Postprint: Effects of Different Tillage Practices on the Carbon Footprint of Rainfed Winter Wheat

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Abstract

To understand the impacts of different tillage management practices on the carbon emission footprint of production inputs and processes throughout the life cycle of crop production in rainfed farmland of northern China, we measured the annual N2O emission fluxes from rainfed winter wheat fields for two consecutive years using the static chamber-gas chromatography method at a long-term stationary experimental site for conservation tillage in Yaodu District, Linfen City, Shanxi Province, under different straw management and tillage practices (straw removal with rotary tillage, straw incorporation with rotary tillage, and straw mulching with no-till). A comprehensive analysis and calculation of carbon emissions from production inputs and processes under different tillage management practices was conducted to estimate the carbon footprint of different tillage practices. The results showed that: 1) The annual cumulative N2O emissions from rainfed winter wheat fields under straw mulching with no-till and straw removal with rotary tillage were reduced by 19.2% and 18.9% on average, respectively, compared with straw incorporation with rotary tillage; 2) Rainfed winter wheat achieved the highest yield under straw mulching with no-till; 3) Nitrogen fertilizer production, direct N2O emission from farmland, and diesel consumption emissions accounted for over 90% of the total carbon footprint in rainfed farmland; 4) Straw mulching with no-till had a lower carbon footprint than other tillage practices. During the two-year experimental period, the carbon footprint was 11.0% and 6.9% lower compared with the straw incorporation with rotary tillage treatment, and 7.9% and 8.3% lower compared with the straw removal with rotary tillage treatment; 5) In semi-arid regions, straw mulching with no-till had the lowest carbon footprint per unit yield and is the recommended practice for low-carbon and low-emission in this study. The results of this study can provide a scientific basis for the sustainable development of rainfed farmland aiming at low-carbon emission reduction.

Full Text

Effect of Tillage Practice on Carbon Footprint of Rainfed Winter Wheat

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Abstract: Sustainable agricultural production requires mitigating greenhouse gas emissions from soil and reducing carbon emissions from the production of agricultural inputs and farming processes. To evaluate the carbon footprint and emission intensity of different tillage practices in rainfed systems, we conducted a 15-year long-term experiment in Linfen, Shanxi Province, a typical semi-arid region of northern China. Three tillage management practices were investigated: rotary tillage without straw incorporation (RT), straw incorporation with rotary tillage (SRT), and straw mulch with no-tillage (SNT). The carbon footprint throughout the production lifecycle of rainfed winter wheat was assessed by measuring field N O emissions using the static chamber-gas chromatography method and calculating emissions from agricultural inputs and associated processes. Results showed that: (1) Annual cumulative N O emissions under SNT and RT were 19.2% and 18.9% lower than under SRT, respectively; (2) Winter wheat yield was highest under SNT conditions; (3) Nitrogen fertilizer production, direct N O emissions from fields, and diesel fuel consumption accounted for over 90% of the total carbon footprint; (4) SNT had the lowest carbon footprint among all practices, being 11.0% and 6.9% lower than SRT, and 7.9% and 8.3% lower than RT during the two experimental years; and (5) In semi-arid regions, SNT produced the lowest carbon footprint per unit of yield, representing the recommended practice for low-carbon, low-emission agriculture. These findings provide a scientific basis for sustainable development of dryland agriculture aimed at carbon mitigation in semi-arid regions.

Keywords: straw incorporation; no-tillage; rainfed wheat; N O emission; carbon footprint

Introduction

N O is a major agricultural greenhouse gas with a global warming potential 298 times that of CO over a 100-year timescale, contributing approximately 5% to the atmospheric greenhouse effect [1]. Agricultural activities represent the most important anthropogenic emission source after energy and industrial sectors, accounting for 10–12% of global anthropogenic emissions [2]. An estimated 90% of annual atmospheric N O emissions originate from soil, with cropland soils making substantial contributions [3-4]. Understanding N O emission characteristics and influencing factors in farmland and identifying mitigation measures are crucial for slowing global climate change and achieving sustainable agriculture.

