

Short-Term Effects of Straw Return, Two-Year Film Mulching, and Intercropping on Cropland Carbon Emissions (Postprint)

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Abstract

To address the issues of high carbon emissions from high-yield crop production models and the lack of emission reduction theories and technologies in practical production, field experiments were conducted to investigate the effects of different straw return methods, two-year use of plastic film mulching, and intercropping on carbon emission characteristics in wheat and maize croplands, aiming to provide theoretical and practical foundations for constructing carbon emission reduction cropping patterns and supporting technologies. The results indicated that intercropping had a significant carbon emission reduction effect. Compared with conventional monoculture wheat and maize, wheat||maize intercropping reduced the average total carbon emissions during the entire growth period by 279–876 kg · hm², with a reduction of 5.1%–16.0%, reaching significant differences. No-tillage with straw return and no-tillage with two-year film use could reduce cropland soil carbon emissions in the following year. No-tillage with straw return in monoculture wheat significantly reduced CO₂ emissions by 648–966 kg · hm² compared with conventional tillage, a reduction of 21.3%–31.8%; no-tillage with two-year film use in monoculture maize reduced carbon emissions by 632 kg · hm² compared with the conventional tillage with new film mulching, a reduction of 10.0%, with significant differences. The integrated application of wheat straw return and two-year film use in wheat-maize intercropping further enhanced the carbon emission reduction effect of intercropping. Compared with the conventional intercropping treatment (CTI1), the total carbon emissions of the intercropped wheat with high stubble no-tillage combined with two-year film use treatment (NTSSI2) and the wheat straw return mulching combined with two-year film use treatment (NTSI2) decreased by 471 kg · hm² and 518 kg · hm², respectively, with reduction rates of 9.2% and 10.1%, reaching significant levels; the NPPC/Ras values (ratio of total carbon sequestration to total carbon released by soil respiration) of NTSSI2 and NTSI2 were 13.7

and 14.0, respectively, which were 19.1% and 21.7% higher than that of CTI1, indicating that NTSI2 had more prominent emission reduction and carbon sink potential. Therefore, wheat-maize intercropping with high stubble (25~30 cm) straw mulching under no-tillage combined with two-year film use (NTSI2) can serve as an efficient cropping system model for carbon emission reduction and carbon sequestration enhancement in arid oasis irrigation areas.

Full Text

Preamble

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Short-term response of farmland carbon emission to straw return, two-year plastic film mulching and intercropping*

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Abstract

Conventional crop production has long associated high yields with high carbon emissions, creating an urgent need to develop theoretical and practical strategies for achieving high yields with low carbon emissions in modern agriculture. This study conducted a field experiment in a typical oasis irrigation region to determine the integrated response of carbon emission in wheat-maize intercropping systems under different straw-return (straw standing, straw mulching and no-mulching), plastic film mulching (mulching for one year and two years), cropping (wheat-maize intercropping, monoculture of wheat and maize) and tillage (no-tillage, conventional tillage) patterns. The results showed that intercropping significantly decreased soil carbon emissions in farmlands. Compared with monoculture wheat and maize under conventional tillage management, the averaged total soil CO₂ emissions in wheat-maize intercropping systems reduced by a range of 279–876 kg · hm⁻², the equivalent of 5.1%–16.0%. No tillage with straw-return and plastic film mulching for two years reduced soil carbon emissions in the next year. No-tillage in combination with straw-return to soil decreased total soil CO₂ emissions by 648–966 kg · hm⁻², the equivalent of 21.3%–31.8%, compared with conventional tillage without straw-return to soil in mono-cropped wheat field. Plastic film mulching for two years reduced total soil CO₂ emissions by 632 kg · hm⁻² compared with conventional tillage in mono-cropped maize. In particular, wheat-maize intercropping in combination with straw-return to soil and two-year plastic film mulching further reduced carbon emissions. Compared with conventional intercropping with plastic film mulching for one year and conventional tillage (CTI1), wheat-maize intercropping with 25–30 cm of standing

straw, two-year plastic film mulching and no-tillage (NTSSI2) and wheat-maize intercropping with 25-30 cm straw mulching on the soil and two-year plastic film mulching and no-tillage (NTSI2) reduced total soil CO₂ emissions by 471 kg · hm⁻² and 518 kg · hm⁻², the equivalent of 9.2% and 10.1%, respectively. The carbon sequestration potential (ratio of total plant carbon fixation to total soil carbon emission, i.e., NPPC/Ras) were 13.7 and 14.0, respectively, in NTSSI2 and NTSI2 treatments, which were higher by 19.1% and 21.5% than that of CTI1, respectively. This indicated that NTSI2 had a more prominent potential for reducing carbon emissions and enhancing carbon sequestration. Thus, NTSI2 was recommended as the best farming pattern due to its high efficiency of carbon emission reduction and carbon sequestration in irrigated arid oasis regions.

