RESEARCH ARTICLE

Corn Yield and Soil Nitrous Oxide Emission under Different Fertilizer and Soil Management: A Three-Year Field Experiment in Middle Tennessee

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Abstract

Background

A three-year field experiment was conducted to examine the responses of corn yield and soil nitrous oxide (N_2O) emission to various management practices in middle Tennessee.

Methodology/Principal Findings

The management practices include 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). Fertilizer equivalent to 217 kg N ha^{-1} was applied to each of the experimental plots. Results showed that no-tillage (NT-URAN) significantly increased corn yield by 28% over the conventional tillage (CT-URAN) due to soil water conservation. The management practices significantly altered soil N_2O emission, with the highest in the CT-URAN (0.48 mg N_2O m^{-2} h^{-1}) and the lowest in the NT-inhibitor (0.20 mg N_2O m^{-2} h^{-1}) and NT-biochar (0.16 mg N_2O m^{-2} h^{-1}) treatments. Significant exponential relationships between soil N_2O emission and water filled pore space were revealed in all treatments. However, variations in soil N_2O emission among the treatments were positively correlated with the moisture sensitivity of soil N_2O emission that likely reflects an interactive effect between soil properties and WFPS.

Conclusion/Significance

Our results indicated that improved fertilizer and soil management have the potential to maintain highly productive corn yield while reducing greenhouse gas emissions.

Introduction

The United States (US) is the largest corn producer in the world, accounting for about 32% of the world's corn crop, with about 87.4 million ha in production in 2012 according to National Corn Grower's Association (2013) [1]. To maintain high corn yield, large amounts of nitrogen (N) fertilizer are applied each year. About 5 million metric tons of N fertilizer were consumed in 2010 for corn production in the US, which accounted for 46% of the overall US consumption of N fertilizer [2]. However, nitrogen use efficiency (NUE) in corn production systems remains generally low: just 30%– 59% [3]. Much of the excess N applied to corn fields is leached into ground water as NO_3^- or emitted to the atmosphere in the form of N_2 and reactive N gases such as ammonia (NH_3) and nitrous oxide (N_2O) [4].

Nitrous oxide is one of the major greenhouse gases and has 310 times the radiative forcing potential of CO_2 [5]. Agricultural soil is the primary source of N_2O and the average annual N_2O emission from corn fields in the US ranges from 1 to 3.2 tons CO_2 equivalent per hectare [4]. The annual total N_2O emission from US corn croplands is greater than 29.4 million tons of CO_2 equivalent [6]. Therefore, knowledge of the trade-offs between soil N_2O emission, fertilizer management practice, and corn yield is essential for the development of sustainable landscapes and best management practices in these agricultural systems.

Nitrous oxide emitted from soil is produced by microbial transformations of inorganic N, through a series of processes usually involving nitrification and denitrification [7]. The potential to produce and emit N_2O increases as the amount of applied N fertilizer (availability of mineral N) increases in soil [8–11]. Due to the strong influence of N fertilizer on corn growth and yield, some emission of N_2O from soil seems to be an unavoidable consequence of maintaining highly productive, economically sustainable corn cropland [12]. However, the relationships between N fertilizer and soil N_2O emission may be more complex in practice [13]. Nitrogen often limits both crop growth and N_2O production in agriculture, so that crops with sufficient N may better compete with microbes for soil inorganic-N [14, 15]. Thus, soil N_2O production may be suppressed when crop NUE is enhanced in croplands [16, 17]. Soil N_2O emission is also affected by several other factors such as crop type, soil type, soil oxygen supply, soil temperature, rainfall and water filled pore space (WFPS) [18–21]. Agricultural practices such as no-tillage and improved fertilizer N management may influence the emission of N_2O by the modification of edaphic properties that affect soil microclimate [22–24]. A number of management practices have been proposed to enhance corn yield and reduce N_2O emission, but they remain controversial because the related influencing factors are still misunderstood [17, 25–27]. So far, there have been very few studies conducted to simultaneously compare the response of corn yield and soil N_2O emission under a range of proposed corn management practices [28, 29].

In this study, we conducted a three-year (2012–2014) field experiment in middle Tennessee to examine the responses of corn yield and soil N_2O emission to a number of proposed sustainable management practices. In order to mimic the normal practice by farmers in middle Tennessee, we contrasted the treatment of conventional tillage + regular applications of urea ammonium nitrate with a range of N fertilizer practices under no-tillage conditions. All

treatments received the same equivalent unit of N (217 kg N ha^{-1}) but in different forms and application scenarios. The objectives of this study were: (1) to evaluate the effects of improved soil and fertilizer management practices on corn yield and soil N_2O emission; (2) to detect any relationships between corn yield, soil N_2O emission and changes in soil properties or microclimate under the different treatments.

Materials and Methods

Ethics statement

The study site is maintained by the College of Agriculture, Human and Natural Sciences, Tennessee State University. The location is within the Tennessee State University Agricultural Research Center. All necessary permits were obtained for the described field study. The field study did not involve endangered or protected species. Data will be made available upon request.

