

EFFECTS OF MAIZE RESIDUE REMOVAL ON SOIL QUALITY AND GREENHOUSE GAS EMISSIONS IN IOWA

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Abstract

Maize residue is an important component of soil carbon (C) budget and development of soil quality indices. However, maize residue in recent years has been considered as another potential feedstock source for ethanol production in addition to or alternative to maize grain. The current emphasis on using maize residue as a feedstock for future ethanol production presents a soil and environmental challenge that needs to be addressed. Additionally, there have been few studies that examine greenhouse gas (GHG) emissions from agriculture soils under different residue removal rates, various N rates, and tillage practices and their interactions effects on soil C dynamics and GHG emissions. The objective of this study was to examine potential changes in soil C sequestration and GHG emissions under no-tillage (NT) and conventional tillage (CT) and nitrogen fertilization rates of 0, 170, and 280 kg N ha⁻¹ with variable rates of residue removal (0, 50, and 100%). Field studies were established in fall of 2008 on two sites, a poorly-drained soil at the Iowa State University Agronomy Research Farm (North central, IA) and a well-drained soil at the Armstrong Research and Demonstration Farm (Southwest, IA) in continuous maize. After two years of residue removal, soil C, water infiltrations, aggregate stability and bulk density was measured. After every harvest, crop measurements included maize grain yield, above-ground biomass, and root-biomass. Weekly measurements of soil surface CO₂, and N₂O emissions coupled with soil moisture and temperatures were collected. Additionally, C budgets were calculated for different treatments. These measurements provide insights on whether these management practices resulted in net gains or losses of C sequestration and atmospheric CO₂. Findings suggest that sites for this study were a significant net sink for atmospheric CO₂-C, even when maize residue was removed and under different tillage and N fertilization (when applied) management. Applications of N had the largest effect on N₂O-N emissions, where greater N₂O-N emission was associated with high N rates. In addition, significant declines in soil quality properties were observed after only two years of residue removal. The severity of soil quality deterioration due to residue removal varied with different tillage and N managements.

Keywords: N₂O, CO₂, soil carbon, tillage

Introduction

Maize residue left on the surface after harvest is a potential feedstock source for bioethanol production which can contribute to the reduction of fossil fuel use and net greenhouse gas (GHG) emissions (1). Although, it is currently more expensive to produce ethanol from lignocellulosics than from starches, it is projected that improvements in technology and scale of production will improve these costs (2). It is projected that lignocellulosic ethanol production will become a viable option and could create an annual market for crop residue from approximately 143 million tons to 583 – 805 million tons (3).

The removal of crop residue, however, may require farmers to change their current tillage and fertilization practices to prevent against potential soil erosion and other soil and environmental negative effects. Crop residues play a significant role in improving soil physical and chemical properties that are essential in controlling wind and water erosion, which ultimately reduce sediment and other contaminant transport to water bodies (4) and is critical for replenishing soil organic carbon (SOC) (5). In addition, agriculture accounts for 10-20 % of the total anthropogenic GHG emissions, but is responsible for 58% of the total anthropogenic N₂O emissions (6). Since current agriculture practices are responsible for large proportion of N₂O emissions, changes in management practices can have significant

changes in N₂O and CO₂ emissions levels. More research is needed to further understand the key sources and mechanisms responsible for generating N₂O and CO₂ emissions in agriculture systems for the development of future mitigation strategies.

One such strategy is the use of agriculture land for the mitigation of elevated atmospheric CO₂ levels through the sequestration of SOC. Soils contain the largest active terrestrial C pool (3,150 Pg C), and contribute 10 times more CO₂ (75 Pg C yr⁻¹ from soil respiration) to the atmosphere than fossil fuel combustion(7). The risk of global warming and interest in adoption of the Kyoto Protocol has increased the attention of the scientific community on SOC sequestration in terrestrial ecosystems. However, precise measurement and verification of the amount of C sequestered in the soil have proven to be difficult. The usage of SOC depleted land as a sink for some of the excess CO₂ appears to be a practical and cost effective method of reducing atmospheric CO₂ levels (8). The basic thought behind reducing atmospheric CO₂ emissions through SOC sequestration by changes in land use relies on the restoration of original native C levels. The magnitude of SOC storage depends on a range of factors such as; soil type, land use, annual input of C from plants, plant type, and the severity of degradation.