Carbon footprint, measured from a lifecycle perspective, quantifies the direct or indirect CO_2 equivalent emissions caused by an activity or accumulated during a product' s lifecycle [5-7]. This approach has become an important analytical framework for low-carbon agriculture research [7-9]. Winter wheat (*Triticum aestivum* L.) is a major food crop in China, with dryland farming being the primary production method in the extensive northern arid regions [10]. Improper nitrogen fertilizer application in dryland systems constitutes a significant source of atmospheric N_2O [11]. Although dryland soils act as weak CH_4 sinks, their low magnitude is generally not calculated separately in national greenhouse gas inventories. Furthermore, under the United Nations Framework Convention on Climate Change (UNFCCC), CO_2 emissions from managed croplands are not yet included in greenhouse gas inventories, which only account for emissions from land-use changes such as deforestation [1].

For dryland agroecosystems, N_2O emissions from nitrogen fertilizer application and diesel consumption from tillage, planting, and harvesting operations represent primary emission sources. Insufficient input of production materials during the production process is a major challenge in semi-arid agricultural production. Returning crop residues—straw—to fields is a simple and effective method to increase carbon inputs to soil and can curb the decline in soil organic carbon (SOC) [10,13-16]. Numerous studies have reported that reasonable straw mulch with no-tillage or reduced tillage can reduce soil water loss and increase crop yields [10,13-16]. However, comprehensive reports on the combined effects of different tillage management practices on N_2O emissions and carbon footprints in dryland systems remain scarce. Studies on the effects of reduced or no-tillage on N_2O emissions have reported both increases and decreases [17]. Chinese scholars have investigated the comprehensive warming potential of greenhouse gases in high-yield farmland in North China under different management practices [18], considering carbon emissions from agricultural activities such as machinery fuel consumption, irrigation electricity use, and fertilizer application [19]. However, soil moisture conditions in China' s semi-arid regions differ substantially from those in the high-yield areas of North China, and the effects of different tillage practices on N_2O emissions and full-chain carbon footprints of agricultural inputs and processes exhibit distinct characteristics. This study addresses this research gap by scientifically evaluating the impacts of different tillage management practices on the carbon footprint and emission intensity of rainfed winter wheat in semi-arid dryland systems. Conducted at a 17-year long-term experimental site in Linfen, Shanxi, this research monitored N_2O emissions for two consecutive years and estimated carbon emissions from machinery fuel consumption and full production chains of all inputs to evaluate the carbon footprint and emission intensity of different tillage practices, aiming to provide data support for greenhouse gas mitigation and sustainable agricultural production in semi-arid dryland systems.

Materials and Methods

1.1 Experimental Site

The field experiment was located at the Conservation Tillage Fixed-Way Long-Term Experimental Site in Chenghuang Village, Xiandian Town, Yaodu District, Linfen City, Shanxi Province (111°30 N, 36°04 E). This site features permanent lanes for tractor and machinery traffic, each 30 cm wide, left untilled and unplanted. The lanes are spaced 150 cm apart, with six rows of wheat planted between them at 20 cm row spacing, ensuring the crop growth zone remains uncompacted by wheels [20]. Established in 1997, the long-term experiment had been running for 15 years by 2012, representing Asia' s earliest fixed-way no-tillage trial and providing an important platform for monitoring long-term effects of different tillage management on crops and soils. The experimental area has a temperate continental climate with an average annual temperature of 12.6°C, average annual precipitation of 527 mm, and a frost-free period of approximately 190 days. The soil is dryland cinnamon soil, and the cropping system is single-crop winter wheat annually under rainfed conditions without irrigation. The winter wheat cultivar 'Linfen 227' was sown in 2011, while the cultivar 'Chang 6359' was used for both the 2012–2013 and 2013–2014 seasons.

1.2 Experimental Design and Field Management

The experiment included three treatments: (1) rotary tillage without straw incorporation (RT, conventional local practice), (2) straw incorporation with rotary tillage (SRT), and (3) straw mulch with no-tillage (SNT). The original long-term experiment included only SRT and SNT treatments without replication for operational convenience, with each treatment area approximately 0.13 ha. For this study, three 30 m^2 sampling plots were established within each original SRT and SNT treatment area as replicates. Additionally, sampling plots and replicates were added in the non-straw-returned protective row area of the original experimental site (with all other operations identical except straw removal) as a conventional control for rotary tillage without straw incorporation (RT). Under RT, wheat straw was completely removed after mechanical harvest, followed by rotary tillage before sowing. Under SRT, straw (chopped to 15–20 cm length) was spread on the surface after mechanical harvest, followed by rotary tillage before sowing. Under SNT, high stubble (approximately 30 cm) remained after mechanical harvest, with the remaining straw chopped and spread on the surface, followed by direct seeding of the next wheat crop using a no-till seeder in late September without further soil tillage. All treatments received a single basal application of nitrophosphate compound fertilizer (containing 25% N and 12% P O) at 450 kg(N) · ha^{1}, equivalent to 112.5 kg(N) · ha^{1} and 123.7 kg(P O) · ha^{1}. Fertilizer application dates were September 24, 2012, and September 26, 2013, synchronized with sowing. Harvest dates were June 13, 2013, and June 15, 2014.

