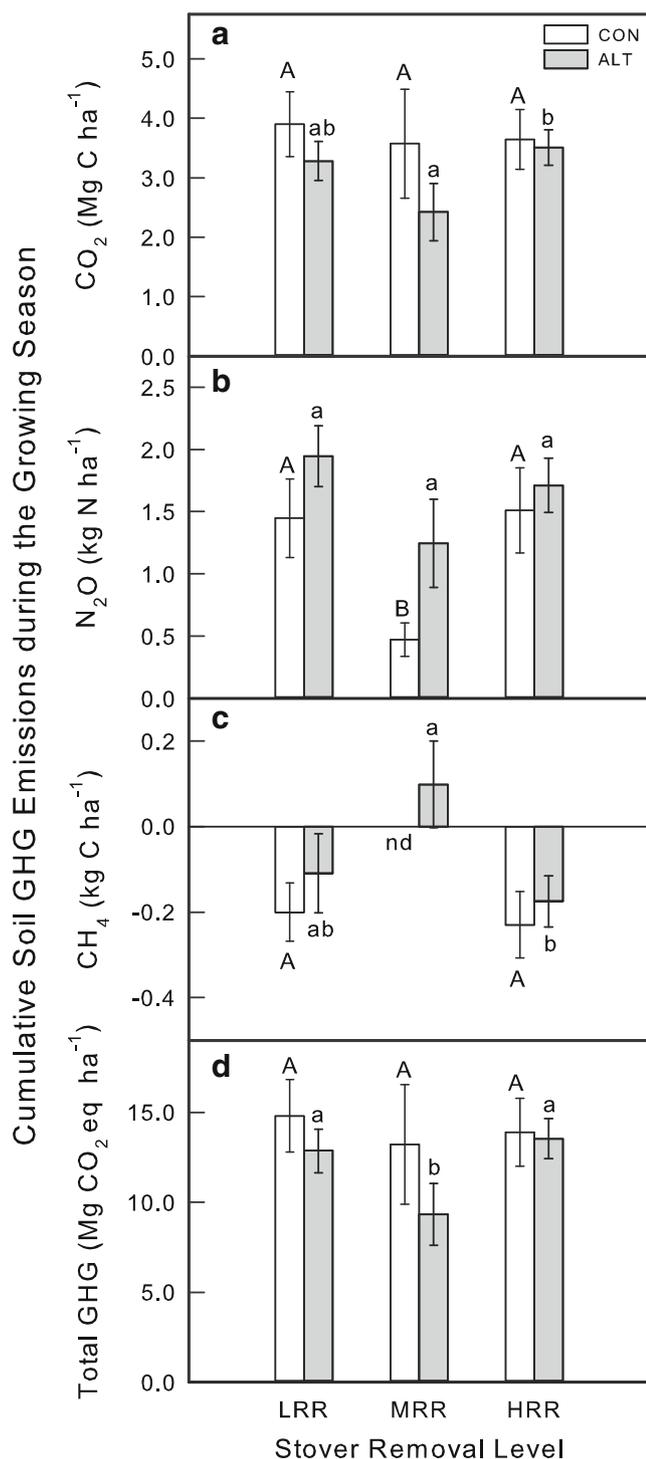
**Fig. 2** Mean (se) cumulative soil emissions of (**a**) $CO_2$, (**b**) $N_2O$, (**c**) $CH_4$, and (**d**) the total GHGs during the growing season across all sites and years by tillage and residue management level. *CON* conventional tillage, *ALT* alternative conservation tillage, *LRR* low residue removal, *MRR* medium residue removal *HRR* high residue removal, *nd* no data. Different *upper case* or *lower case letters* indicate significant differences between residue removal rates under conventional tillage and reduced/no tillage practices, respectively

0.2 kg $N_2O$–N $ha^{-1}$) were lower relative to no removal (LRR; 1.9±0.2 kg $N_2O$–N $ha^{-1}$). Emission factors for ALT soils with

residue removal versus no removal were 1.10±0.15 % and 1.39±0.18 %, respectively.

