Effects of Straw Incorporation and Nitrogen Application on Yield, Greenhouse Gas Emissions, and Soil Enzyme Activity in Spring Maize Fields in the Black Soil Region (Postprint)

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Abstract

Investigating the effects of straw return and nitrogen application on spring maize yield and greenhouse gas emission characteristics in high-latitude black soil regions is of great significance for promoting grain production increase and reducing environmental costs. This study, through a long-term field experiment located in the black soil region and using the static chamber-gas chromatography method, investigated the comprehensive greenhouse effect and emission intensity of CO_2, N_2O, and CH_4 from farmland soil, as well as changes in soil catalase and urease activities, during different growth stages of spring maize under conditions of straw return and no straw return with three nitrogen application rates (pure N: 120~kg · hm^{-2}, 240~kg · hm^{-2}, and 300~kg · hm^{-2}). The results showed that: without straw return, the high nitrogen rate treatment had the highest spring maize yield; after straw return, the medium nitrogen rate treatment (240~kg · hm^{-2}) had the highest spring maize yield, with no significant difference from the high nitrogen rate treatment without straw return. Without straw return, as nitrogen application rate increased, CO_2, N_2O, and CH_4 emissions all increased significantly, and the comprehensive greenhouse effect and soil greenhouse gas emission amount and intensity increased significantly ($P < 0.05$); with increased nitrogen application combined with straw return, CO_2 and N_2O emissions increased, while the carbon sink function of soil CH_4 was enhanced, and greenhouse gas emission amount and intensity did not increase significantly ($P > 0.05$). Without straw return, increased nitrogen application decreased soil catalase activity but increased soil urease activity; whereas straw return intensified the decrease in soil catalase activity caused by increased nitrogen application but diminished the increase in soil urease activity. Therefore, the combination of straw return with medium nitrogen rate

treatment (240~kg · hm^{-2}) achieved the highest maize yield and could suppress the promoting effect of nitrogen application alone on the comprehensive greenhouse effect and soil greenhouse gas emission intensity, which is recommended for reference in production practice.

Full Text

Effects of Straw Return and Nitrogen Application on Spring Maize Yield, Greenhouse Gas Emissions, and Soil Enzyme Activity in Black Soils

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Abstract
Investigating the effects of straw return and nitrogen application on spring maize yield and greenhouse gas emission characteristics in high-latitude black soil regions is crucial for promoting grain production while reducing environmental costs. Through a long-term field experiment in a black soil region, this study examined the integrated greenhouse effect and emission intensity of CO , N O, and CH , as well as changes in soil catalase and urease activities, under straw return versus no straw return conditions and three nitrogen rates (pure N: 120 kg · hm ^{2}, 240 kg · hm ^{2}, and 300 kg · hm ^{2}) using the static chamber–gas chromatography method. The results showed that without straw return, the highest spring maize yield was achieved with high nitrogen application; with straw return, the medium nitrogen rate (240 kg · hm ^{2}) produced the highest yield, which was not significantly different from the high nitrogen treatment without straw return. Without straw return, CO , N O, and CH emissions all increased significantly with nitrogen rate, leading to a substantial increase in the comprehensive greenhouse effect and soil greenhouse gas emission intensity ($P < 0.05$). When nitrogen application was combined with straw return, CO and N O emissions increased, but the soil's CH carbon sink function was enhanced, and greenhouse gas emissions and intensity did not increase significantly ($P > 0.05$). Without straw return, increasing nitrogen application reduced soil catalase activity but increased urease activity; straw return intensified the reduction in catalase activity caused by nitrogen application but diminished the increase in urease activity. Therefore, the combination of straw return with medium nitrogen application (240 kg · hm ^{2}) achieved the highest maize yield while suppressing the promotion of comprehensive greenhouse effect and soil greenhouse gas emission intensity caused by nitrogen application alone, making it a recommended practice for production.