1.3 Soil Properties

On September 23, 2012, soil samples from 0–20 cm depth were collected from each treatment for physicochemical analysis. The soil texture was light loam, with other properties shown in .

Precipitation from September 2012 to September 2013 was 593.7 mm, with 180.6 mm during the wheat growing season. From September 2013 to September 2014, precipitation was 731.6 mm, with 283.5 mm during the wheat growing season [Figure 1: see original paper]. Precipitation was concentrated during the summer fallow period from July to September.

1.5 Sample Collection

N O emissions were measured using the static chamber-gas chromatography method. Sampling chambers were made of opaque PVC material, 25 cm in diameter and 30 cm in height, with matching PVC base rings featuring grooves to seal the chamber-base interface. Gas samples (35 mL) were collected at 0, 10, 20, and 30 minutes using syringes and injected into 12 mL vacuum vials (Labco, UK). Sampling occurred between 9:00–11:00 AM, a period closest to the daily mean temperature and representative of average daily flux [18]. One chamber was placed in each experimental plot, with three replicates per treatment. Gas sampling was conducted from September 25, 2012, to September 20, 2014. During the growing season, samples were collected every 7 days; in winter (November to January), every 10–20 days; and after fertilization and rainfall, every 2 days for three consecutive collections. Simultaneously, chamber temperature and soil temperature at 5 cm depth were measured using self-made thermistors (±0.5°C error). Soil volumetric water content at 5 cm depth was measured using a portable soil moisture meter (Model TZS- , Zhejiang Top Instrument Co., Ltd.). Precipitation was measured using an automatic rain gauge. Serum vials were analyzed within one week using a gas chromatograph (Agilent 7890B) to determine N O concentrations, with fluxes calculated based on concentration change rates and chamber volume.

1.6 Sample Measurement and Calculation

N O gas samples were analyzed using an Agilent 7890B gas chromatograph equipped with an electron capture detector (ECD) operating at 330°C. The analytical column was a Porpak Q packed column at 70°C, with pure N as carrier gas at 25 mL · min ¹. Detection precision was ±5.5 L · L ¹. The N O flux calculation formula was:

F = × H × k × (273.15 / (273.15 + T))

where F is the N O flux (g · m ² · h ¹), is the N O gas density under standard conditions (0°C and 100 kPa) (1.96 kg · m ³), H is the chamber height (m), k is the N O concentration change rate in the chamber (L · L ¹ · h ¹), and T is the average temperature inside the chamber (°C).

1.7 Carbon Footprint Calculation

This study employed carbon footprint analysis for comprehensive greenhouse effect assessment. The lifecycle assessment (LCA) method established by Brentrup et al. [21] was used for carbon footprint calculation, encompassing three stages: raw material extraction, agricultural input production, and crop production. This methodology enables systematic and comprehensive analysis of greenhouse gas emissions from crop production processes and associated activities. The calculation formula was:

$fC = \Sigma(i=1 \text{ to } n)\ (mi \times\ i)$

where fC is the agricultural production carbon footprint, n represents the number of consumed materials (energy or production inputs), fCi is the carbon footprint of the i-th material, mi is the consumption amount of the i-th material, and i is the carbon emission factor of the i-th material. Carbon footprint was expressed as CO equivalent emissions [kg(CO -e)], with N O emissions multiplied by 298 to convert to CO equivalent, in units of kg(CO -e) $\cdot$ ha^{1} $\cdot$ yr^{1} [21]. Carbon emission factors for agricultural inputs and activities are shown in .