Site description

This study was conducted at the Tennessee State University Agricultural Research Center (Latitude 36.12'N, Longitude 86.89'W, elevation 127.6 m) in Nashville, TN, USA. Climate in the region is a warm humid temperate climate (http://weatherspark.com/averages/29787/Nashville-Tennessee-United-States), with an average annual temperature of 15.1°C, and total annual precipitation of 1200 mm. The experimental site is a Talbott silt clay loam soil (Fine, mixed, semiactive, thermic Typic Hapludalfs; 25% sand, 55% silt, 20% clay) with a bulk density of 1.45 g cm^{-3}, slightly acidic (pH = 5.97), low in both carbon (2.37 g kg^{-1}) and nitrogen (0.14 g kg^{-1}) in the upper 0–30 cm soil layer.

Experimental Design

The experiment was laid out as a randomized complete block design with six replications in 2012–2013 and four replications in 2014 (two blocks were not used due to weed problems). Each block contained six plots. Six treatments were randomly assigned among the 6 plots within each block. Referring to the normal 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, 100%) as the control (CT-URAN). Improved fertilizer and soil management were used as the other five treatments, which included: no-tillage + regular applications of URAN (URAN-32-0-0 liquid N, 100%) (NT-URAN); no-tillage + regular applications of URAN (URAN-32-0-0 liquid N, 90%) + dicyandiamide (DCD) nitrification inhibitor with 67% N content (N, 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 g cm^{-3} and with an application rate of 2.5 kg m^{-2} (NT-biochar); no-tillage + 20% applications of URAN (URAN-32-0-0 liquid N, 20%) + chicken litter with 4% N, 3% P and 4% K contents (N, 80%) (NT-litter); and no-tillage + split applications of URAN (URAN-32-0-0 liquid N, 100%) (NT-split). The total number of plots was 36. Plot size was 5.5 m in 7.0 m encompassing 12 rows of corn. Corn seeds (Roundup Ready BT Hybrid Corn, P1412 HR, Pioneer Hi-Bred International Inc., Johnston, IA) were sown on April 9 of 2012, April 25 of 2013 and May 14 of 2014, respectively. Rows were planted at 0.5 m intervals at a density of 100,500 seeds ha^{-1}, resulting in 12 rows in 7.0 m direction per plot. Prior to planting, a non-selective herbicide (glyphosate) was sprayed to kill existing weeds in the plots. The CT plots were tilled to about 6 cm depth using a rotary harrow. At the planting, a total of 99 kg N ha^{-1} of chicken litter were applied to all the plots. During the experiment period, two applications of URAN fertilizer were applied on jointing stage (39 kg N ha^{-1}) and heading stage (79 kg N 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 kg N ha^{-1} occurred (4 fertilizer applications in total). As a result, equivalent units of (217 kg N ha^{-1}) were applied to all treatments, albeit in different forms to each experimental plot. Due to the severe drought in June of 2012, we irrigated all plots on June 14–15 at an equivalent amount of 50 mm water and June 30-July 2 at an equivalent amount of 90 mm, respectively.

Soil N$_2$O flux measurements

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 [30]. The static chamber was made of polyvinyl chloride (PVC) material and consisted of two parts: a soil ring without a top and bottom of 20 cm in diameter and 30 cm in height, and a removable cover of 20 cm in diameter and 6 cm in height. The ring was inserted directly into the soil about 25 cm below the soil surface leaving 5 cm above the soil surface, and the cover was placed on top during sampling and removed afterwards. A fan of 10 cm in diameter was installed on the top wall of each cover to create gentle turbulent mixing when the chamber was closed. A typical measurement started from 09:00–10:00 am and lasted for about 30 min. Gas samples (20 ml each) were generally collected at three time intervals (0, 15 and 30 minutes) using 20 ml plastic syringes. All gas samples were stored in sealed vacuum vials and then were transferred to analyze at the University of California, Davis within 96 h of collection for N$_2$O concentrations using a gas chromatograph (Model GC-2014, Shimadzu Scientific Instruments, Columbia, MD) equipped with a ^{63}Ni electron capture detector for quantifying N$_2$O. Instantaneous soil N$_2$O emission was calculated based on the rate of change in N$_2$O concentration within the chamber, which was estimated as the slope of linear regression between concentration and time [31]. If linear regression has an $R^2 \geq 0.9$, it is accepted for instantaneous N$_2$O flux rate estimate, if not, then a quadratic regression ($R^2 \geq 0.9$) is employed [32].

Soil temperature and water filled pore space measurements

Soil temperature at 10 cm below the soil surface and volumetric soil moisture content of the top 10 cm soil depth layer were monitored in-situ when gas samples were collected. Soil temperature was measured using a digital thermometer probe (Taylor Thermometers USA, model number Taylor 9842). Volumetric soil moisture content was measured using a soil moisture probe (Extech Instruments USA, model number MO750). Water filled pore space (WFPS, %) was calculated from the equation: WFPS = SWC/(1-BD/PD), where SWC is the volumetric soil moisture (θv), BD is the bulk density (Mg m^{-3}), and PD is the particle density (2.65 Mg m^{-3}). Climatic data (rainfall and air temperature) were obtained from a weather station at the experimental site.

