

# In-Field Management Practices for Mitigating Soil CO<sub>2</sub> and CH<sub>4</sub> Fluxes under Corn (*Zea mays*) Production System in Middle Tennessee

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## Abstract

The United States continues to be the largest corn producer in the world. How to maximize corn yield and at the same time reduce greenhouse gas emissions, is becoming a challenging effort for growers and researchers. As a result, our understanding of the responses of soil CO<sub>2</sub> and CH<sub>4</sub> fluxes to agricultural practices in cornfields is still limited. We conducted a 3-yr cornfield experiment to study the responses of soil CO<sub>2</sub> and CH<sub>4</sub> fluxes to various agricultural practices in middle Tennessee. The agricultural practices included no-tillage + regular applications of urea ammonium nitrate (NT-URAN); no-tillage + regular applications of URAN + denitrification inhibitor (NT-inhibitor); no-tillage + regular applications of URAN + biochar (NT-biochar); no-tillage + 20% applications of URAN + chicken litter (NT-litter); no-tillage + split applications of URAN (NT-split); and conventional tillage + regular applications of URAN as a control (CT-URAN). A randomized complete block design was used with six replications. The same amount of fertilizer equivalent to 217 kg·N·ha<sup>-1</sup> was applied to all of the experimental plots. The results showed that improved fertilizer and soil management, except the NT-biochar treatment significantly increased soil CO<sub>2</sub> flux as compared to the conventional tillage (CT-URAN, 487.05 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>). Soil CO<sub>2</sub> flux increased exponentially with soil temperature (T < 30°C), and linearly with soil moisture (T ≥ 30°C) in all treatments. Across all treatments, soil CO<sub>2</sub> flux tended to be positively related to corn yield and/or soil moisture. Soil CH<sub>4</sub> flux increased linearly with soil moisture in all treatments. Improved fertilizer and soil management did not alter soil CH<sub>4</sub> flux, but significantly affected its moisture sensi-

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**tivity. Our results indicated that agricultural practices enhancing corn yield may also result in a net increase in carbon emissions from soil, hence reducing the potential of carbon sequestration in croplands.**

## Keywords

**Tillage, Fertilizer Management, Soil CO<sub>2</sub> Flux, Soil CH<sub>4</sub> Flux, Greenhouse Gases**

## 1. Introduction

The potential increase in the concentrations of greenhouse gases (GHGs) in the atmosphere due to anthropogenic activities has been linked to the observed climate change [1]. Carbon dioxide (CO<sub>2</sub>) is the most important GHG, contributing 60% to the anthropogenic GHG effect [2]. Agricultural lands cover 37% of the Earth's land surface, and hold large reserves of carbon (C) in soil organic matter [1]. Historically, agriculture soils have lost more than 50 Pg C, mostly in the form of CO<sub>2</sub> emitting back into the atmosphere [3]. The issue of how to reduce soil C emissions in croplands while maintaining high crop yields has become an important task [4] [5]. In recent years many agricultural practices, such as no-tillage, alternative use of fertilizer sources or methods (e.g., manure, split applications), and soil management (e.g., use of denitrification inhibitor or biochar), have been proposed as effective ways to enhance crop production and hence sequester atmospheric CO<sub>2</sub> in soils [6].

However, whether C accumulation is in croplands or not, it depends largely on the trade-offs between the biomass C input and soil organic C decomposition [7]. Increase of crop growth that may result in high yield may also increase soil CO<sub>2</sub> flux from croplands, and as a result may weaken the potential of soil C sequestration [8] [9]. Soil CO<sub>2</sub> flux involves complex biological processes that are controlled by many environmental factors such as soil temperature and soil moisture [10]-[12]. Shifts of soil properties or microclimate following agricultural practices may influence CO<sub>2</sub> flux [13]-[15]. There are minimal supporting data on which agricultural practices are more effective in reducing soil CO<sub>2</sub> flux, especially with an increase in crop yields. Thus, a better understanding on the impacts of various agricultural practices on soil CO<sub>2</sub> flux is critical for sustainable agriculture and future climate change [1].

Methane (CH<sub>4</sub>) is another important GHG that contributes 15% to the anthropogenic GHG effect and has about 21 times the global warming potential of CO<sub>2</sub> [2]. Agriculture is believed to be responsible for about 50% of global CH<sub>4</sub> emission induced by human activity [16]. Methane is produced when organic C decomposition in oxygen-deprived conditions, notably from crop grown under flooded conditions [17]. The processes of CH<sub>4</sub> flux, including production, oxidation, and transport into the atmosphere are influenced by agricultural practices [18]-[21]. For instance, no-tillage reduces CH<sub>4</sub> emissions from paddy soils because soil conditions under no-tillage are more oxidative than those of conventional tillage [19] [20]. Applications of swine manure in a continuous corn cropping system result in net CH<sub>4</sub> emission, whereas similar plots receiving urea fertilizer are sinks of CH<sub>4</sub> in the eastern United States [21]. Similarly, biochar applications were reported to decrease emissions of CH<sub>4</sub> in many croplands [18]. However, several studies also reported a negligible difference of CH<sub>4</sub> flux under various agricultural practices, particularly in the cornfields [7] [14]. Consequently, the responses of soil CH<sub>4</sub> flux to agricultural practices in cornfields are still unclear.