Emissions per unit yield were calculated as:

Unit yield emissions = Carbon footprint per unit area / Wheat yield per unit area

1.8 Data Processing

Microsoft Excel 2007 was used for chart preparation. SAS 8.0 software was used for statistical analysis, with analysis of variance to compare differences among treatments at a significance level of = 0.05.

Results

2.1 Soil N O Emission Characteristics Under Different Tillage Practices

Precipitation in this region is concentrated in summer when soil moisture and temperature are high. Spring soil water content in 2014 was 6.4% higher on average than in 2013 [Figure 2a: see original paper], while summer soil temperature in 2013 was 5.7°C higher on average than in 2014 [Figure 2b: see original paper]. During summer (June–August), the 5 cm soil temperature under SNT was 0.54°C lower than under SRT but 0.42°C higher than under RT [Figure 2b: see original paper]. In spring, surface soil moisture under SNT was 3.5% and 1.7% higher than under RT and SRT, respectively [Figure 2a: see original paper]. Overall, N O emission fluxes under SRT were higher than under SNT (averaging 22.2% higher), particularly evident from the wheat regreening stage in 2013 through the autumn sowing period [Figure 2c: see original paper].

Total annual N O emissions under RT and SNT were lower than under SRT, with average reductions of 19.2% and 18.9% over two years, respectively. The reduction was greater in 2013, reaching 26.0% and 25.6% compared to SRT. Except for RT, where N O emissions showed no significant correlation with soil moisture, emissions under other tillage practices were significantly positively correlated with both soil temperature and moisture, though the correlation with 5 cm soil temperature was stronger . Higher precipitation and lower soil temperature in 2014 likely contributed to lower N O emissions compared to 2013.

[Figure 2: see original paper]

2.2 Carbon Footprint of Different Tillage Methods

Components contributing to the winter wheat carbon footprint from sowing to harvest are shown in . Factors other than N O emissions contributed similarly to the carbon footprint each year, while field N O emissions varied with annual climate conditions. The greenhouse effect of N O was calculated as 298 times that of CO by mass. Annual carbon footprints for each treatment were: RT—490.3 kg(CO -e) · ha ^{1} · yr ^{1} and 507.5 kg(CO -e) · ha ^{1} · yr ^{1}; SRT—451.5 kg(CO -e) · ha ^{1} · yr ^{1} and 465.9 kg(CO -e) · ha ^{1} · yr ^{1}; and SNT—458.7 kg(CO -e) · ha ^{1} · yr ^{1} and 427.1 kg(CO -e) · ha ^{1} · yr ^{1}. The contribution ranking to total carbon footprint was consistent across treatments: chemical fertilizer production (46.4% average) > field N O emissions (21.6% average) > diesel consumption from tillage and sowing (25.2% average) > seed production emissions (4.4% average) > pesticide production and use emissions (2.4% average). Field N O emissions, nitrogen fertilizer production emissions, and diesel consumption emissions accounted for over 90% of the total carbon footprint, representing the three main contributing factors. Seed and pesticide production contributed less than 5% each.

Carbon footprint estimation showed SNT had lower emissions than other practices, reducing the footprint by 11.0% and 6.9% compared to SRT, and by 7.9% and 8.3% compared to RT during the two years. SNT represents an effective emission-reduction management practice for dryland wheat systems. Compared to RT, SNT primarily reduced diesel consumption from tillage (accounting for over 6% of emission reduction), while compared to SRT, N O emission reduction accounted for 4% of the total reduction.

2.3 Yield of Rainfed Wheat Under Different Tillage Methods

As shown in [Figure 3: see original paper], SNT increased wheat yield by 41.7% in 2013 and 14.3% in 2014 compared to SRT. The increase was greater in the dry year of 2013, with an average yield increase of 21.8% over two years.

[Figure 3: see original paper]

2.4 Carbon Cost Analysis of Winter Wheat Under Different Tillage Methods

Based on wheat yield per unit area and carbon footprint values, carbon emissions per unit of wheat production were calculated . Under rainfed conditions, SNT produced the highest yield with the lowest carbon footprint, resulting in the lowest carbon footprint per unit of yield. In 2013, the carbon footprint per unit yield under SNT was lower than under RT and SRT.