Soil inorganic nitrogen measurements

Soil from each plot was sampled using a 5-cm diameter stainless steel soil probe. Samples were taken eleven times in 2012 from a depth of 0–30 cm at five random locations within each plot. At each time, a total of 6 composited samples were collected to represent each treatment, with a grand total of 36 mixed samples across all six treatments. Soil samples were air-dried and sieved to pass thru a 2-mm mesh. Soil NH$_4^+$-N and NO$_3^-$-N were extracted with a 2 M potassium chloride (KCl) solution (soil:solution, 1:5) and then filtered through a 0.45μm filter. The extracted solutions were measured via colorimetric techniques at 645 nm and 420 nm to determine NH$_4^+$-N and NO$_3^-$-N concentrations, respectively. All measurements were performed in the Soil, Water and Forage Analytical Laboratory (SWFAL, a USDA certified lab) at the Oklahoma State University, Stillwater, OK.

Corn yield measurements

In each year of harvest, ten corn plants in each plot were selected to quantify grain yield in each year. Corn ears were removed by hand at harvest, then shelled and dried to a constant level. After harvest, most of crop residues were removed out of plots in each year.

Statistical analysis

All data analyses were carried out with the SPSS software Version 13.0 (SPSS Inc., Chicago, IL). Repeated-measures Analysis of Variance (ANOVA) was used to determine the statistical significance of treatment, sampling year and their interactive effects on soil temperature, WFPS, and soil N_2O emission in the corn fields. Multiple comparisons (Least Significant Difference, LSD method) were conducted if significant effects of treatment or sampling time were found. Two-way ANOVA with LSD test was used to determine the statistical significance of treatment, sampling year and their interactive effects on corn yield. The relationship between soil N_2O emission rate (NE) and water filled pore space (WFPS) in each treatment was developed using the exponential model [NE = $NE_0 \times$exp($b \times$WFPS), where parameter NE_0 is basal soil N_2O emission when WFPS = 0, and b is related to soil water sensitivity]. The t-test was used to determine the difference in the soil moisture sensitivity (b value) of N_2O emission between the treatments.

Results

Microclimates and soil properties

Soil temperature ranged from 17.1°C to 35.4°C, with no significant difference among the treatments (Tables 1 and 2). WFPS ranged from 12.7 to 53.8%. The CT-URAN and NT-biochar treatments had significantly lower WFPS than those in other treatments (Tables 1 and 2). Seasonal

Table 1. Significance of the effects of treatment, sampling year and their interactions on soil temperature, water filled pore space (WFPS), N_2O emission, and corn yield based on ANOVAs.

Source	Soil temperature	WFPS	N_2O emission	Yield
Treatment	0.10	3.44**	3.11*	3.04*
Year	36.92**	30.48**	5.35**	21.77**
Treatment×year	0.49	0.69	0.36	0.15

Numbers are F-values. Asterisks indicate the level of significance (* $p<0.05$, ** $p<0.01$).

doi:10.1371/journal.pone.0125406.t001

Table 2. Soil temperature (°C), water filled pore space (WFPS; %), and inorganic-N (NH4+-N and NO_3^--N for 2012 only; mg kg^{-1}) under different tillage and fertilizer treatments in the corn fields at the Tennessee State University Agricultural Research Center in the southeastern United States.

Treatment	Soil temperature	WFPS	NH_4^+-N	NO_3^--N
NT-URAN	28.70±0.33[a]	41.16±0.95[a]	5.02±0.42[bc]	13.01±1.04[bc]
NT-inhibitor	28.69±0.30[a]	40.46±0.99[ab]	5.57±0.35[abc]	15.60±1.15[ab]
NT-biochar	28.48±0.29[a]	38.42±0.93[bc]	6.89±0.82[a]	15.43±1.37[ab]
NT-litter	28.40±0.30[a]	41.12±0.87[a]	4.29±0.31[c]	14.30±1.00[b]
NT-split	28.82±0.30[a]	41.31±0.87[a]	4.79±0.31[c]	11.79±0.86[c]
CT-URAN	28.58±0.29[a]	36.26±0.85[c]	6.23±0.48[ab]	17.88±1.56[a]

Different letters in the same column indicate statistical significance at α = 0.05. 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.

doi:10.1371/journal.pone.0125406.t002

patterns of soil temperature and WFPS were consistent with air temperature and rainfall, respectively. There was a severe drought in June 2012 with only 6.6 mm rainfall. Mean soil NH_4^+-N concentration was the highest in the NT-biochar treatment (26.77 mg kg^{-1}), and the lowest in the NT-litter treatment (16.65 mg kg^{-1}). Mean soil NO_3^--N concentration was highest in the CT-URAN treatment (69.45 mg kg^{-1}), and lowest in the NT-split treatment (45.78 mg kg^{-1}).

Corn yield and Soil N_2O emission

Corn yield was generally lower in the drought year of 2012 than the other two years ($p<0.05$). The management practices had significant effects on corn yield (Table 1). Specifically, corn yield was significantly affected by no-tillage with a higher value in the NT-URAN treatment (7.77 tones ha^{-1}) than in the CT-URAN treatment (5.94 tones ha^{-1}) across all three years ($p<0.05$, Fig 1a). No significant difference of corn yield was detected among the other fertilizer and soil management practices (Fig 1a). Corn yields were 7.79, 7.23, 7.81 and 7.41 tones ha^{-1} in the NT-inhibitor, NT-biochar, NT-litter and NT-split treatments, respectively.