The objectives of this study were to address these soil and air quality concerns by assessing the impacts of crop residue removal under different N fertilization rates, and tillage practices, to see how much (if any), residue can be removed and still sustain high soil and crop productivity.

Materials and Methods

Study Description

Study was established in fall of 2008 on a Nicollet-Canisteo association soil at Iowa State University Agronomy Research Farm west of Ames, IA (42.4°N; 95.5°W) and a Marshall soil association at Armstrong Research and Demonstration Farm southwest of Atlantic, IA (41.3°N; 95.1°W) in continuous maize. Both sites were previously in maize/soybean rotation under conventional tillage (CT, chisel plow in fall and field cultivation in spring). Typical agronomic rates of 170 kg N ha⁻¹ were applied in maize. There were three treatments; the main treatment was tillage practice (no-till and chisel plow in fall, field cultivation in spring), which

was split into three different residue removal rates (0, 50, and 100%) which will then was further split into six N fertilization rate treatments of 0, 60, 120, 170, 225, and 280 kg N ha⁻¹. Source of N was urea and ammonium nitrate (UAN) which was side dressed in May after planting. The experiment design for this study was randomized complete block with split-split arrangement with three replications. In general, data were analyzed using the general linear procedure (GLM) (9). Statistical significance was evaluated at P ≤ 0.1.

Soil Organic Carbon and Bulk Density

Soil samples were collected every August/September since 2008. Ten to twelve 1.85 cm diameter soil cores were randomly taken to a depth of 15 cm in each plot and then homogenized into a single sample. Samples were 2 mm sieved and then air dried before being analyzed for total organic carbon (TOC) by dry combustion using a LECO CN analyzer (LECO, St. Joseph, MI). Bulk density (p_b, cm⁻³) samples were collected using a 1.85 cm diameter soil probe for each plot at depths of 0 to 7.5 and 7.5 to 15 cm, which were then oven dried at 105°C for 24 h and weighed. Then, p_b (g cm⁻³) was calculated as the dried soil mass divided by the soil core volume. The average of the two depths was used. Concentrations of TOC (g kg⁻¹ dry soil) were multiplied by mean p_b values and soil depth to convert concentrations to mass per area basis (Mg ha⁻¹) for comparing TOC stocks of different management practices.

Water Infiltration Rates

Water infiltration rates were determined in August after two years of residue removal using a Cornell Sprinkle Infiltrometer (Cornell University, Ithaca NY). This system consisted of a portable rainfall simulator placed on a single 24.1 cm inner diameter ring inserted 7 cm into the soil and aboveground vegetation was clipped. The ring was equipped with an overflow tube to determine the time to runoff and runoff rate. Rainfall simulator intensity rates of 0.42 cm min⁻¹ were used. Every three minutes, runoff was measured until steady water infiltration occurred. Water infiltration (i_t) was calculated by using the following equation:

$$i_t = r - r_{ot} \quad (1)$$

where, r is rainfall intensity and r_{ot} is surface runoff.