Keywords: black soil; straw return; nitrogen application; greenhouse gas; soil enzyme activity; spring maize

Introduction

The black soil region in the central Northeast Plain of China, renowned as a "high-yield soil," serves both production and ecological security functions. However, due to its high latitude and relatively intense human disturbance, crop yield and greenhouse gas emissions in this region have attracted increasing attention. Long-term agricultural production, improper tillage and fertilization, and soil erosion have led to reduced quantity and quality of soil organic matter, severely affecting soil productivity. Previous studies have shown that increased emissions of atmospheric CO , N O, and CH are major contributors to global warming, with farmland soil being one of the important sources of these three greenhouse gases. In recent years, climate warming and unreasonable agronomic practices have further reduced soil fertility and significantly increased greenhouse gas emissions. Therefore, appropriate field management measures are urgently needed in high-latitude agricultural production to steadily improve land productivity while effectively controlling greenhouse gas emissions.

Straw return not only reduces environmental pollution from straw burning but also serves as a crucial measure for increasing soil organic matter content and renewal rate, thereby improving soil fertility. However, in the Northeast black soil region, insufficient heat and moisture after maize harvest result in slow straw decomposition, and spring tillage can cause mechanical entanglement and blockage, severely constraining sowing quality. Consequently, traditional straw mulching and standing stubble return have proven ineffective in practical production and application. With the continuous improvement of mechanized harvesting of spring maize in Northeast China, straw crushing and return will become the development direction for production. After straw return, the soil C/N ratio increases, directly affecting soil enzyme and microbial activities, which in turn influence crop root respiration and key greenhouse gas emission processes such as nitrification-denitrification. Nitrogen management, as one of the most active elements in agricultural production, has been extensively studied in Northeast maize production. However, research on how increased nitrogen application balances crop growth and microbial decomposition of straw, and its subsequent impact on greenhouse gas emissions, remains limited in this region. The characteristics of greenhouse gas emission intensity and integrated greenhouse effect during the crop growing season are still unclear.

Soil enzymes, primarily including urease, invertase, and catalase, are closely related to soil carbon and nitrogen transformation. Their activity serves as a sensitive soil biological indicator that reflects both soil fertility and its relationship with crop root growth and soil greenhouse gas emissions. Agronomic measures such as straw return and fertilization affect greenhouse gas emissions and soil urease and catalase activities by providing essential nutrients (N, P, K) for crop growth and altering the soil C/N ratio, thereby influencing microbial activities and greenhouse gas emissions. While the primary goal of agricultural production is to continuously improve economic yield and promote sustainable development, farmland ecosystems must balance economic and environmental 协同发展, which is particularly important for the high-latitude Northeast agricultural region. Although numerous studies have reported on the effects of fertilization methods and tillage systems on farmland greenhouse effects in double- or multiple-cropping regions, research on single-cropping systems in Northeast China remains relatively weak. Therefore, this study focused on spring maize fields in the Northeast black soil region to examine: (1) the effects of straw crushing-return and nitrogen rates on spring maize yield, soil CO , N O, and CH emissions, and soil catalase and urease activities; and (2) the relationship between soil greenhouse gas emission fluxes and soil enzyme activities under straw return and increased nitrogen application. The results provide theoretical basis and technical support for sustained and stable yield increase and greenhouse gas emission reduction in spring maize production in Northeast black soil regions.

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1. Materials and Methods

1.1 Experimental Site

The long-term field experiment was initiated in 2010 at the experimental farm of Jilin Agricultural Science and Technology College (126°28 2.6 E, 43°56 16.5 N). The region features a mid-temperate humid climate with an annual mean temperature of 3.9°C, average precipitation of 650–750 mm, a frost-free period of 189–200 days, and sunshine duration of 2,300–2,500 h. The long-term (1997–2013) and 2013 temperature and precipitation patterns are shown in [Figure 1: see original paper]. The experimental soil was classified as black soil with the following properties: pH 6.57, organic matter 19.6 g · kg^{1}, total nitrogen 1.21 g · kg^{1}, total phosphorus 1.2 g · kg^{1}, total potassium 30.64 g · kg^{1}, available nitrogen 86.58 mg · kg^{1}, available phosphorus 63.73 mg · kg^{1}, and available potassium 70 mg · kg^{1}.