Soil N_2O emission was also significantly affected by improved fertilizer and soil management practices (Table 1). Within the experimental period, the highest N_2O release from soil occurred in the CT-URAN (0.48 mg N_2O m^{-2} h^{-1}), which was significantly higher than those in the NT-URAN (0.29 mg N_2O m^{-2} h^{-1}) and NT-litter (0.32 mg N_2O m^{-2} h^{-1}) treatments, and much higher than those in the NT-inhibitor (0.20 mg N_2O m^{-2} h^{-1}), NT-biochar (0.16 mg N_2O m^{-2} h^{-1}), and NT-split (0.25 mg N_2O m^{-2} h^{-1}) treatments (Fig 1b).
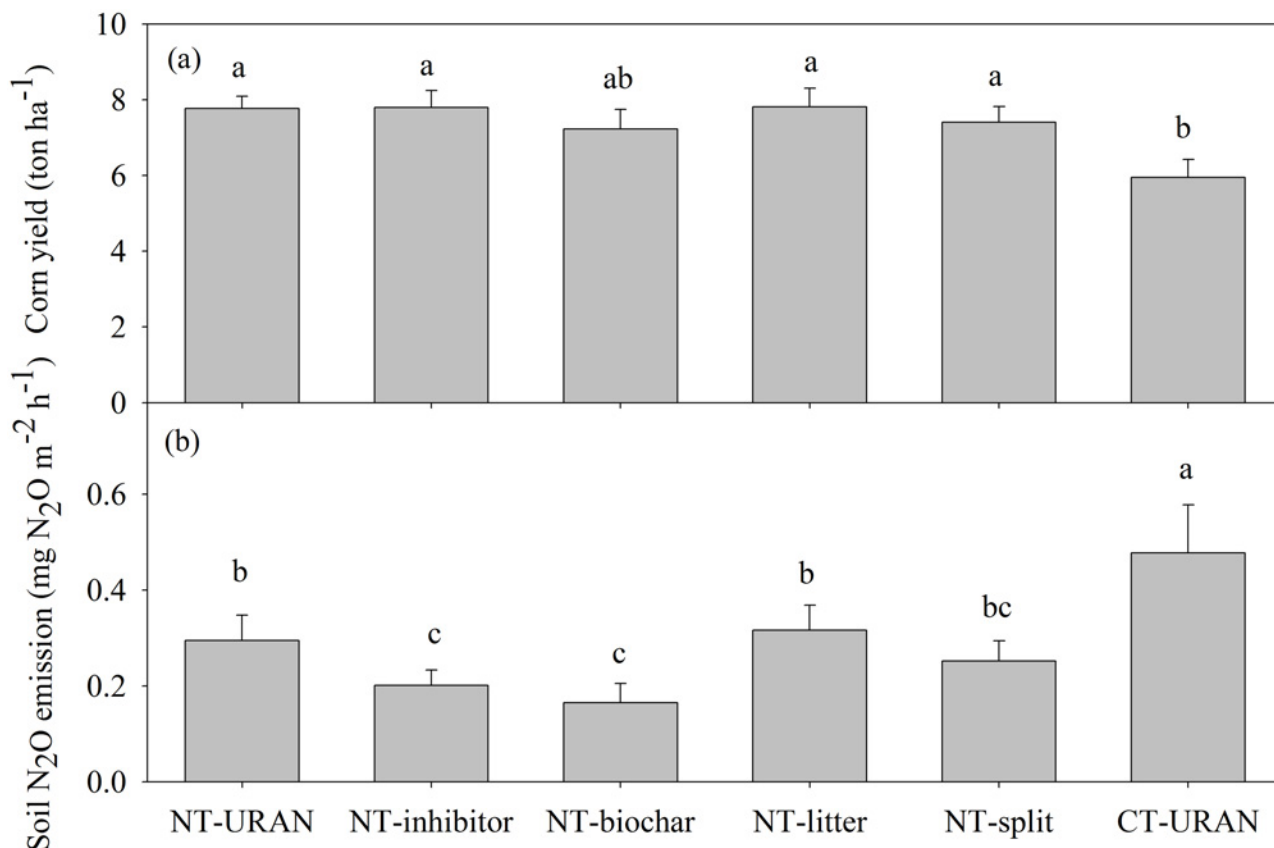

Fig 1. The average values of corn yield (a) and soil N_2O emission (b) under different tillage and fertilizer treatments in the corn fields. Different letters over the bars indicate statistically significant differences at $\alpha = 0.05$.