Water Stable Aggregate Size Distributions

Soil samples for water stable aggregate size (WSA) distributions were taken using a 7.6 cm diameter golf course hole cutter to a soil depth of 15 cm for each plot in August after two years of residue removal. Soil samples were then gently passed through 8 mm sieve to remove any undesirable plant residue and rocks. Soil samples were then air dried and stored for analysis. The WSA size distributions were determined following the procedure from Kemper and Rosenau (10) in deionized water at 21°C. By lowering and then raising the sieves with a stroke length of 20 mm and a frequency of 90 strokes min⁻¹, using a custom made sieving machine where 20 cm diameter sieves could fit. Seven aggregate size fractions were collected, >4, 2 to 4, 1 to 2, 0.5 to 1, 0.25 to 0.5, and 0.053 to 0.25 mm. For the remaining sample that passed through the last sieve, 0.053 mm, it was considered <0.053 mm. Following wet sieving, soil sample of each aggregate fraction was transferred by washing it into tubs and then oven dried at 65°C until all water was evaporated. Dry weight of each fraction size was recorded. The aggregate stability for each soil sample was then expressed by mean weight diameter (MWD):

$$MWD = \sum_{i=1}^7 x_i w_i \quad (2)$$

where, x_i is the mean diameter of size fraction, and w_i is the weight of each size fraction of aggregates of total sample.

Soil Surface CO₂ and N₂O Efflux

During the growing season from April to October, weekly soil surface CO₂ efflux readings coupled with soil moisture (TRIME-FM Time Domain Reflectometry, Mesa Corp., Medfield, MA) and temperature (thermometer attached to LI-COR 6400) at 5-cm soil depth were taken in each plot using a portable infrared CO₂ gas analyzer (LI-COR 6400, LI-COR, Inc., Lincoln, NE) with a soil respiration chamber. Readings were taken between 0800 and 1100 h to approximate the 24 h mean soil surface CO₂ efflux. During the non-growing season, bi-weekly or monthly readings were taken. Soil N₂O efflux was measured weekly from April to October, biweekly during March and November, and monthly in December, January, and February following sampling protocol of GRACenet Chamber-based Trace Gas Flux

Measurement (2003). Two polyvinyl chloride (PVC) rings (30 cm diameter and 10 cm tall) were installed in each plot to a depth of approximately 6 cm. In each plot one ring was placed directly in the plant row. The other ring was placed between plant rows on top of UAN band. Flux measurements were performed by placing vented chambers (30 cm diameter and 10 cm tall) on the PVC rings and collecting gas samples 0, 30, and 60 min following chamber deployment. At each time point chamber headspace gas samples (10 mL) were collected with polypropylene syringes and immediately injected into evacuated glass vials (6 mL) fit with butyl rubber stoppers. Nitrous oxide concentrations in samples were determined with a gas chromatography instrument (Model GC17A; Shimadzu, Kyoto, Japan) equipped with a ⁶³Ni electron capture detector and a stainless steel column (0.3175 cm diameter and 74.54 cm long) with PorapakQ (80–100 mesh).

Estimation of Carbon Budget

The carbon budget for each site was estimated by measuring net ecosystem productivity (NEP):

$$NEP = (ANPP + BNPP) - R_h \quad (3)$$

where, ANPP is potential C content input from aboveground plant biomass, BNPP is potential C content input from belowground root biomass, RT is root turnover, and R_h is C loss as CO₂ due to heterotrophic respiration (11).

Results and Discussion

Residue Removal effects on Total Soil Carbon

After three years of residue removal, significant decreases in soil TOC were observed, although varied with tillage system (Figure 1). In the North central site, residue removal of 50 % resulted in approximately 2.5 Mg C ha⁻¹ loss in CT, however in NT, there was not a significant change in TOC. When 100 % of the residue was removed, there were significant decreases in TOC, although not significantly different from 50 % removal in CT. Adoption of NT reduced significant losses of TOC by 1.6 Mg C ha⁻¹, when 100 % of the residue was removed compared to CT. There were slight increases in TOC when no residue was removed in both CT and NT, but not significantly different from zero change in TOC. Changes in TOC and variability in the Southwest site were not as

great as in the North central site. Under CT, decreases of TOC of 0.38 and 0.60 Mg C ha⁻¹ were observed with 50 and 100 % residue removal respectively. Under NT, significant decreases in TOC were only observed when 100 % of the residue was removed at 0.61 Mg C ha⁻¹.