1.2 Experimental Design

The experiment employed a two-factor randomized block design with straw return and nitrogen application rate as factors. The straw return treatment (S1) involved crushing and spreading straw on the soil surface in spring followed by plowing, with a straw return rate of 6,000 kg · hm^{2}; no straw return served as the control (S0). Nitrogen fertilizer (urea, 46.6% N) was applied at three rates: 120 kg · hm^{2} (low nitrogen, N1), 240 kg · hm^{2} (medium nitrogen, N2), and 300 kg · hm^{2} (high nitrogen, N3). Six treatments were established with three replications, with each plot measuring 32.5 m^2 (3.25 m × 10 m). Following local production practices, P O at 100 kg · hm^{2} and K O at 100 kg · hm^{2} were applied as base fertilizers together with nitrogen through uniform broadcasting in each plot before sowing. The maize variety 'Xianyu 335' was planted at a row spacing of 65 cm, plant spacing of 28 cm, and density of 55,000 plants ·

hm ^{2}. Sowing occurred on May 4 and harvest on September 28, with other management practices following conventional field production.

1.3 Measurements

1.3.1 Greenhouse Gas Emission Flux Gas samples were collected at 44 days (jointing stage, V6), 76 days (tasseling stage, VT), 116 days (milk stage, R3), and 142 days (maturity stage, R6) after sowing, between 9:00 and 11:00 AM. The static chamber-gas chromatography method was used for greenhouse gas collection. The sampling chamber was constructed from organic glass without a bottom and featured a 1.5 cm diameter hole sealed with a rubber stopper fitted with a 60 mL syringe. Four gas samples were collected at 10-minute intervals after chamber placement. Gases were stored in 0.5 L aluminum foil sampling bags with polyethylene coating (Dalian Delin) and analyzed within 36 hours using gas chromatography (Agilent 7820A, USA) to determine CO , CH , and N O concentrations. A linear relationship between the four gas sample concentrations and sampling time intervals was required, with all samples having correlation coefficients r > 0.95 considered valid. The gas emission flux was calculated using the formula:

$$F = \rho \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273}{273 + T} \quad (1)$$

where F is the gas emission flux (mg · m ^{2} · h ^{1} for CO ; g · m ^{2} · h ^{1} for N O and CH), is the gas concentration under standard conditions, V is the sampling chamber volume (m^{3}), A is the chamber base area (m^{2}), Δc is the gas concentration difference (10 L · L ^{1} for N O; 10 L · L ^{1} for CO and CH), Δt is the sampling time interval (h), 273 is the absolute temperature, and T is the sampling temperature (°C).

Based on the emission fluxes, greenhouse gas emissions during the maize growing season were calculated using the sliding average method. The comprehensive greenhouse effect produced by CO , N O, and CH in farmland was characterized using CO equivalent (CO -eq) to evaluate different straw return and nitrogen treatments from the perspective of greenhouse gas emission scale:

$$\mathrm{CO_2\text{-}eq\ (kg \cdot hm^{-2}) = CO_2\ emission\ (kg \cdot hm^{-2}) + N_2O\ emission\ (kg \cdot hm^{-2}) \times 298 + CH_4\ emission\ (kg \cdot hm^{-2}) \times}$$

where 298 and 25 represent the global warming potentials (GWP) of N O and CH relative to CO on a 100-year timescale, respectively.

The greenhouse gas emission intensity (GHGI), defined as CO equivalent per unit yield, was used to further evaluate the comprehensive greenhouse effect of each treatment:

$$\text{GHGI (kg} \cdot \text{kg}^{-1}) = \frac{\text{CO}_2\text{-eq (kg} \cdot \text{hm}^{-2})}{\text{crop yield (kg} \cdot \text{hm}^{-2})}$$

1.3.2 Soil Enzyme Activity Soil samples were collected on the same day as gas sampling using an "S" shaped sampling pattern with five random points per plot. A soil auger was used to collect samples from the 0–20 cm layer. After air-drying, samples were passed through a 20-mesh sieve for determination of urease and catalase activities. Urease activity was measured using the phenol-sodium hypochlorite colorimetric method, and catalase activity was determined using the potassium permanganate titration method [30].