Correlations with Precipitation and Minimum Air Temperature

Cumulative growing season $CO_2$ emissions were positively correlated to growing season precipitation received (mm) and the sensitivity of $CO_2$ emissions in response to precipitation (i.e., regression slope) was not affected by tillage or residue management (all data: $y=0.0048x+1.4401$, $R^2=0.34$, $P<0.0001$) (Fig. 4). No correlations were found between cumulative growing season $CO_2$ emissions and average daily minimum or maximum air temperatures over the growing season (data not shown).

Cumulative growing season $N_2O$ emissions also were positively correlated to growing season precipitation received (mm), which included irrigation amounts for Sites 6 and 8 (Fig. 5a). In ALT soils, residue removal (RR=MRR and HRR) decreased the sensitivity of this relationship as evidenced by a lower slope value compared with soils where no residue was removed (ALT: LRR, $y=0.005x-0.008$, $R^2=0.52$, $P=0.0001$; RR, $y=0.004x+0.13$, $R^2=0.40$, $P=0.0003$). In contrast, cumulative growing season $N_2O$ emissions were negatively correlated with average daily minimum air temperature over the growing season, and the sensitivity of this relationship was not affected by residue removal (Fig. 5b) (ALT: LRR, $y=-0.25x+5.29$, $R^2=0.19$, $P=0.05$; RR, $y=-0.25x+5.00$, $R^2=0.27$, $P=0.004$).

The nitrogen emission factor (EF) showed similar relationships with the total growing season precipitation received (Fig. 5c) (ALT: LRR, $y=0.003x+0.31$, $R^2=0.30$, $P=0.008$; RR, $y=0.002x+0.29$, $R^2=0.21$, $P=0.0144$) and average daily minimum air temperature (Fig. 5d) (ALT: LRR, $y=-0.28x+5.12$, $R^2=0.43$, $P=0.0009$; RR, $y=-0.25x+4.52$, $R^2=0.44$, $P=0.0001$). Emission factors were not correlated to annual N fertilizer rates across all sites, treatments, and years.

Discussion

For nine research sites spanning five states across the US Corn Belt, the magnitude of measured growing season GHGs emitted directly from soils (12.9±0.7 Mg $CO_2$eq $ha^{-1}$) approximated those reported by other empirical or modeled studies in maize production systems [8, 24, 25]. Growing season soil GHG emissions were dominated by $CO_2$ (>90 %) with a small contribution from $N_2O$ (<10 %). Soil $CH_4$ production did not contribute significantly to the total GHG emissions; rather, soils were a slight sink for $CH_4$ as has been noted in other agroecosystem studies [42, 57].

Overall, conventional tillage practices (CON) (i.e., disk tillage, chisel tillage, and moldboard plow) increased

**Table 3** Minimum (min), maximum (max), and mean (standard error) residue removal effects on cumulative growing season $CO_2$, $N_2O$, and the total GHG emissions for medium and high residue removal rates (MRR and HRR) relative to no stover removal (LRR) by tillage treatment across all site years. Relative removal effect calculated as percent change from LRR=[(MRR or HRR)−LRR]/LRR×100. *CON* conventional tillage, *ALT* reduced/no tillage