There were slight increases in TOC when no residue was removed in both CT and NT. Increasing N fertilization in general reduced losses in TOC when residue was removed, but was not significant (data not shown).

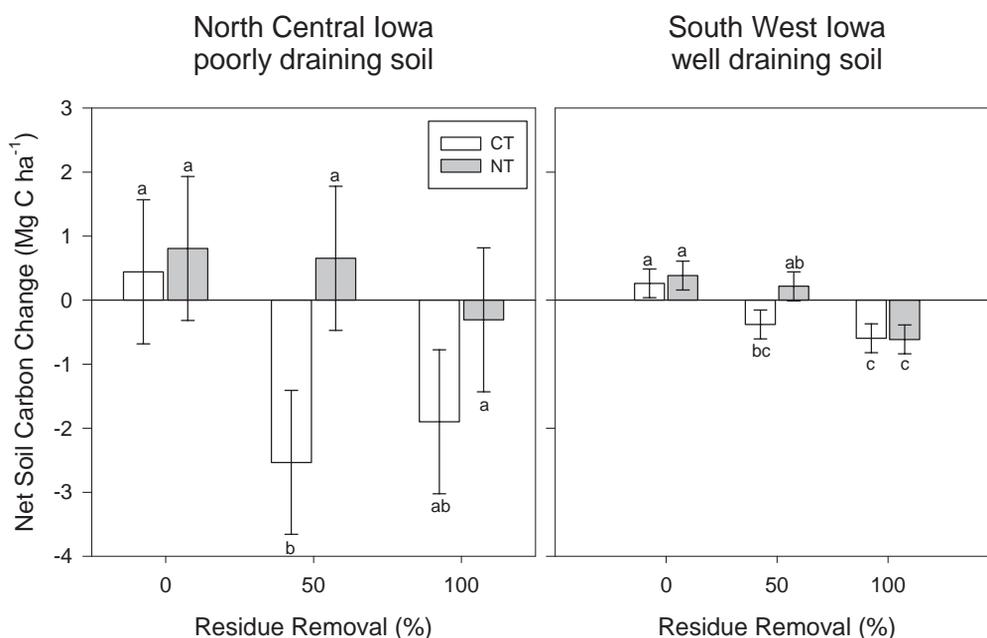


Figure 1. Total soil carbon as affected by three years of residue removal for poorly and well-drained soils in the top 15 cm soil depth. Different letters indicate significant difference between residue removal at p=0.1 with standard error bars.

Residue Removal effects on Potential Carbon Sequestration

A carbon budget approach by estimating net ecosystem productivity was used to determine if residue removal under different N rates and tillage management had net gains or losses in potential C sequestration (Figure 2.). Results from the C budget show that only under high N rates and no-till with very little residue removal, were there potential gains in C sequestration in both poorly and well-drained soils. In the poorly-drained soil site, approximately 42 % of the residue can be removed without having a net loss in potential C sequestration under 280 kg N ha⁻¹ N rate. In the well-drained soil site, only approximately 22 % of the residue can be removed

without having a net loss in potential C sequestration under 280 kg N ha⁻¹ N rate. Under typical N rates in Iowa (170 kg N ha⁻¹) with continuous maize, even when no residue was removed and under no-till, it was observed a potential net losses of C in the well-drained soil and no net changes in soil C in the poorly-drained soil. Furthermore, potential losses of C sequestration were greatly increased when residue was removed. The adoption of NT did lessen the potential losses of C sequestration due to residue removal in the poorly-drained soil site, but not in the well-drained soil site. Potential losses of SOC sequestration were greatest under management practice with high residue removal, no N application, and CT.