1.4 Data Analysis and Processing

This study utilized data from the fourth year (2013) of a long-term straw crushing and mulching experiment. Differences in greenhouse gas emission fluxes and enzyme activities among treatments at the same growth stage were analyzed using SPSS 18.0 software with one-way ANOVA, and mean comparisons were performed using the least significant difference (LSD) method at a significance level of 0.05. Correlation analysis between soil greenhouse gas emission fluxes and enzyme activities and graphing were conducted using Microsoft Excel 2013.

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2. Results

2.1 Effects of Straw Return and Nitrogen Application on Maize Yield

As shown in [Figure 2: see original paper], the highest grain yield was obtained with the medium nitrogen treatment under straw return (S1N2), which was not significantly different from the highest nitrogen treatment without straw return (S0N3) ($P > 0.05$). The 100-kernel weight followed a similar pattern. Under straw return, both insufficient (S1N1) and excessive (S1N3) nitrogen applications significantly reduced grain yield, with the medium nitrogen treatment (S1N2, 240 kg · hm ^{2}) performing best. No significant difference in 100-kernel weight was observed between S1N2 and S1N3 treatments ($P > 0.05$). In contrast, without straw return, grain yield and 100-kernel weight increased with nitrogen application rate.

2.2 Effects of Straw Return and Nitrogen Application on Soil Greenhouse Gas Emissions

Table 1 shows that without straw return, nitrogen application increased CO and N O emissions and CH uptake. CO and N O emissions increased significantly with nitrogen rate, peaking in the S0N3 treatment. No significant difference in CH uptake was observed between S0N2 and S0N3 treatments. Straw return significantly increased soil CO emissions, with no significant differences among nitrogen treatments ($P > 0.05$). The combination of straw return and nitrogen application increased CH sequestration and enhanced carbon sink function, with S1N2 showing the maximum effect. Both straw return and nitrogen application significantly increased the comprehensive greenhouse effect (CO -eq) and greenhouse gas emission intensity (GHGI). Without straw return, increasing nitrogen rate significantly increased CO -eq and GHGI, with S0N3 showing the highest values. When nitrogen application was combined with straw return, CO -eq and GHGI did not increase significantly, while the medium nitrogen treatment (S1N2) significantly reduced GHGI. Excessive or insufficient nitrogen application with straw return significantly increased the environmental cost of maize production, making the medium nitrogen rate (240 kg · hm ^{2}) the most appropriate.

2.3 Effects of Straw Return and Nitrogen Application on Soil Enzyme Activities

Soil catalase activity gradually increased while urease activity gradually decreased throughout the maize growth period [Figure 3: see original paper]. At maturity (142 days after sowing), catalase activity was 1.3–5.0 times that at the jointing stage (44 days), while urease activity at jointing was 1.2–2.9 times that at maturity. Straw return amplified the increase in soil catalase activity but reduced the magnitude of decrease in soil urease activity. From jointing to maturity, catalase activity increased by 3.1–4.6 times under straw return treatments compared with only 1.3–2.6 times without straw return [FIGURE:3A, B]. Urease activity decreased by 0.5–0.7 times under straw return treatments versus 0.3–0.7 times without straw return [FIGURE:3C, D]. Nitrogen application reduced soil catalase activity but increased urease activity. Without straw return, high nitrogen level (N3, 300 kg · hm ^{2}) consistently showed lower catalase activity [FIGURE:3A, C], while with straw return, medium nitrogen level (N2, 240 kg · hm ^{2}) showed higher catalase activity [FIGURE:3B, D].

2.4 Relationship Between Soil Enzyme Activities and Greenhouse Gas Fluxes

As shown in [Figure 4: see original paper], greenhouse gas fluxes in maize fields were highly significantly correlated with soil enzyme activities ($r = 0.61$–0.95^{**}). CO and N O fluxes decreased exponentially with increasing catalase activity, while CH flux increased. Both CO and N O fluxes showed a quadratic relationship with soil urease activity (increasing then decreasing), whereas CH flux showed the opposite pattern (decreasing then increasing).