| Tillage | Residue removal | Relative removal effect $CO_2$-C emitted (%) | | | | Relative removal effect $N_2O$-N emitted (%) | | | | Relative removal effect Total GHG $CO_2$ eq emitted (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Min | Max | Mean | *n* | Min | Max | Mean | *n* | Min | Max | Mean |
| CON | MRR | 6 | −30 | +68 | +12 (15) | 3 | −20 | +54 | +25 (23) | 6 | −30 | +54 | +10 (13) |
| | HRR | 11 | −32 | +41 | −5 (5) | 8 | −58 | +35 | +4 (11) | 11 | −32 | +41 | −5 (5) |
| ALT | MRR | 13 | −36 | +5 | −9 (6) | 10 | −56 | +34 | −16 (9) | 13 | −35 | +8 | −9 (4) |
| | HRR | 20 | −36 | +27 | −6 (3) | 17 | −45 | +62 | −14 (6) | 20 | −33 | +25 | −6 (3) |
| All till | MRR | 19 | −36 | +68 | −2 (6) | 13 | −56 | +54 | −7 (10) | 19 | −35 | +54 | −3 (5) |
| | HRR | 31 | −36 | +41 | −6 (3) | 25 | −58 | +62 | −8 (5) | 31 | −33 | +41 | −6 (3) |
| | All RR | 50 | −36 | +68 | −4 (3) | 38 | −58 | +62 | −7 (5) | 50 | −35 | +54 | −4 (3) |