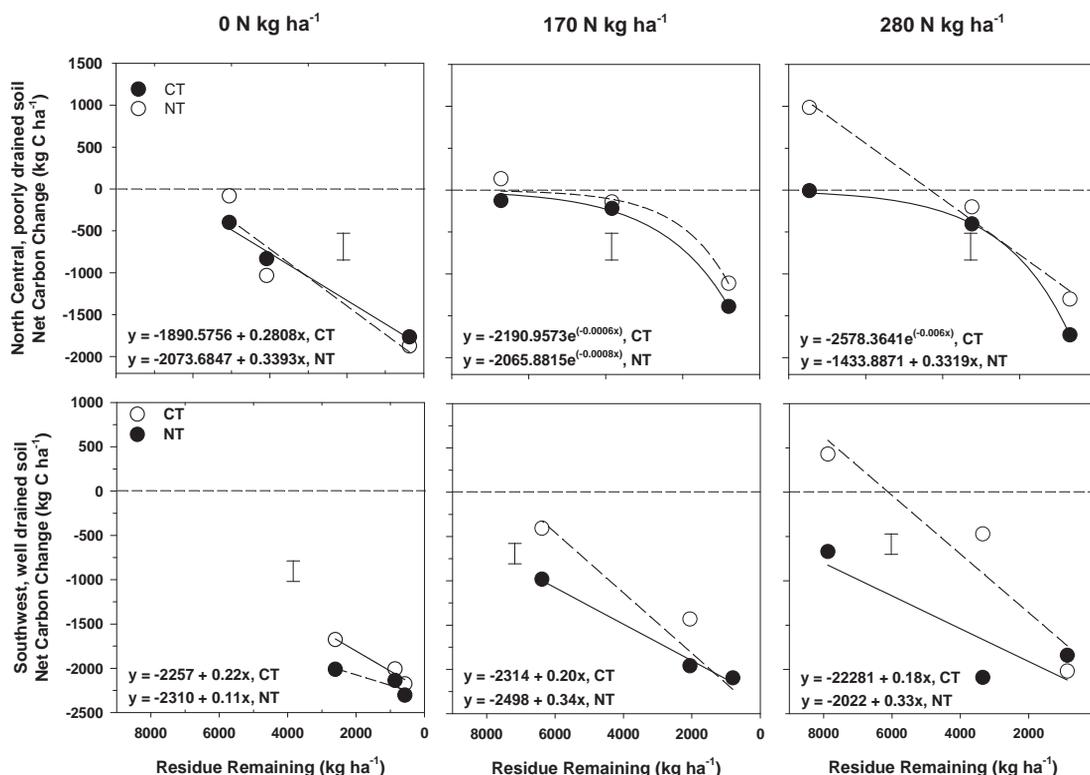


Figure 2. Potential net carbon change (above- and below-ground biomass minus losses from microbial respiration) at the 15 cm soil depth.

Residue Removal effects on Soil Physical Properties

After two years of residue removal and under different N rates and tillage practices, there were significant differences in p_b compared to the baseline year in 2008 for both sites (Figure 3). In the poorly-drained soil site, p_b was significantly greater when 100% of the residue was removed under both tillage systems. Similar results were observed in the well-drained soil site, except there were also significant increases in p_b under no-till when 50% of the residue was removed. In addition, the lack of N application also significantly increased p_b under both sites and tillage practices, where significant reduction

in root biomass took place which has direct impact on soil structure and p_b (data not shown). Maize residue removal also negatively impacted soil aggregation after only two years (Figure 4). In general, the greatest soil aggregation occurred under no-till and when no residue was removed. Significant decreases in soil aggregation occurred when 50% of residue was removed compared to 0%, and tended to further decrease with 100% residue removal, although not significantly different. The addition of higher N rates did not appear to significantly affect soil aggregation. However when no N was applied, significant decreases in soil aggregation were observed.