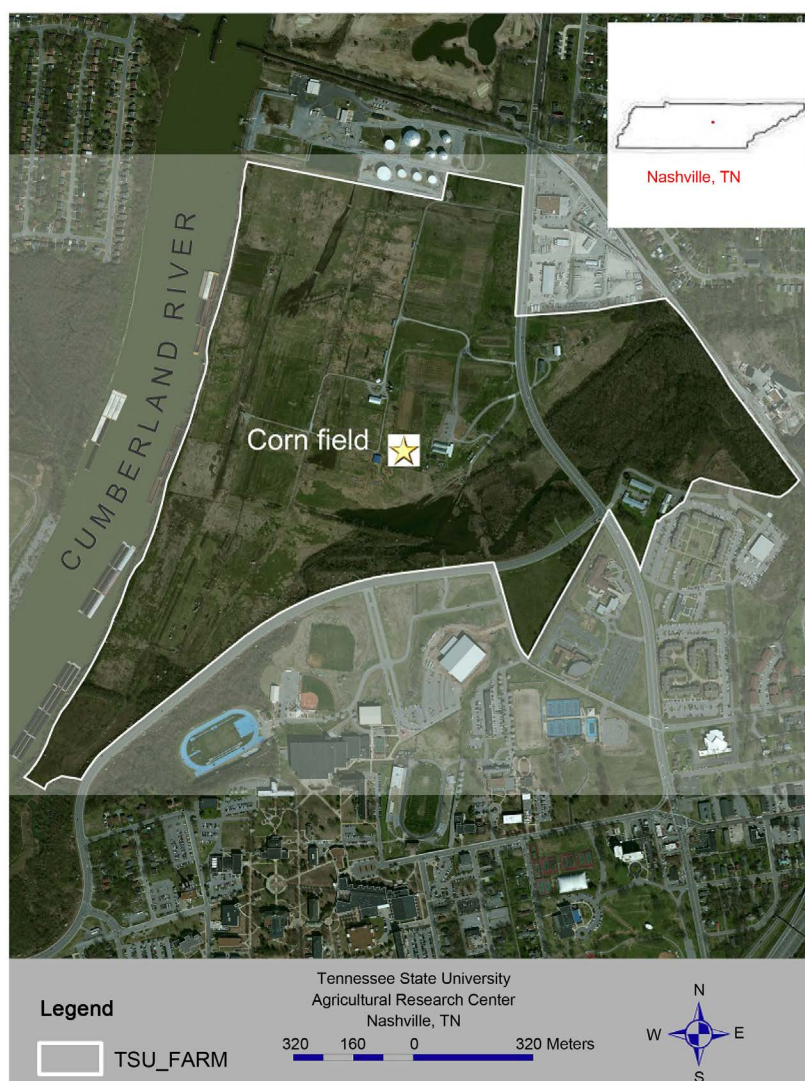
As previously stated the United States is the largest corn producer in the world and produces about 32% of the world's corn crop [22]. Demand for corn in the world is high due to the population increase and the rapidly rising feedstock demand as well as its use for biofuel production [23]. In order to satisfy this demand while maintaining low C emission, the effects of different agricultural management practices such as the use of no-tillage and alternative fertilizer sources or methods (e.g. manure and split applications), and soil (e.g. inhibitor and biochar applications) management on soil CO<sub>2</sub> and CH<sub>4</sub> fluxes in cornfields need to be investigated.

We conducted a 3-yr field scale experiment in middle Tennessee to examine the responses of soil CO<sub>2</sub> and CH<sub>4</sub> fluxes in corn plots to different agricultural practices. In order to mimic the current practice by farmers in middle Tennessee, we considered the treatment of conventional tillage + regular applications of urea ammonium nitrate as a control. The no-tillage and alternative fertilizer sources or methods (manure and split applications) and soil (inhibitor and biochar applications) management were considered as the other five treatments. All

treatments received the same equivalent unit of nitrogen ( $217 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ ) but in different forms and application scenarios. Previous work has demonstrated that improved fertilizer and soil management have significantly enhanced corn yield while decreasing soil  $\text{N}_2\text{O}$  emission [24]. The objectives of this study were: 1) to evaluate the effects of improved fertilizer and soil management on soil  $\text{CO}_2$  and  $\text{CH}_4$  fluxes; and 2) to relate the change of soil  $\text{CO}_2$  and  $\text{CH}_4$  fluxes to corn yield or microclimate under different treatments. The information generated from this study will be useful for corn cropping technique innovation and policy selection or decisions.

## 2. Materials and Methods

This study was conducted at the Tennessee State University Agricultural Research Center (Latitude  $36.12^\circ\text{N}$ , Longitude  $86.98^\circ\text{W}$ , elevation 127.6 m) in Nashville, Tennessee, USA (**Figure 1**). Climate in the region is warm humid temperate, with average annual temperature of  $15.1^\circ\text{C}$ , and total annual precipitation of 1199.5 mm (<http://weatherspark.com/averages/29787/Nashville-Tennessee-United-States>). The soil texture is Talbott silt clay loam with 25% sand, 55% silt, and 20% clay. The soil is slightly acidic ( $\text{pH} = 5.97$ ), with a bulk density of  $1.45 \text{ g}\cdot\text{cm}^{-3}$ . At the beginning of the experiments (May 4, 2012), both the soil organic carbon and total nitrogen were low with  $2.37$  and  $0.14 \text{ g}\cdot\text{kg}^{-1}$ , respectively and the concentrations of inorganic  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  in the upper 0 - 30 cm soil depth were  $10.15$  and  $24.33 \text{ mg}\cdot\text{kg}^{-1}$ , respectively.