**Fig. 3** Mean (se) effect of residue removal (MRR and HRR) relative to no stover removal (LRR) on cumulative growing season (**a**) $CO_2$, (**b**) $N_2O$, and (**c**) the total GHG emissions by tillage treatment across all sites from 2008 to 2012. Relative removal effect calculated as percent change from LRR (relative removal effect %=[(MRR or HRR)−LRR]/LRR×100). *CON* conventional tillage, *ALT* alternative conservation tillage. Number of sites (*n*) used for each mean calculation indicated. *Asterisks* indicate mean values significantly different from zero ($P \leq 0.10$)
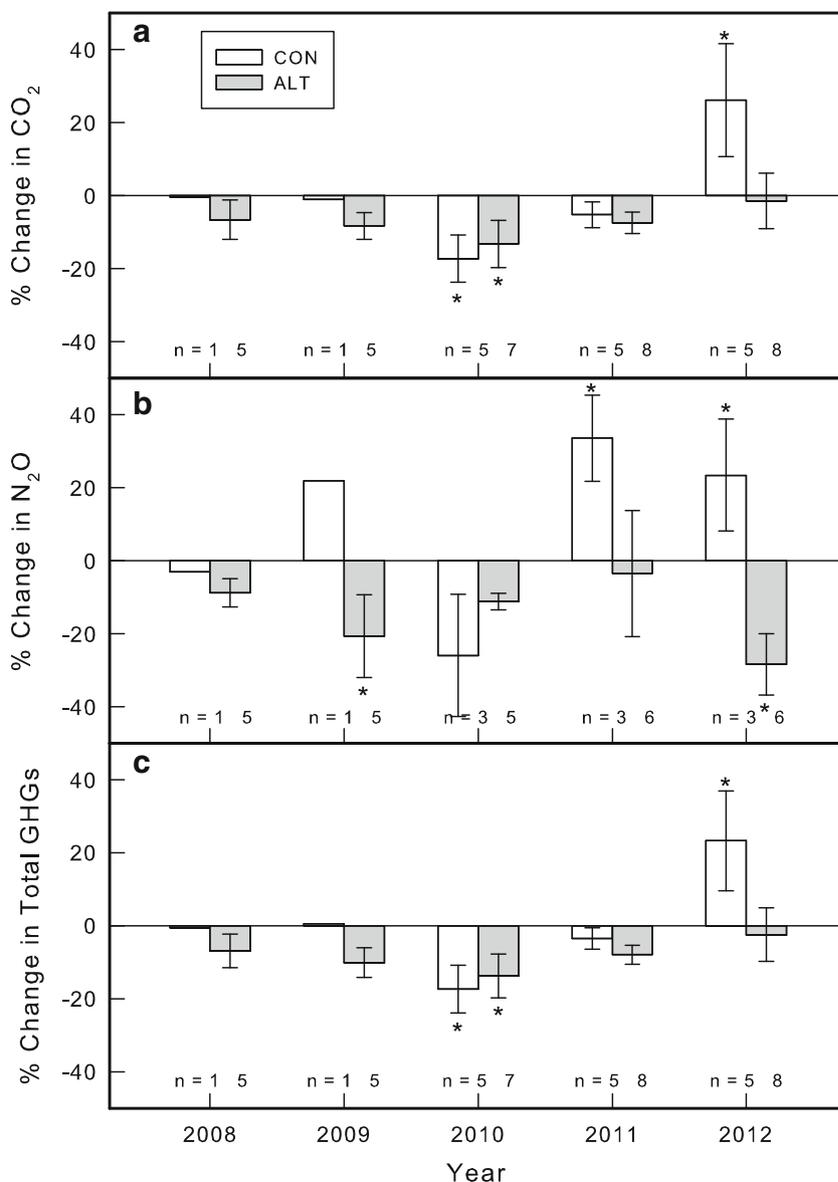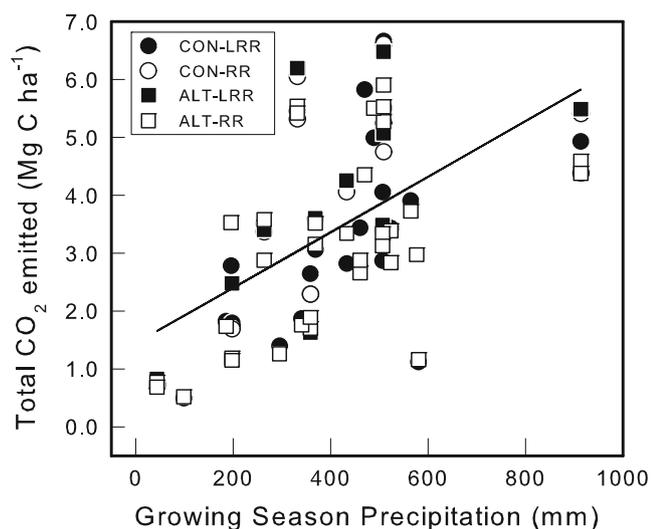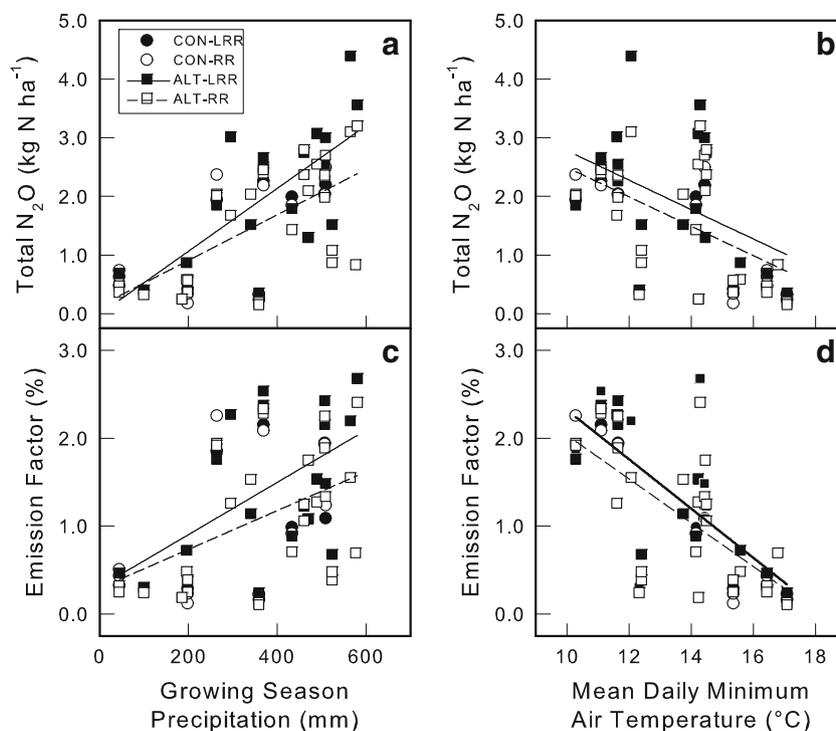
**Fig. 4** Tillage and stover removal treatments did not affect the correlation between growing season cumulative soil $CO_2$ emitted (Mg C ha$^{-1}$) and growing season precipitation (mm). Irrigation amounts were included in growing season precipitation values for Sites 6 and 8 to account for all water inputs. For all data, $y=0.0048x+1.4401$, $R^2=0.34$, $P<0.0001$