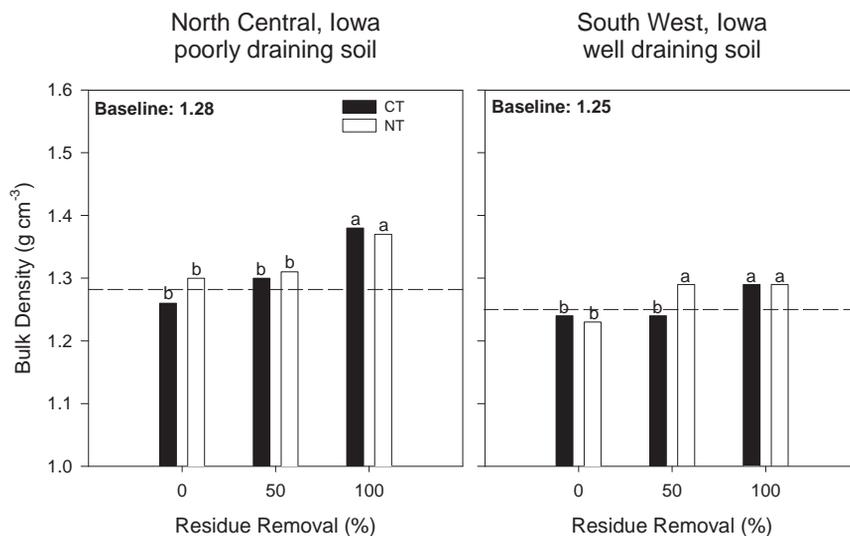


Figure 3. Soil bulk density as affected by two years of residue removal and tillage systems for poorly and well-drained soils. Different letters indicate significant difference between residue removal and tillage at p=0.1.

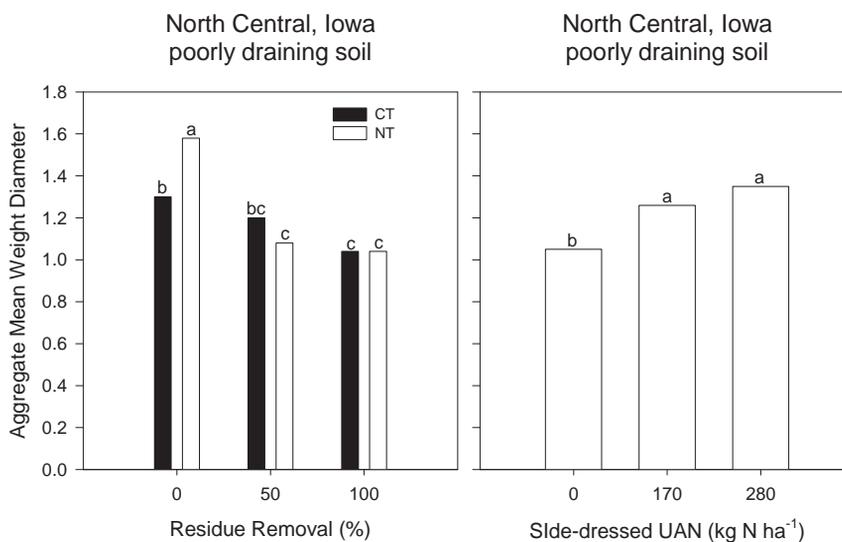


Figure 4. Aggregate mean weight diameter as affected by two years of residue removal, tillage and nitrogen rate systems for a poorly-drained soil site. Different letters indicate significant difference between residue removal, tillage and nitrogen rate at p=0.1.

The results of higher p_0 and lower soil aggregation due to residue removal and subsequently reduced steady water infiltration rates (SWIR) in the well-drained soil site only (Figure 5). These decreases in SWIR were only observed under chisel plow and 100% residue removal. Consequently, the adoption of no-till did help maintain SWIR when maize residue was removed. In the poorly-drained soil site, SWIR were already low, with only 17% of the water infiltrated into the soil and 83% as runoff when simulated rainfall rates of 0.42 cm per minute were used.