**Figure 1.** A map of the Tennessee state university agricultural research center.

A total of 36 plots ( $5.5 \times 7.0$  m) was used in this experiment and 6 fertilizer or soil management were randomly assigned among each of 6 replicates. The experimental design and the agricultural management are described in details in Deng *et al.* (2015) [24]. Briefly, the treatments consisted of tillage and no-till as well as alternative fertilizer sources or methods (e.g. manure and split fertilizer applications) and soil treatment that included nitrogen inhibitor and incorporation of biochar. Referring in attempted to follow the cultural practice by farmers in middle Tennessee, we considered the treatment with conventional tillage + regular applications of aqueous urea ammonium nitrate (URAN-32-0-0 liquid N, containing 100% of total N) as the control (CT-URAN). The other five treatments were: no-tillage + regular applications of URAN (URAN-32-0-0 liquid N, 100%) (NT-URAN); no-tillage + applications of URAN (URAN-32-0-0 liquid N, 90%) + dicyandiamide (DCD) nitrification inhibitor with 67% N content (N in the inhibitor, 10%) (NT-inhibitor); no-tillage + regular applications of URAN (URAN-32-0-0 liquid N, 100%) + woodchips biochar with density of  $1.5 - 1.7 \text{ g}\cdot\text{cm}^{-3}$  and with an application rate of  $2.5 \text{ kg}\cdot\text{m}^{-2}$  (NT-biochar); no-tillage + applications of URAN (URAN-32-0-0 liquid N, 20%) + chicken litter (4% N, 3% P and 4% K) (N in the chicken litter, 80%) (NT-litter); and no-tillage + split applications of URAN (URAN-32-0-0 liquid N, 100%) (NT-split). All treatments were applied an equivalent units of  $217 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$  albeit in different forms and method to each experimental plot. At the planting, a total of  $99 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$  of chicken litter or URAN were applied to all the plots. During the experiment period, two applications of fertilizer-N were applied on jointing stage ( $39 \text{ kg N ha}^{-1}$ ) and heading stage ( $79 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ ) in the NT-URAN, NT-inhibitor, NT-biochar, NT-litter and CT-URAN plots, respectively. For the NT-split treatment, the applications of fertilizer-N were split by half, and therefore two additional fertilizer applications of 19.5 and  $39.5 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$  occurred (4 fertilizer applications in total).

In order to measure the fluxes of  $\text{CO}_2$  and  $\text{CH}_4$ , gas samples were collected after rainfall event(s) or fertilizer applications or every two weeks during the growing season over three years using static chambers. The construction of the static chambers and the gas sampling are described in details in Deng *et al.* (2015) [24]. All gas samples were stored in sealed vacuum vials and then they were sent for analysis via overnight mail to the University of California, Davis, California. Analysis was completed within 96 h of collection for  $\text{CO}_2$  and  $\text{CH}_4$  concentrations using gas chromatography (Model GC-2014, Shimadzu Scientific Instruments, Columbia, MD) equipped with a  $^{63}\text{Ni}$  electron capture detector. Instantaneous rates of soil  $\text{CO}_2$  and  $\text{CH}_4$  fluxes were calculated based on the rate of change in  $\text{CO}_2$  and  $\text{CH}_4$  concentration within the chamber; this was estimated as the slope of linear regression between concentration and time [25]. During each sampling, soil temperature was taken in-situ in each plot at 10 cm below the soil surface with a digital thermometer probe (Taylor Thermometers USA, model number Taylor 9842). In addition, volumetric soil moisture for 0 - 10 cm depth was also taken *in-situ* with a TDR probe interfaced with a digital display (Extech Instruments USA, model number MO750).

Repeated-measures Analysis of Variance (ANOVA) was used to determine the statistical significance of treatment, sampling year and their interactive effects on soil temperature, soil moisture, soil  $\text{CO}_2$  and  $\text{CH}_4$  fluxes in the corn field. Multiple comparisons (Least Significant Difference, LSD method) were conducted if significant effects of treatment, or sampling time were found. The relationships of soil  $\text{CO}_2$  or  $\text{CH}_4$  flux rates with soil temperature or moisture in each treatment were examined using model fitting. The *t*-test was used to determine the difference in the temperature sensitivity of  $\text{CO}_2$  flux and the moisture sensitivity of  $\text{CH}_4$  flux between the treatments. Simple regressions were also performed to correlate the soil  $\text{CO}_2$  and  $\text{CH}_4$  fluxes with corn yield, soil temperature or soil moisture across all the plots. All data analyses were carried out with the SPSS software Version 13.0 (SPSS Inc., Chicago, IL).