tillage). Conservation tillage is a key strategy for mitigating $CO_2$ emissions from agriculture [5, 36] and has been shown to build soil organic carbon (SOC) in surface soils in the central US Corn Belt [27]. Net increases in SOC under no-till practices can also be accompanied by higher soil $CO_2$ emissions due to greater microbial activity in surface layers [14, 34]. Accumulation of SOC and reduced soil disturbance in conservation tillage systems can also increase soil water content and create microsite conditions more favorable for denitrification [34, 47], a microbially mediated process that contributes significantly to agricultural soil $N_2O$ emissions [37]. Other factors including climate regime, duration of adoption, and N fertilizer placement can influence the effect of ALT practices on $N_2O$ emissions [55].

Removal of corn stover decreased plant C and N inputs into soils, limiting substrate availability of labile C and N sources for microbial use and decreased subsequent emissions of $CO_2$ and $N_2O$. Moderate or high levels of corn stover removal (MRR and HRR) resulted in small but marginally significant decreases in the total growing season soil emissions of $CO_2$ compared with the no stover removal treatment (LRR) when evaluated over all sites and all years. Stover removal also tended to interact with tillage such that only ALT soils showed a decrease in the total direct $N_2O$ emissions when stover was removed

cumulative growing season soil $CO_2$ emissions and tended to decrease soil $N_2O$ emissions compared with alternative conservation tillage management (ALT) (i.e., strip tillage and no



**Fig. 5** Correlations between growing season cumulative soil $N_2O$ emissions and emission factors with environmental conditions, (**a**) the total growing season $N_2O$–N emitted versus the total growing season precipitation (ALT: LRR, $y=0.005x-0.008$, $R^2=0.52$, $P=0.0001$; RR, $y=0.004x+0.13$, $R^2=0.40$, $P=0.0003$); (**b**) the total $N_2O$–N emitted versus the average daily minimum air temperature during the growing season (ALT: LRR, $y=-0.25x+5.29$, $R^2=0.19$, $P=0.05$; RR, $y=-0.25x+5.00$,

$R^2=0.27$, $P=0.004$); (**c**) emission factor versus the total growing season precipitation (ALT: LRR, $y=0.003x+0.31$, $R^2=0.30$, $P=0.008$; RR, $y=0.002x+0.29$, $R^2=0.21$, $P=0.0144$); and (**d**) emission factor versus the average daily minimum air temperature during the growing season (ALT: LRR, $y=-0.28x+5.12$, $R^2=0.43$, $P=0.0009$; RR, $y=-0.25x+4.52$, $R^2=0.44$, $P=0.0001$). Irrigation amounts were included in growing season precipitation values for Sites 6 and 8 to account for all water inputs

compared with no removal. In other words, the effects of stover removal on the total growing season soil $N_2O$ emissions were diminished by the effect of conventional tillage. Retention of corn stover decreases evaporation and increases infiltration [4, 44, 45], leading to higher soil water availability and soil stability [1, 33, 61]. As a result of greater resource availability (water, energy and nutrients), improvements in soil microsite conditions also likely contributed to greater GHG emissions from ALT soils when corn stover was retained.

Although the overall effect of stover removal was to decrease soil GHG emissions, inter-annual variability in regional weather affected whether relative residue removal effects (% difference from LRR) were positive or negative for any given year. Expected negative residue removal effects on direct emissions of $CO_2$, and to a lesser extent $N_2O$, in both tillage treatments were measured in 2010. For conventionally tilled soils, significant positive effects of stover removal on soil $CO_2$ in 2012 and $N_2O$ emissions in 2011–2012 appeared to reflect drier-than-normal conditions that began in 2011 and led into the prolonged extreme drought of 2012 that disproportionately affected the US Corn Belt [51].