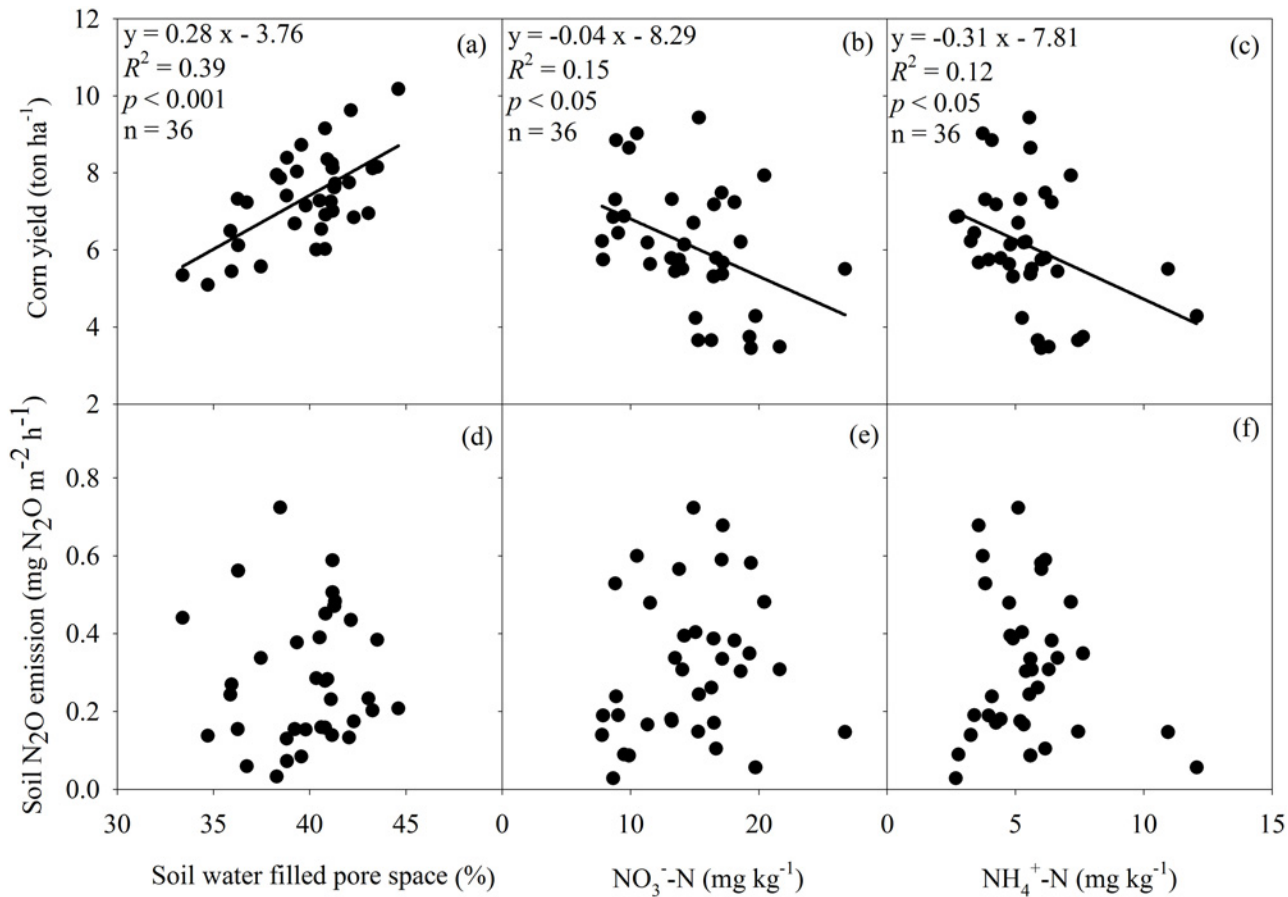doi:10.1371/journal.pone.0125406.g001

Fig 2. Relationships of corn yield (a, b, c) and soil N_2O emission (d, e, f) with water filled pore space and soil inorganic-N (NH4+-N and NO_3^--N, for 2012 only), respectively across all the plots.

Controls on corn yield and soil N_2O emission

Corn yield was positively correlated with WFPS across all plots (Fig 2a). In contrast, corn yield was negatively correlated with inorganic-N (NH_4^+-N and NO_3^--N) in all treatments (Fig 2b and 2c). No significant relationship between soil N_2O emission rate and WFPS or inorganic-N was detected across all plots (Fig 2d–2f). There were significant exponential relationships between soil N_2O emission and WFPS in each treatment (Fig 3). The management practices significantly altered the moisture sensitivities (b values) of soil N_2O emission, with the highest in the CT-URAN (b = 0.23), relatively low in the NT-inhibitor (b = 0.06), NT-biochar (b = 0.05) and NT-split (b = 0.08), and intermediate in the NT-URAN (b = 0.10) and NT-litter (b = 0.11) treatments (Table 3). Soil N_2O emission was positively correlated with its moisture sensitivity (b value) among the six treatments (Fig 4).