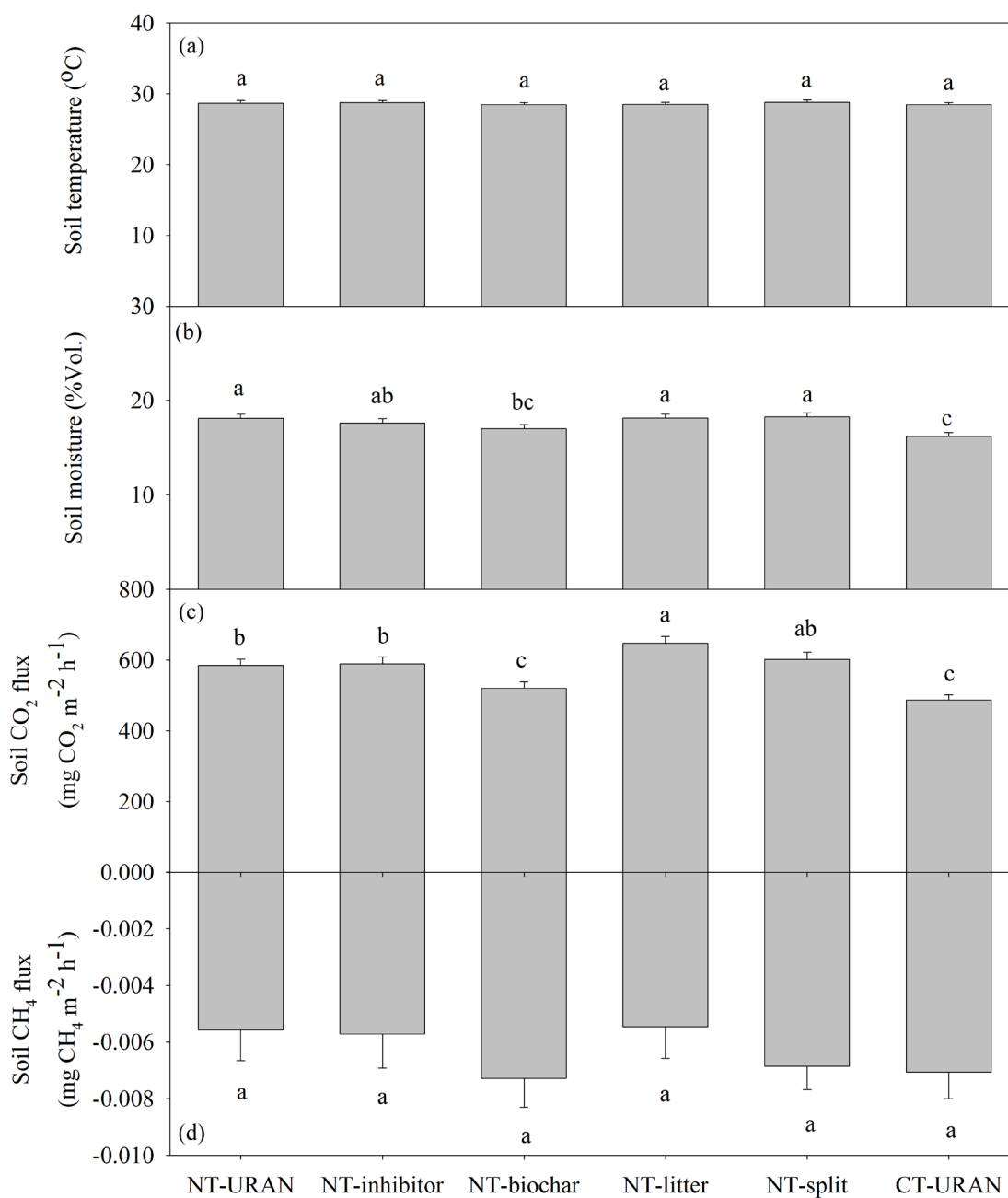
### 3. Results

#### 3.1. Microclimates

The seasonal patterns of soil temperature and moisture were consistent with those of air temperature and rainfall. Across all treatments, seasonal soil temperature ranged from  $18.2^\circ\text{C}$  to  $35.4^\circ\text{C}$ , and seasonal soil moisture ranged from 5.8% to 24.4% Vol. Treatments did not significantly alter soil temperature (Figure 2(a)), but significantly affected soil moisture (Table 1; Figure 2(b)). Soil moistures in the CT-URAN and NT-biochar treatments were significantly lower than those in other treatments (Figure 2(b)). Soil moistures were 18.0%, 17.9%, 17.0%, 18.1%, 18.1% and 16.2% Vol. in the NT-URAN, NT-inhibitor, NT-biochar, NT-litter, NT-split and CT-URAN treatments, respectively (Figure 2(b)).

**Table 1.** Significance of the effects of treatment, sampling year and their interactions on soil temperature, soil moisture, soil CO<sub>2</sub> and CH<sub>4</sub> fluxes based on repeated measures ANOVA. Numbers are F-values. Asterisks indicate the level of significance (\* $p < 0.05$ , \*\* $p < 0.01$ ).