Keywords: Straw-return to soil; Two-year plastic film mulching; Wheat-maize intercropping; Carbon emission; Carbon budget

Introduction

Soil ecosystems provide nutrients and water for plant growth and development while simultaneously emitting large amounts of CO₂. Relevant data indicate that approximately 5%-20% of atmospheric CO₂ originates directly from soil annually, with farmland serving as the primary emission source. Developing effective planting patterns and tillage measures to reduce farmland CO₂ emissions represents an important research topic for sustainable agricultural development. Production practices have demonstrated that intercropping provides a foundation for the three-dimensional utilization of ecological niches in both time and space for crops with different resource demand characteristics, facilitating interspecific complementarity and efficient resource utilization, thereby establishing the basis for increasing yield and effectively reducing farmland soil carbon emissions. Wheat-maize intercropping is a typical high-yield multi-cropping pattern in China that has made important contributions to national food security, yet its large-scale application faces the challenge of coordinating high yield with emission reduction.

Research has shown that conservation tillage, as an important agricultural practice for achieving sustainable development, can significantly reduce farmland soil carbon emissions and increase CO₂ sequestration and retention. However, few studies have reported on the application of this technology in intercropping systems, preventing the advantages of integrated yield increase and emission reduction from being realized. Additionally, with increasing drought stress and food demand pressure, plastic film mulching has been widely applied as a cultivation technique for water conservation, temperature increase, and high yield. However, the fact that plastic film mulching increases carbon input and energy consumption while generating carbon emissions necessitates further research on reduced plastic film crop production technologies.

A comprehensive review of low-input, carbon-reducing crop production theory and technology research reveals that few studies have integrated intercropping, conservation tillage, and plastic film reduction technologies into a single system, leaving a lack of theoretical basis for constructing high-yield, low-input, emission-reducing farming systems based on intercropping in production practice. Therefore, this study, based on wheat-maize intercropping and integrating straw return, two-year plastic film use, and no-tillage techniques, explored the effects of combined agronomic measures on farmland carbon emission characteristics to provide practical and theoretical foundations for establishing high-yield, low-emission farming systems in oasis irrigation regions.

Materials and Methods

1.1 Study Site

The study was conducted at the Oasis Agriculture Research and Teaching Base of Gansu Agricultural University (103°5 E, 37°30 N). The experimental area is located at the eastern end of the Hexi Corridor and belongs to a cold temperate arid climate zone, with an altitude of 1,506 m, a frost-free period of approximately 155 days, multi-year average rainfall of about 156 mm, annual evaporation of about 2,400 mm, and an average annual temperature of 7.2°C. The 10°C accumulated temperature is 2,985.4°C, with 2,945 hours of sunshine. The 0–30 cm soil layer contains total nitrogen of $1.41\text{ g}\cdot\text{kg}^{-1}$, total phosphorus of $1.41\text{ g}\cdot\text{kg}^{-1}$, and organic matter of $14.31\text{ g}\cdot\text{kg}^{-1}$, making it suitable for developing intercropping systems. Wheat-maize intercropping is the main intercropping pattern in this region, with traditional cultivation practices involving no straw return, annual plowing, and plastic film mulching in maize strips. During the 2014 experimental period, precipitation from wheat sowing to harvest was 100.9 mm, while precipitation from maize sowing to harvest was 241.7 mm.

1.2 Experimental Design

A preliminary experiment was established in 2013, with the formal experiment conducted in 2014. The experiment employed a three-factor randomized block design. The three factors were: cropping pattern (monoculture wheat, monoculture maize, wheat-maize intercropping), wheat straw management method (25–30 cm high stubble harvest with no-tillage, 25–30 cm high equivalent straw mulching with no-tillage, low stubble harvest with conventional tillage), and plastic film mulching method (conventional tillage with new film annually, no-tillage with two-year film use). These factors comprised eight treatments, each with three replicates. Treatment codes and operation specifications for different treatments are shown in Table 1.