Discussion

The findings from our three-year field experiment provide insights into the effects of various management practices on corn yield and N_2O emission in southeastern US and may have significant implications for sustainable agriculture and climate change mitigation. First, we found that no-tillage (NT-URAN) significantly increased corn yield by 28% over the conventional tillage (CT-URAN) probably due to soil water conservation. Second, we detected significant exponential
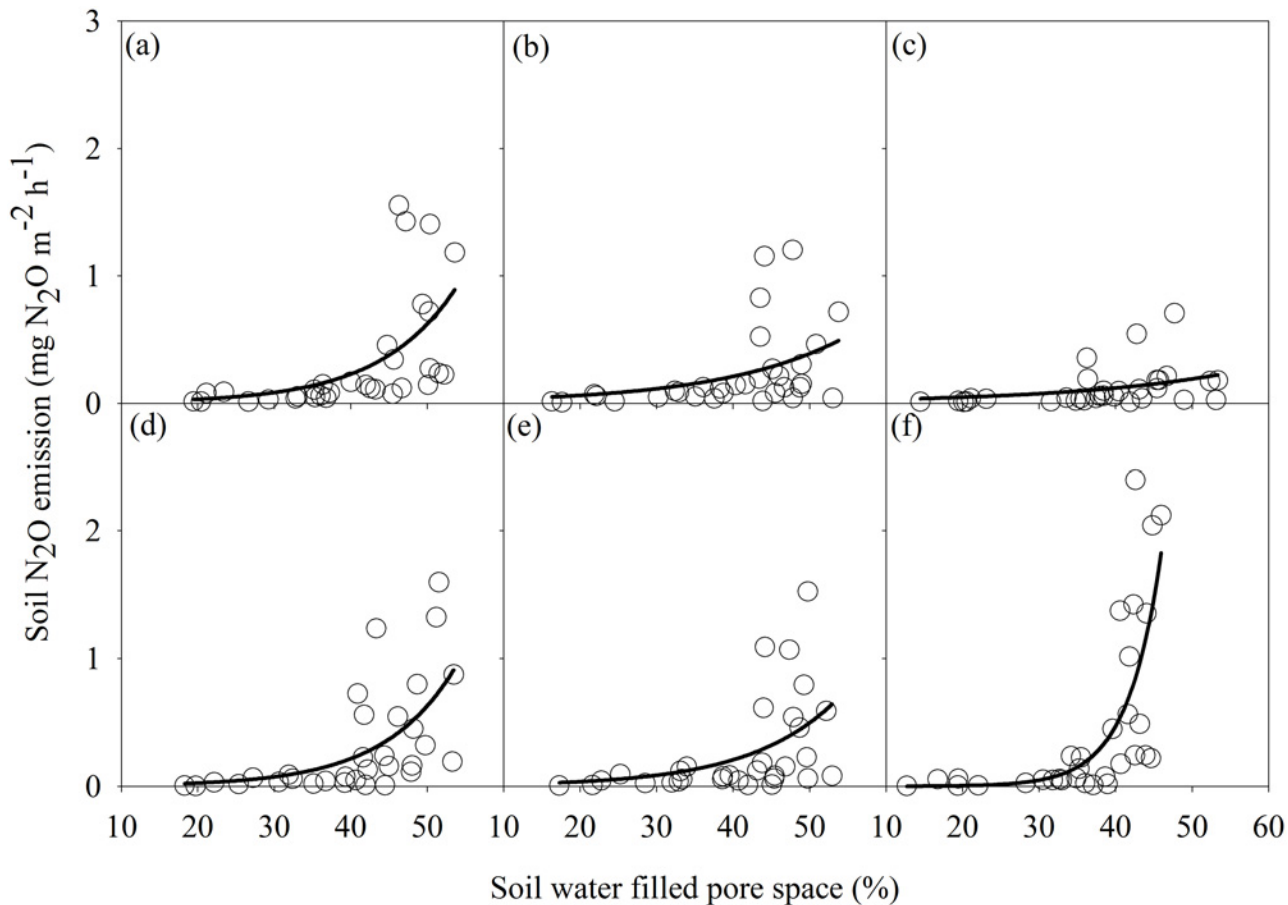
Fig 3. Relationships between soil N₂O emission (NE, mg N₂O m⁻² h⁻¹) and water filled pore space (WFPS, %) under different tillage and fertilizer treatments (a, b, c, d, e, f represent the NT-URAN, NT-inhibitor, NT-biochar, NT-litter, NT-split, CT-URAN treatments) in the corn fields. The equations are listed in Table 3.

doi:10.1371/journal.pone.0125406.g003

Table 3. Relationships between soil N₂O emission rate (NE, mg N₂O m⁻² h⁻¹) and water filled pore space (WFPS, %) under different tillage and fertilizer treatments in the corn fields at the Tennessee State University Agricultural Research Center in the southeastern US.

Treatment	NE_0	b	R^2
NT-URAN	0.0042±0.0081	0.1000±0.0390[AB]	0.30**
NT-inhibitor	0.0181±0.0295	0.0614±0.0347[B]	0.22**
NT-biochar	0.0186±0.0236	0.0466±0.0281[B]	0.13*
NT-litter	0.0030±0.0052	0.1069±0.0351[AB]	0.43**
NT-split	0.0063±0.0128	0.0875±0.0405[B]	0.22**
CT-URAN	0.0001±0.0001	0.2270±0.0521[A]	0.47**

An exponential equation [$NE = NE_0 \times exp(b \times WFPS)$ is applied, where parameter NE_0 is basal soil N₂O emission when WFPS = 0, and b is related to soil water sensitivity] (parameter estimate ± standard error). Different capital letters in the same column indicate statistical significance at $\alpha = 0.05$. * and ** indicate significant at $\alpha = 0.05$, and 0.01 levels, respectively. 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.