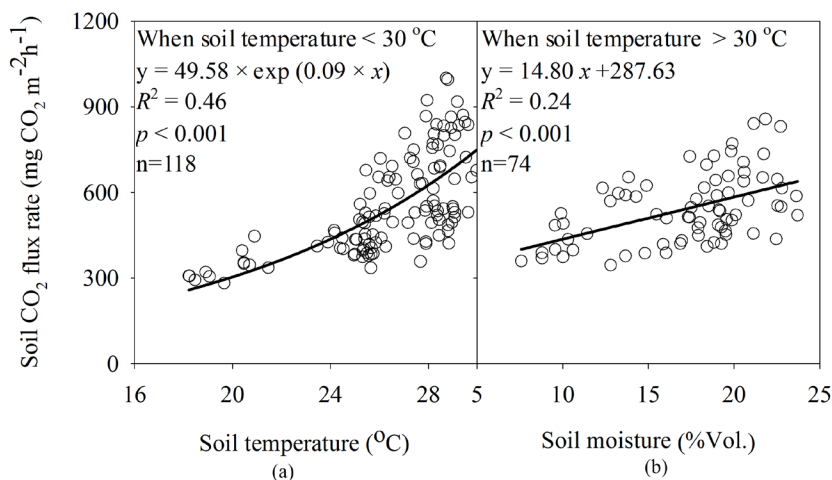
Source	Soil temperature	Soil moisture	Soil CO <sub>2</sub> flux	Soil CH <sub>4</sub> flux
Treatment	0.10	2.91*	8.70**	0.20
Year	36.92**	5.04**	6.74**	4.83**
Treatment × year	0.49	2.55*	0.11	0.73



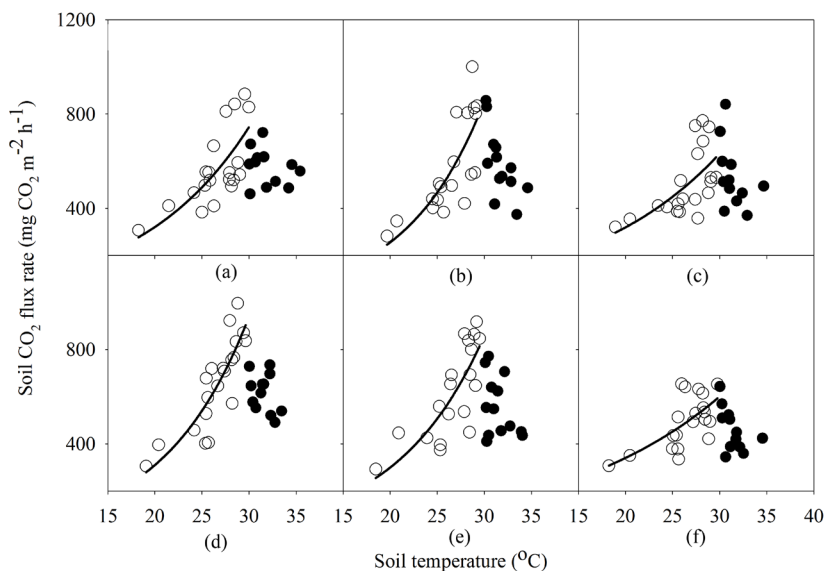
**Figure 2.** Average values of soil temperature (a), soil moisture (b), soil CO<sub>2</sub> and CH<sub>4</sub> fluxes (c) (d) under different fertilizer and soil management within the experimental period in the corn fields. Different letters over the bars indicate statistically significant differences at  $\alpha = 0.05$ .

### 3.2. Soil CO<sub>2</sub> Flux

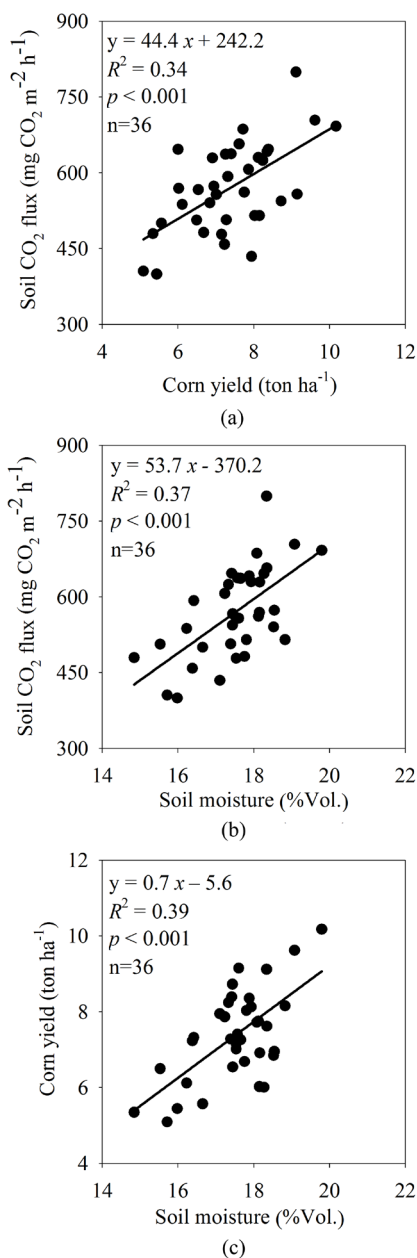
Soil CO<sub>2</sub> flux in all treatments increased exponentially with soil temperature when soil temperature was below 30°C (Figure 3(a) and Figure 4), and increased linearly with soil moisture when soil temperature was above 30°C (Figure 3(b)). Soil CO<sub>2</sub> flux was significantly affected by the improved fertilizer and soil management (Table 1). General, the NT-litter treatment had the highest average values of soil CO<sub>2</sub> flux (647 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>), followed by the NT-split (601 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>), NT-inhibitor (589 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>), NT-URAN (584 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>), NT-biochar (520 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>) treatments, and the CT-URAN (487 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>) treatments (Figure 2(c)). Changes in soil CO<sub>2</sub> flux was positively related to soil moisture and corn yield, respectively, across all the experimental plots (Figure 5). The soil temperature sensitivity (*Q*<sub>10</sub>) of soil CO<sub>2</sub> flux was also significantly affected by the treatments, and was estimated as 2.3, 3.3, 2.0, 3.0, 2.9 and 1.8 in the NT-URAN, NT-inhibitor, NT-biochar, NT-litter, NT-split and CT-URAN treatments, respectively (Table 2).