Discussion

3.1 Analysis of N O Emission Reduction Effects of Different Tillage Practices on Dryland Wheat Fields

Soil N O emissions are primarily produced through microbial nitrification-denitrification processes. Soil temperature, moisture, and mineral nitrogen content are the main environmental factors affecting N O emissions, and different tillage practices can alter these soil properties, thereby influencing emissions [24-25]. Straw incorporation increases soil organic matter content, affects soil physical structure, and changes the microbial environment, consequently impacting N O emissions. By increasing carbon supply to soil, straw incorporation promotes denitrification, resulting in significantly higher N O emissions from wheat fields compared to no straw incorporation [26]. Straw mulch no-tillage can increase soil moisture and alter surface temperature, affecting N O emissions. During early no-tillage implementation, increased soil bulk density enhances water retention in surface soil, creating anaerobic conditions that increase potential denitrification rates and promote N O emissions [27]. However, this study was conducted under long-term straw mulch no-tillage conditions (17-year long-term experiment), and soil N O emissions were lower than under straw incorporation with rotary tillage , consistent with some studies in arid and semi-arid regions [28-30] but differing from reports from Australia, Europe, and Canada [17,31]. This discrepancy may be attributed to generally low soil moisture in arid and semi-arid regions, where volumetric water content remains below 60% year-round. Soil moisture under straw mulch no-tillage is slightly higher than under rotary tillage during non-rainy seasons, with smaller differences during rainy seasons relative to baseline moisture values. Additionally, straw mulch no-tillage reduces soil temperature in the plow layer (surface straw provides insulation during hot months, lowering soil temperature). Correlation analysis between soil N O emissions and temperature confirmed that temperature variation significantly affects emissions. Furthermore, Rochette [32] found that no-tillage increases N O emissions in poorly aerated soils but has little effect on well-aerated soils. The long-term fixed-way no-tillage system used in this study avoided the widespread soil compaction typical of conventional no-tillage, improving soil porosity and increasing surface soil aeration (bulk density in the 0–10 cm layer under no-tillage was lower than under rotary tillage, as described in the Materials and Methods). This reduced anaerobic conditions, decreased denitrification rates, and reduced N O emissions. The experimental soil was light loam with light texture, so no-tillage did not impair soil aeration, and thus straw mulch no-tillage did not increase N O emissions.

3.2 Comprehensive Emission Reduction Effects of Different Tillage Practices

Conservation tillage reduces surface evaporation and significantly improves soil water storage and moisture content, with the water conservation effect of straw mulch no-tillage being particularly prominent in low-precipitation years [16]. Under rainfed conditions, straw mulch no-tillage helps maintain soil moisture and can increase winter wheat yield. Carbon footprint analysis of rainfed winter wheat production under different tillage practices revealed that emissions from chemical fertilizer production and direct N O emissions after fertilizer application accounted for the largest proportion of the total carbon footprint. This is primarily because fertilizer production and transportation consume substantial fossil fuels, and China' s grain production relies heavily on fertilizers, particularly nitrogen, with usage rates exceeding optimal levels [33]. Excessive nitrogen application further increases field N O emissions [34]. Therefore, rational nitrogen reduction would significantly decrease emissions from both industrial production (e.g., fertilizer manufacturing) and field application. Our analysis of carbon footprints in rainfed winter wheat production systems under different tillage practices demonstrated that straw mulch no-tillage not only reduced soil N O emissions but also decreased mechanical tillage fuel consumption, resulting in the lowest total carbon footprint. Moreover, the carbon footprint per unit of wheat yield under straw mulch no-tillage was lower than under other practices, demonstrating the best comprehensive emission reduction effect, consistent with findings by Wu et al. [35]. Additionally, straw mulch no-tillage provides other benefits such as water conservation and soil temperature improvement [16]. Therefore, straw mulch no-tillage represents an optimal low-carbon, high-efficiency management model for light-textured dryland farming systems.

The main components of the carbon footprint in dryland farming are field N O emissions, nitrogen fertilizer production emissions, and diesel consumption emissions. In semi-arid and semi-humid regions, straw mulch no-tillage can reduce both field N O emissions and carbon emissions from mechanical fuel consumption. In the semi-arid and semi-humid region of southern Shanxi, straw mulch no-tillage increased rainfed winter wheat yield while maintaining the lowest carbon footprint per unit of wheat production, demonstrating the best comprehensive emission reduction effect.

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Note: Figure translations are in progress. See original paper for figures.