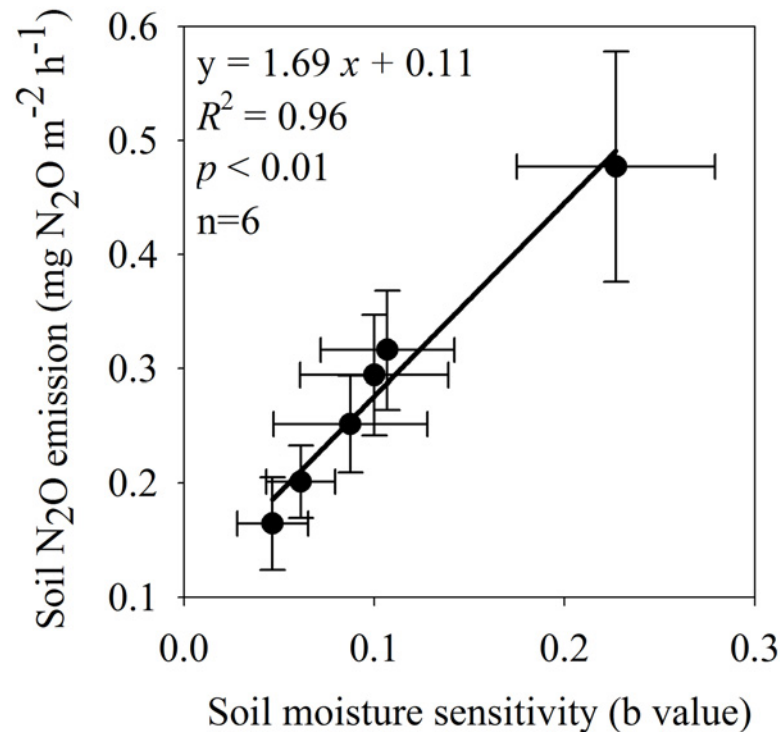doi:10.1371/journal.pone.0125406.t003

Fig 4. Relationships between soil N_2O emission and its moisture sensitivity (b value) across all the treatments.

relationships between soil N_2O emission and WFPS in this study. The alternative fertilizer sources and improved soil management could decrease N_2O emissions by reducing its moisture sensitivity. These findings are useful for better optimizing agricultural practices to maintain highly productive corn yield while reducing greenhouse gas emissions in the southeastern US.

Corn yield

Our results demonstrated that corn yield was significantly affected by no-tillage, with a higher value in the NT-URAN treatment (7.77 tones ha^{-1}) than in the CT-URAN treatment (5.94 tones ha^{-1}) ($p<0.05$, Fig 1a). The corn yields presented here fall in the range of corn yield (1.0–17.5 ton ha^{-1}) reported by a number of similar studies worldwide [33]. Our results for the no-tillage effect were different from DeFelice et al. [34] who reviewed 687 site-years of data in the US and Canada, and found that the average difference in corn yields between tillage and no-tillage treatments was negligible. In their analysis, they compared corn yields using total or region-level means. The total or mean yields were calculated from different climate, soil types and agricultural practices such as timing of planting, fertilizer placement, fertilizer rates, planting populations, irrigation and weed control methods. It is quite likely that the mean status of soil condition and management practices for tilled corn fields was different from that for no-tillage corn fields.

Our results were also different from a recent study that reported an approximate 30% decrease in corn yield in no-tillage corn fields compared to tilled corn fields in the cool humid region of Northeast China [35]. Temperature was often a dominant factor influencing agricultural production in that region. Consequently, they explained that a shift in soil temperature contributed to the difference in corn yield between no-tillage and tilled corn fields. Our

study site in the southeastern US has a warm humid temperate climate with an average annual temperature of 15.1°C, and daily mean temperature ranged from 14.1°C to 32.7°C during this study. Thus, temperature should not be a dominant factor influencing agricultural production in this region. Indeed, we did not find any significant difference in soil temperature between all the treatments (Table 2). In contrast, crop yield in this study likely benefited from water conservation under no-tillage treatments even in this humid climatic region, as we often face short-term droughts in the summer months like that observed in June 2012 when only 6.6 mm of rainfall felt. Higher WFPS in the no-tillage compared to the tillage corn fields could contribute to higher yield in the NT treatment (Table 2). A similar result was reported in a 6-yr corn study, reporting that no-tillage conserved soil water and enhanced yield [26]. The positive relationships detected between corn yield and WFPS across all treatments further suggested that the no-tillage and improved fertilizer management influence corn yield mainly though a modification of WFPS, probably interactively due to the presence of drought events. Our results supported Franzluebbers's [36] conclusion that soil water is likely a significant factor limiting crop production in the southeastern US.

Fertilizer management did not significantly change corn yield, perhaps due to the large amount of N fertilizer (217 kg N ha^{-1}) applied to each treatment. The applied N fertilizer likely exceeded the demand of corn growth, so corn production was not subject to N limitation. A long-term corn (*Zea mays* L.) cropping system study has also shown that corn yields increase with N fertilizer from 0 to 101 kg N ha^{-1} and then level off at higher applications of N [14]. The maximum yield in that study varies from 5.4 to 9.0 ton ha^{-1} depending on the climate conditions. In addition, we detected a negative rather than positive relationship between corn yield and extractable soil N (NH_4^+-N and NO_3^--N). It is probably that low corn yield or NUE consumed less N and let more inorganic N remaining in the soil [3]. Other ecological processes such as leaching and microbial assimilation may also contribute to the results for extractable soil N [4].