**Figure 3.** Relationships of soil CO<sub>2</sub> flux with soil temperature (a) and soil moisture (b), respectively across all treatments in the cornfields.



**Figure 4.** Relationships of soil CO<sub>2</sub> flux and soil temperature (<30°C) using an exponential equation under different fertilizer and soil management (a-f) represent the NT-URAN, UT-inhibitor, NT-biochar, NT-litter, NT-split, CT-URAN treatments in the cornfields. The black points represent the soil CO<sub>2</sub> flux measured at soil temperature above 30°C. The equations are listed in Table 2.



**Figure 5.** Relationships among soil CO<sub>2</sub> flux, corn yield and soil moisture across all the plots in the cornfields.

### 3.3. Soil CH<sub>4</sub> Flux

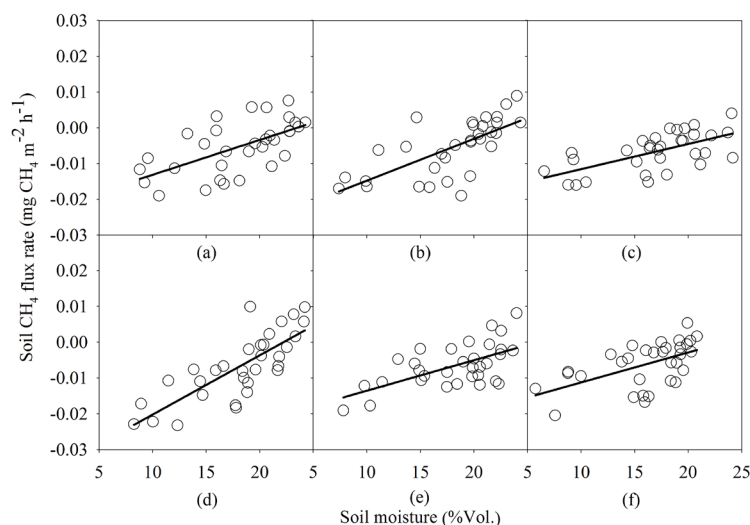
Overall, the corn soil in this study was a sink for CH<sub>4</sub> flux in all treatments (**Figure 2(d)**). The seasonal variations of soil CH<sub>4</sub> flux were not correlated with soil temperature, but increased linearly with soil moisture in all treatments (**Table 3**; **Figure 6**). Soil CH<sub>4</sub> flux did not significantly vary among the treatments (**Figure 2(d)**). Soil CH<sub>4</sub> fluxes were 0.006, 0.006, 0.007, 0.005, 0.007 and 0.007 mg CH<sub>4</sub> m<sup>-2</sup>·h<sup>-1</sup> in the NT-URAN, NT-inhibitor, NT-biochar, NT-litter, NT-split and CT-URAN treatments, respectively (**Figure 2(d)**). However, the moisture sensitivity (c value) of soil CH<sub>4</sub> flux was significantly affected by the treatments, and was estimated as 0.0010, 0.0012, 0.0007, 0.0017, 0.0009 and 0.0008 in the NT-URAN, NT-inhibitor, NT-biochar, NT-litter, NT-split, and CT-URAN treatments, respectively (**Table 3**).

**Table 2.** Relationships of soil CO<sub>2</sub> flux ( $SR$ , mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>) with soil temperature ( $ST$ , °C) when soil temperature is below 30°C using an exponential equation [ $SR = R_0 \times \exp(b \times ST)$ , where parameter  $R_0$  is basal soil CO<sub>2</sub> emission when  $ST = 0$ , and  $b$  is related to soil temperature sensitivity] under different fertilizer and soil management in the cornfields in middle Tennessee. NT-URAN = no-tillage + regular applications of URAN; NT-inhibitor = no-tillage + regular applications of URAN + nitrification inhibitor; NT-biochar = no-tillage + regular applications of URAN + biochar; NT-litter = no-tillage + chicken litter; NT-split = no-tillage + split applications of URAN; and CT-URAN = conventional tillage + regular applications of URAN. \* and \*\* indicate significant at  $\alpha = 0.05$ , and 0.01 levels, respectively. Different capital letters in the same column indicate statistical significance at  $\alpha = 0.05$ .