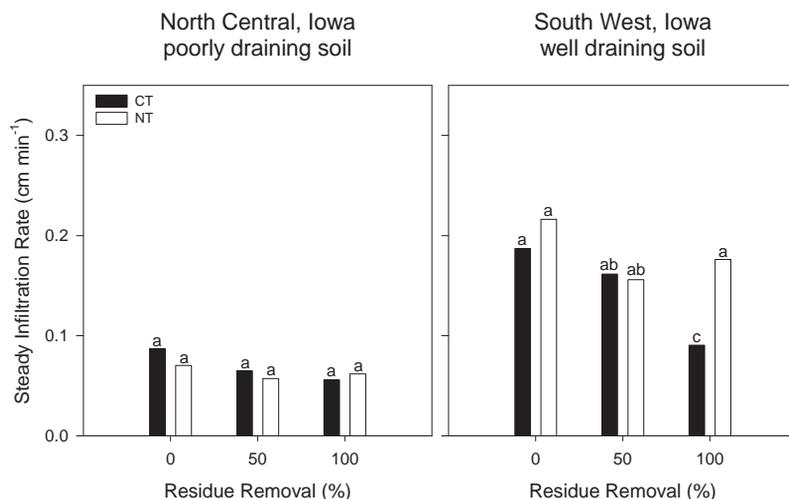


Figure 5. Steady water infiltration rates as affected by residue removal and tillage for poorly and well-drained soil sites. Different letters indicate significant difference between residue removal and tillage at $p=0.1$.

Residue Removal effects on Greenhouse Gas Emissions

Sites for this study were a significant net sink for atmospheric CO₂-C, even when maize residue was removed and under different tillage and N fertilization (when applied) management (Figure 6). Potential C losses from microbial decomposition were greater under CT compared to NT, especially during early in the growing season (data not shown). During this period, soil temperatures in the top 15 cm were greater in CT compared to NT, until the maize canopy completely covered the soil surface, resulting in no difference in soil temperature or slightly greater in NT. Emissions of N₂O-N in 2009 and 2010 were also slightly greater in CT compared to NT (Figure 7). This was a bit surprising since current literature cites that NT systems typically have higher N₂O-N emissions due to soils being more frequent to be under anaerobic conditions compared to CT systems. However for this study in 2009 and 2010, both years were very wet, which may explain why CT treatments had higher N₂O-N emissions. In general, removing maize residue lowered N₂O-N emissions, but was only significantly different when the entire maize residue was removed, due to soils having less water content. Applications of N had the largest effect on N₂O-N emissions, where greater N₂O-N emission was associated with high N rates (data not shown).

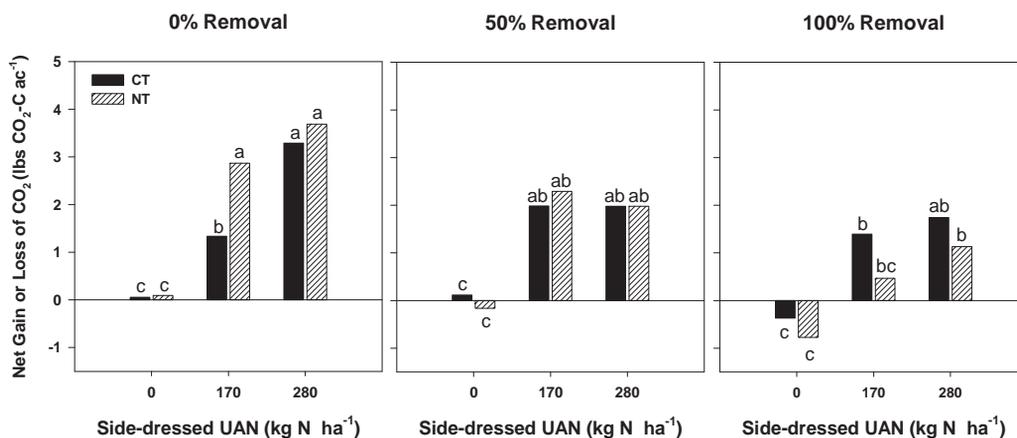


Figure 6. Potential sink or source for Atmospheric CO₂-C. Estimated by measuring CO₂-C sequestered by above ground biomass, grain, and root biomass and losses from microbial decomposition. Positive values indicate a sink for atmospheric CO₂-C. Different letters indicate significant difference between residue removal and tillage at $p=0.1$.