The effect of environmental conditions on direct emissions of $CO_2$ and $N_2O$ over the growing season was supported by observed relationships with precipitation inputs (which included irrigation amounts at Sites 6 and 8) and air temperature. Soil water availability and temperature have been found to be positively correlated with $CO_2$ and $N_2O$ emissions from grain production systems [2, 13, 38]. In the current survey, direct emissions of both $CO_2$ and $N_2O$ increased as the amount of the total growing season precipitation increased. No significant relationships, however, were observed between average daily maximum air temperature and the total $CO_2$ or $N_2O$ emissions during the growing season across the nine sites included in this study. Instead, average daily minimum air temperature was negatively correlated with cumulative growing season $N_2O$ emissions. In contrast to the previously referenced studies, the observed negative temperature relationship appeared to correspond with the 2011–2012 drought that affected the US Corn Belt. Under the extreme drought conditions that developed, persistent high daytime air temperatures caused the average minimum daily temperature to also increase, resulting in the apparent negative temperature relationship for direct $N_2O$ emissions over the growing season. For both gases, the sensitivity of soil responses tended to be greater when corn stover was retained (i.e., higher values of regression slopes), again suggesting that resource availability and conditions in soils with residue cover enhanced microbial responses (both positive and negative) to environmental conditions.

Emission factors (EF) estimate direct $N_2O$ emissions as a percentage of fertilizer N applied [7, 9, 31], and at sufficiently large scales, modeled $N_2O$ emissions tend to converge with those estimated using the IPCC default EF value [10, 12]. For the nine sites in this regional survey, the absence of any correlation between N fertilization rate and emission factor (EF) across sites over the 5-year measurement period supports IPCC assumptions that applying an EF is a robust approach for estimating direct $N_2O$ emissions. Emission factors calculated in this study across all sites, years, and management approximated the 1.00 % EF in the 2006 IPCC guidelines [9]. When N fertilizer application rates exceed plant N demand, residual fertilizer N can lead to greater $N_2O$ emissions and results in an exponential relationship between N application rate and $N_2O$, emphasizing that other processes such as plant N uptake can significantly affect the direction, magnitude, and shape of this relationship [54]. In this study, results showing no relationship between N application rates and direct $N_2O$ emissions indicated that N was not applied in excess and that site-specific N management practices were appropriate. Negative correlations between EF and total growing season precipitation (including irrigation inputs) and mean daily minimum temperature suggest that environmental conditions will affect direct $N_2O$ emissions and shift EF values when N is applied at site-appropriate rates.

## Conclusion

Agricultural management plays an important role in the mitigation of rising atmospheric greenhouse gas levels by promoting C sequestration in cropland soils and biomass and by potentially reducing GHG emissions. In this survey of nine sites across five states in the US Corn Belt, field measurements of cumulative growing season GHG emitted directly from soils demonstrated that (1) conventional tillage (CON) increased soil $CO_2$ emissions and tended to decrease soil $N_2O$ emissions compared with alternative conservation tillage (ALT); (2) corn stover removal generally lead to reduced GHG emissions, particularly under ALT management; and (3) regionally scaled emission factors for direct emissions of $N_2O$ over the growing season as a percentage of N fertilizer applied could be predicted by environmental conditions such as the total growing season precipitation and annual daily minimum temperature. The use of ALT practices when corn stover is removed can ameliorate potential soil erosion issues as well as decrease direct GHG emissions. Initial estimates indicate that removing 30 % of stover produced in intensive no-till corn production areas in the US Corn Belt could adequately support annual bioenergy feedstock demand of ~100 million Mg of stover [17]. Updated estimates suggest that stover removal rates could vary from 15 to 50 % under ALT practices [52]. Optimal stover removal rates, however, will depend on site specific management decisions and environmental conditions and is the subject of an ongoing research.

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