Treatments	$R_0$	$b$	$R^2$
NT-URAN	59.23 ± 35.58	0.08 ± 0.02 <sup>AB</sup>	0.48**
NT-inhibitor	22.84 ± 17.46	0.12 ± 0.03 <sup>A</sup>	0.58**
NT-biochar	81.17 ± 51.69	0.07 ± 0.02 <sup>AB</sup>	0.34**
NT-litter	33.63 ± 17.45	0.11 ± 0.02 <sup>A</sup>	0.71**
NT-split	36.59 ± 24.57	0.11 ± 0.02 <sup>AB</sup>	0.59**
CT-URAN	109.24 ± 52.97	0.06 ± 0.02 <sup>B</sup>	0.38**

**Table 3.** Relationships of soil CH<sub>4</sub> flux rate ( $CH$ , mg CH<sub>4</sub> m<sup>-2</sup>·h<sup>-1</sup>) and soil moisture ( $SM$ , %Vol.) using an exponential equation [ $CH = a + c \times SM$ ], where parameter  $a$  is basal soil CH<sub>4</sub> flux rate when  $SM = 0$ , and  $c$  is related to soil water sensitivity] (parameter estimate ± standard error) under different fertilizer and soil management in the cornfields in middle Tennessee. NT-URAN = no-tillage + regular applications of URAN; NT-inhibitor = no-tillage + regular applications of URAN + nitrification inhibitor; NT-biochar = no-tillage + regular applications of URAN + biochar; NT-litter = no-tillage + chicken litter; NT-split = no-tillage + split applications of URAN; and CT-URAN = conventional tillage + regular applications of URAN. \* and \*\* indicate significant at  $\alpha = 0.05$ , and 0.01 levels, respectively. Different capital letters in the same column indicate statistical significance at  $\alpha = 0.05$ .

Treatments	$a$	$c$	$R^2$
NT-URAN	-0.0229 ± 0.0043	0.0010 ± 0.0002 <sup>B</sup>	0.35**
NT-inhibitor	-0.0265 ± 0.0041	0.0012 ± 0.0002 <sup>AB</sup>	0.46**
NT-biochar	0.0187 ± 0.0029	0.0007 ± 0.0002 <sup>B</sup>	0.37**
NT-litter	0.0368 ± 0.0045	0.0017 ± 0.0002 <sup>A</sup>	0.60**
NT-split	0.0221 ± 0.0038	0.0009 ± 0.0002 <sup>B</sup>	0.35**
CT-URAN	0.0197 ± 0.0039	0.0008 ± 0.0002 <sup>B</sup>	0.28**



**Figure 6.** Relationships of soil CH<sub>4</sub> flux and soil moisture under different fertilizer and soil management (a)-(f) represent the NT-URAN, UT-inhibitor, NT-biochar, NT-litter, NT-split, CT-URAN treatments) in the cornfields. The equations are listed in Table 3.

## 4. Discussion

### 4.1. Soil CO<sub>2</sub> Flux under Different Fertilizer and Soil Management

The production of CO<sub>2</sub> in soils is almost entirely from root respiration and microbial decomposition of organic C. Like all chemical and biochemical reactions, these processes are subject to soil temperature and water limitation [12]. In this study, we found that the release rate of CO<sub>2</sub> from soil was controlled by both soil temperature and soil moisture, and that 30°C soil temperature seems to be a threshold of soil temperature (Figure 3). Similar results were also reported in other cropland or forest ecosystems [8] [12] [13]. For example, Inclan *et al.* [26] found that soil moisture regulates soil CO<sub>2</sub> flux when soil moisture is below a certain threshold and varying soil texture [27]. Our results suggested that soil water may play an important role in soil CO<sub>2</sub> flux as the soil became drier in summer induced by hot temperature and drought in the southeastern US [6].

Our results demonstrated that the use of improved fertilizer and soil management could significantly increase soil CO<sub>2</sub> flux compared to the conventional tillage (CT-urea) (Figure 3(c)). Despite the large difference in soil CO<sub>2</sub> flux among the treatments, the average CO<sub>2</sub> fluxes (487 - 647 mg CO<sub>2</sub> m<sup>-2</sup>·h<sup>-1</sup>, Figure 2(c)) in the growing season in our study were within typical ranges for corn soils [7] [14] [28]. The increase in soil CO<sub>2</sub> flux could be attributed to greater corn yield (corn growth) that might directly influence root respiration and/or indirectly provide substrate for microbial respiration, thus the positive linear relationships between soil CO<sub>2</sub> flux and corn yield was observed in this study (Figure 5). The results reported here-in were similar with the studies in other ecosystems, for instance, Raich and Tufekcioglu (2000) [29] conducted an extensive literature review and found that soil CO<sub>2</sub> flux were positively correlated to litter fall in forests and annual net primary production in grasslands. Several experimental studies conducted in the southeastern United States also found that soil CO<sub>2</sub> flux varied significantly between tillage and no-tillage or among crop types because of shift of crop production [8] [9] [13]. In addition, cropland often had relatively lower soil organic C like that observed in this study (2.37 g·kg<sup>-1</sup>), thus soil CO<sub>2</sub> flux in these croplands should be more subject to substrate limitation than those in forests and grasslands.

The improved fertilizer and soil management may also influence soil CO<sub>2</sub> flux by modifying soil microclimate, for instant, soil temperature and moisture [8] [13]. Soil temperature did not significantly change among the treatments, thus soil temperature should not be directly responsible for the variation in soil CO<sub>2</sub> flux. However, we found that the temperature sensitivity of soil CO<sub>2</sub> flux varied significantly among the treatments (Table 2). Moreover, the temperature sensitivity tended to be positively related to corn yield across all treatments (Table 2; [24]). This further supports our conclusion that improved fertilizer and soil management increased soil CO<sub>2</sub> flux primarily by increasing corn growth.