Soil N_2O emission

Previous studies have indicated that the level of N fertilizer application is one of the main factors influencing soil N_2O emission [11, 14, 37]. The large amount of N fertilizer applied in our study might have led to high emission of N_2O from corn fields (Fig 1b). The average rate of N_2O release from soil in our study ranged from 0.16 to 0.48 mg N_2O m^{-2} h^{-1}, which was generally higher than those from a recent analysis of global mean level in N_2O emissions (0.16 mg N_2O m^{-2} h^{-1}) where global average level of N fertilizer was only 152 kg N ha^{-1} [33]. Similarly, with less application of fertilizer to corn fields [38–40], less N_2O emissions were reported. When equal amounts of N fertilizer were applied in an adjacent commercial corn field in Nolensville [41], we found similar N_2O emission in the NT-URAN treatment, although N_2O fluxes were measured using the eddy-covariance technique.

In addition to the level of N fertilizer application, the improved fertilizer and soil management significantly affected soil N_2O emission compared with the CT-URAN treatment, where relatively low emissions were observed from the NT-URAN and NT-litter treatments and much lower emissions were observed in the NT-inhibitor, NT-biochar and NT-split treatments (Fig 1b). It is well-known that DCD as a nitrification inhibitor reduced the rate of nitrification, and resulted in a low emission of N_2O [21, 42]. Significant differences of NH_4^+-N and NO_3^--N between the treatments were detected perhaps due to shifts in corn yield and NUE (Fig 2b and 2c). However, variations in soil inorganic-N did not explain the difference of soil N_2O emission among these treatments (Fig 2e and 2f). This indicated that soil inorganic-N probably interacted with other soil properties or microclimate to influence soil N_2O emission under the different treatments [22, 43].

Rainfall or WFPS is one of the major factors driving soil N_2O emission. Several studies have confirmed that there are connections between increased soil N_2O emissions and rainfall or WFPS [19–21, 44]. We detected significant exponential relationships between soil N_2O emission and WFPS in all treatments (Fig 3). Although there were large differences of WFPS among the treatments, however, no significant relationship between soil N_2O emission and WFPS was detected across all treatments (Fig 2d–2f). Interestingly, we found that the variation in soil N_2O emission was positively correlated with its moisture sensitivity (b value) among treatments (Fig 4). This indicated that improved fertilizer and soil management reduced soil N_2O emission mainly though decreasing its moisture sensitivity that likely reflects a synthesized impact of soil properties.

Several soil properties might contribute to the shift of soil moisture sensitivity between treatments (Table 3) observed in this study. First, N_2O emitted from soil is produced by bacterial transformations of inorganic-N, particularly of NO_3^--N [8–10]. Concentrations of both NH_4^+-N and NO_3^--N were highest in the CT-URAN treatment (Table 2), probably due to the reduced corn growth and in turn lower NUE. The higher extractable soil mineral-N provides more substrate for bacterial nitrification and denitrification [7, 14], and hence led to larger N_2O emission during the periods of high WFPS (Table 3). In contrast, extractable NH_4^+-N and NO_3^--N concentrations were low in the NT-split treatment, leading to lower moisture sensitivity of N_2O emission (Table 3). This indicated that decreasing synthetic fertilization rate or reasonably arranging fertilization time could enhance corn NUE, and ultimately reduce N_2O emission. Second, nitrification inhibitors such as DCD have been shown to reduce emissions of N_2O directly by reducing the rate of NH_4^+-N oxidation to NO_3^--N associated with nitrification, or indirectly by reducing microbial activity [21, 42]. Consequently, the NT-inhibitor treatment significantly decreased N_2O emission and its moisture sensitivity (Table 3; Fig 1b), even though soil mineral-N availability was high (Table 2). However, it is notable that increasing inorganic N possibly results in subsequent losses by leaching and denitrification after DCD has been degraded [45, 46]. Similarly, biochar has high total porosity [47, 48] and can both retain water in small pores and maintain aerobic conditions in soil by letting water flow through the larger pores after heavy rain from topsoil to deeper soil layers [49, 50]. Thus, the NT-biochar treatment significantly decreased N_2O emission and its soil moisture sensitivity (Table 3; Fig 1b). Our results differed from a recent study that reported biochar addition affected N_2O emission via soil moisture and crop N uptake [17]. The difference was probably due to different biochar materials, crop types and fertilizer levels supplied in our as compared to their study [24].

Conclusions

This study demonstrated that no-tillage could significantly reduce soil N_2O emission while improving corn yield in the southeastern US. Split-application of fertilizer, nitrification inhibitor and bichar addition did not change corn yield, but did significantly reduce N_2O emissions. Changes in corn yield were positively related to WFPS, indicating that any management that saves water could probably improve corn yield in this region. The seasonal dynamic of N_2O emission from soil showed significant exponential relationships with WFPS in each treatment. However, alternative fertilizer sources (regular, spilt and chicken litter applications) and soil management (e.g., no-tillage, inhibitor and biochar) can decrease N_2O emissions by reducing its moisture sensitivity of N_2O emission rather than WFPS, This likely indicates an existing interaction of soil properties and WFPS impacts on N_2O emissions from corn fields under various management practices. Overall, this study provides evidence that alternative soil and fertilizer management have the potential to maintain highly productive corn yield while reducing greenhouse gas emissions in the southeastern US.

Acknowledgments

Author Contributions

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