Discussion

The goal of agricultural production is to enhance crop economic yield and promote sustainable development. Farmland ecosystems must balance economic and environmental benefits, which is particularly crucial for high-latitude Northeast agricultural regions. This study demonstrated that both rational fertilization and straw return significantly increased maize yield, with the highest yield achieved under straw return with medium nitrogen application, which was not significantly different from the highest nitrogen treatment without straw return. This indicates that continuous straw return for over three years can substitute for part of the nitrogen fertilizer while maintaining high maize yields. Since microbial decomposition of straw consumes soil nitrogen, supplemental nitrogen application is needed to resolve the "nitrogen competition" with crops. This study identified the optimal nitrogen rate as 240 kg · hm ^{2}, which produced the highest grain yield. Additionally, the results showed that without straw return, increasing nitrogen application significantly increased the comprehensive greenhouse effect and soil greenhouse gas emission intensity, whereas the combination of nitrogen application with straw return did not significantly increase these parameters. Therefore, straw return with appropriate nitrogen application can significantly reduce the comprehensive greenhouse effect and soil greenhouse gas emission intensity; otherwise, both would increase the environmental cost of maize production.

In spring maize fields of the Northeast black soil region, straw return primarily increased soil CO emissions, while the combination of straw return and nitrogen application enhanced the soil' s function as a "weak" CH carbon sink. Without straw return, increasing nitrogen application significantly increased both CO and N O emissions. Previous studies have shown that both fertilization and straw return can promote CO emissions, a conclusion supported by this study. This may occur because straw return combined with nitrogen application alleviates the competition for nitrogen between soil microorganisms and crops, with appropriate soil nitrogen levels promoting microbial activity, enhancing root growth and respiration, and ultimately increasing CO emissions. Although debate continues regarding whether nitrogen application promotes N O emissions, the prevailing view holds that nitrogen application increases N O emissions, a finding supported by this study. This may result from direct N O generation through microbial nitrification and denitrification of externally applied nitrogen. Therefore, effectively controlling nitrogen input in spring maize production in black soil regions can reduce soil N O emissions.

The characterization of soil catalase and urease activity changes in this study supports these conclusions. The relationship between soil enzyme activities and greenhouse gas emission fluxes further demonstrated that nitrogen application reduced catalase activity but increased urease activity, while straw return amplified the increase in catalase activity and diminished the decrease in urease activity. Regression analysis between the three greenhouse gas fluxes and the two soil enzyme activities revealed that greenhouse gas fluxes varied exponentially with catalase activity (CO and N O decreasing while CH increased) and quadratically with urease activity (CO and N O increasing then decreasing, while CH showed the opposite trend). Approximately 85% of CO in farmland ecosystems originates from soil microbial activity and 15% from crop root respiration. Strong catalase activity helps remove "toxic" reactive oxygen species from metabolism, enhancing maize root and microbial activity and increasing CO emissions.

This study addresses the global warming context by examining the effects of straw crushing-return and nitrogen rates on spring maize grain yield, soil greenhouse gas (CO , N O, and CH) emissions, and key soil carbon and nitrogen metabolic enzymes (catalase and urease activity). It clarifies the relationship between soil greenhouse gas emission fluxes and soil enzyme activities under straw return and increased nitrogen application, providing valuable insights for sustained yield increase and greenhouse gas emission reduction in Northeast black soil spring maize production. The findings offer important reference value for improving farmland soil, enhancing farmland carbon sequestration, and reducing agricultural greenhouse gas emissions. Future research should quantitatively analyze the relationship between climatic factors (temperature, precipitation) and greenhouse gas emissions under straw return conditions, and quantitatively characterize the effects of straw return on key processes of maize root morphological development and senescence and their relationship with yield formation.

Conclusion

Straw return combined with nitrogen application significantly increased maize yield, with the highest yield achieved at medium nitrogen level (240 kg·hm ^{2}) under straw return. Nitrogen application promoted CO and N O emissions, while straw return increased CO emissions but significantly reduced emission intensity. The combination of straw return and nitrogen application enhanced the soil' s CH carbon sink function. Nitrogen application reduced soil catalase activity but increased urease activity, whereas straw return amplified the increase in catalase activity and diminished the decrease in urease activity. This study demonstrates that straw return with 240 kg·hm ^{2} nitrogen application had the lowest environmental cost and could effectively inhibit the promotion of comprehensive greenhouse effect and soil greenhouse gas emission intensity caused by nitrogen application alone.

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