Unlike soil temperature, we found that soil moisture was significantly affected by the treatments (Figure 3(a)). Moreover, soil CO<sub>2</sub> flux tends to be positively related to soil moisture and corn yield across all the treatments (Figure 5(a) and Figure 5(b)). This is a little surprising, as we found that soil moisture only controlled soil CO<sub>2</sub> flux when soil temperature was above a certain threshold (Figure 3). Because of the fact that crop yield benefited from water conservation [6], a positive relationship between corn yield and soil moisture across all experiment plots was also observed (Figure 5(c)). It is therefore difficult though to distinguish whether the change of soil CO<sub>2</sub> flux was a direct effect of soil moisture change, or an indirect effect through the increase of corn yield, or both.

### 4.2. Soil CH<sub>4</sub> Flux under Different Fertilizer and Soil Management

Our results demonstrated that the soils in our cornfields were a net sink for CH<sub>4</sub> (Figure 2(d)). The generally low values and net uptake of CH<sub>4</sub> presented in our study were consistent with those reported for other cornfields [7] [14] [21]. Soil CH<sub>4</sub> is often formed under anaerobic conditions by methanogens [18]. It is therefore reasonable especially considering the fact that we often face short-term droughts in the summer months like the one observed in June 2012 when only 6.6 mm of rain was received. Other croplands such as rice fields with high soil water but relatively low soil aeration and oxygen concentration tend to have relatively high CH<sub>4</sub> production [19] [20]. The use of improved fertilizer and soil management did not significantly affect soil CH<sub>4</sub> flux (Figure 3(d)). Similar results were also revealed in some other cornfields studies [7] [14] [30]. However, several studies reported that no-tillage, alternative fertilizer sources (manure) and soil management (biochar application) can significantly alter soil CH<sub>4</sub> flux [18]-[21]. Different results from these studies are probably due to the differences in

soil texture or climate. For example, relatively dry climate and sandy loam soil, probably allow greater air diffusion and thus limit the production of CH<sub>4</sub>; while clay soil and wet climate may produce more soil CH<sub>4</sub> [30]. The positive relationships between soil CH<sub>4</sub> flux and soil moisture detected in all treatments in this study also suggested that soil moisture might play a major role driving soil CH<sub>4</sub> flux (Figure 6). In addition, we found that improved fertilizer and soil management significantly affected soil moisture sensitivity (c value) of soil CH<sub>4</sub> flux (Table 3). This indicated that increasing soil moisture has potential to result in a significant change in soil CH<sub>4</sub> flux among the treatments. The result reported here supported our hypothesis, and might help explain the contradicting results of previous studies that the effects of agricultural practices on soil CH<sub>4</sub> flux depend on the levels of soil moisture at the study sites [7] [14] [18]-[21] [30].

### 4.3. Implications for Policies to Mitigate Climate Change

Given the increasingly growing attention to global climate change our results have potential to drive policies that will enhance the mitigation of greenhouse gases in croplands. Especially gases emitted from agronomic crops such as corn; as uncertainty remain regarding greenhouse gas emissions from croplands under different agricultural practices.

While many agricultural practices, such as no-tillage, alternative use of fertilizer sources or methods (e.g., manure, split applications), and soil management (e.g., use of denitrification inhibitor or biochar), has been proposed as effective ways to enhance crop production and hence sequester atmospheric CO<sub>2</sub> in soils [6], our results indicated an increasing CO<sub>2</sub> flux from soil as well as the enhancement in crop yield under different agricultural practices. A phenomenon of this nature provides government and policy makers with tools to make informed decisions on how to maximize crop production and climate change mitigation.

Increased atmospheric concentration of CO<sub>2</sub> is expected to increase global surface temperatures and alter precipitation regimes. Many climate change predictions suggest that warming, extreme rainfall events and droughts will become more common [1]. Our result also highlighted the relative importance of soil temperature and moisture in determining the seasonal variations of soil C fluxes. Consequently, increase in air temperature and changes in precipitation pattern may alter the responses of soil C fluxes to agricultural practices or management. By employing improved management techniques, prime agricultural lands have the potential to not only sequester carbon but also mitigate CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions, thereby reducing agriculture's greenhouse gas footprint. In retrospect, approximately 9% of all greenhouse gases emissions originating in the United States come from agricultural activities [31].

## 5. Conclusion

Our findings demonstrated that improved fertilizer and soil management could significantly increase soil CO<sub>2</sub> flux in cornfields in the southeastern US, but did not change CH<sub>4</sub> flux probably due to relatively good condition of air diffusion. Changes in soil CO<sub>2</sub> flux among the treatments were positively correlated to corn yield and/or soil moisture. The rate of soil CO<sub>2</sub> flux varied with soil temperature and soil moisture in all treatments, while the CH<sub>4</sub> flux rate tended to be positively related to soil moisture only. Both temperature sensitivity of soil CO<sub>2</sub> flux and moisture sensitivity of soil CH<sub>4</sub> flux were affected by either alternative fertilizer sources or soil management. This tends to indicate that agricultural practice that enhances corn yield could also increase C emissions from soil, and hence reduce the potential of C sequestration in cornfields in the southeastern US.

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