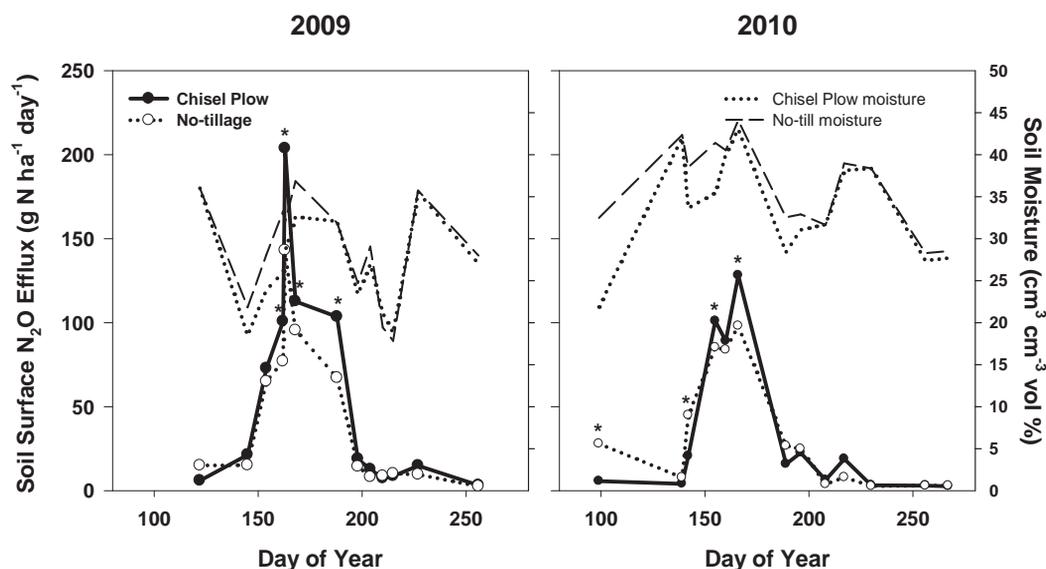


Figure 7. Seasonal N_2O emissions under different tillage management in 2009 and 2010 for the poorly drained soil site in Ames.

Conclusions

After three years of maize residue removal, significant decreases in soil TOC varied with tillage and N fertilization management. The largest decreases in TOC occurred under CT when 50% or greater of the residue was removed in both poorly and well-drained soils. Decreases in TOC were greater in the poorly-drained soil than the well-drained soil. Adoption of NT in general reduce significant losses of TOC when 50 % of the residue was removed in both sites, however significant decreases similar to CT were observed when 100% of residue was removed. Results from a C budget show that the adoption of NT and increased N rates did reduce some of the C losses due to residue removal. However, only with adoption of NT and N rates greater than 170 kg N ha⁻¹ with very little residue removed, were there potential increases in soil C. In the poorly drained soil site, approximately 42% of maize residue can be removed without seeing a net loss in potential C sequestration under 280 kg ha⁻¹ N rate. In the well-drained site, only approximately 22% of the residue can be removed without having a net loss in potential C sequestration. Significant short term effects (2 years) of residue removal on soil physical properties were observed. Increases of p_b were observed with 100% residue removal regardless of tillage and increased N fertilization

rate. Furthermore, decreases in soil aggregation were observed with residue removal, regardless of tillage and increased N fertilization rate. Subsequently, SWIR were significantly reduced in the well-drained soil site. Sites for this study were a significant net sink for atmospheric CO₂-C, even when maize residue was removed and under different tillage and N fertilization (when applied) management. Applications of N had the largest effect on N₂O-N emissions, where greater N₂O-N emission was associated with high N rates. In general, the adoption of NT over chisel plow and increased rates of N fertilization did offset some of the negative impacts of residue removal, but potential losses of SOC sequestration and deterioration of soil physical properties were still observed.

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