Wheat (*Triticum aestivum*) variety ‘Ningchun 4’ and maize (*Zea mays*) variety ‘Xianyu 335’ were used. Wheat was sown on March 21 and harvested on July 24; maize was sown on April 25 and harvested on October 1. Monoculture wheat density was 6.75 million plants $\cdot\text{hm}^{-2}$, and monoculture maize density

was 82,500 plants \cdot hm⁻² with film mulching. The intercropping band width was 160 cm, with each crop occupying 80 cm. Wheat was planted in six rows per band with 12 cm row spacing at a density of 3.75 million plants \cdot hm⁻². Maize was planted in two rows with 40 cm row spacing and 24 cm plant spacing, with film mulching before sowing at a density of 52,500 plants \cdot hm⁻². Each plot contained three natural bands with an area of 48 m².

Monoculture wheat received pure nitrogen of 225 kg \cdot hm⁻² and P₂O₅ of 150 kg \cdot hm⁻² as base fertilizer. Monoculture maize received pure nitrogen of 450 kg \cdot hm⁻² applied in a 3:6:1 ratio at base, large trumpet stage, and grain filling stage, with P₂O₅ of 225 kg \cdot hm⁻² as base fertilizer. In the intercropping system, the wheat band received pure nitrogen of 225 kg \cdot hm⁻² and P₂O₅ of 150 kg \cdot hm⁻² as base fertilizer, while the maize band received pure nitrogen of 450 kg \cdot hm⁻² with the same base and topdressing ratio as monoculture maize, and P₂O₅ of 225 kg \cdot hm⁻² as base fertilizer.

1.3 Measurements and Calculations

1.3.1 Soil Respiration Rate (Rs) Soil respiration rate was measured using the LI-8100A soil respiration measurement system (LI-COR, USA) with its attached 20 cm diameter respiration chamber. During measurement, the chamber was placed between wheat and maize rows in the plots to collect CO₂ released from the soil, with five values recorded per point over a measurement period of 180 seconds. Diurnal variation was measured from 8:00 to 20:00 at 2-hour intervals, totaling seven measurements per day. Seasonal variation was measured according to crop growth stages, with nine measurements conducted throughout the entire growth period, and the data represent daily averages.

For maize strip measurements, the plastic film was removed 12 hours before measurement to expose a bare area the size of the respiration chamber edge, allowing accumulated CO₂ under the film to dissipate. The measurement was then considered as the respiration value of the maize strip soil. The intercropping respiration rate was calculated as the mean of the respiration rates of the two crop strips. After the early crop was harvested, the respiration rate of the bare strip of that crop was averaged with that of the late crop to represent the CO₂ respiration value of the entire plot (mol \cdot m⁻² \cdot s⁻¹). The cumulative CO₂ emission was calculated using the following formula [16]:

Where: Rs is the CO₂ emission rate, i+1 and i represent two adjacent measurements, t represents days after sowing, 0.1584 is the coefficient for converting carbon emission values from μ mol(CO₂) \cdot m⁻² \cdot s⁻¹ to g(CO₂) \cdot m⁻² \cdot h⁻¹, 0.2727 is the coefficient for converting from (CO₂) \cdot m⁻² \cdot h⁻¹ to g(C) \cdot m⁻² \cdot h⁻¹, and 10 and 24 are coefficients for converting carbon emission values from g(C) \cdot m⁻² \cdot h⁻¹ to kg(C) \cdot hm⁻².

1.3.2 Plant Sample Collection and Measurement Aboveground dry biomass was sampled every 20 days, with 20 wheat plants and 10 maize plants

taken per plot. Samples were killed at 105°C for 2 hours, then dried at 80°C to constant weight for measurement. Belowground biomass was sampled using the excavation profile method at wheat and maize maturity. For intercropping, the profile dimensions were 50 cm × 80 cm × 100 cm (length × width × depth), while for monoculture wheat and maize, the dimensions were 50 cm × 40 cm × 100 cm. Excavated soil was placed in 200-mesh nylon bags, soaked in water for several hours, rinsed, and roots were collected, rinsed again with clean water, dried, and weighed.

1.3.3 Farmland Ecosystem Carbon Budget Calculation Net ecosystem productivity (NEP) was used to represent the ecosystem carbon balance: $NEP = NPPC - R_m$ [17]. Where NPP is net primary productivity, which in this study was represented by the total carbon fixation in aboveground and belowground parts of crops as NPPC [18]. R_m is the carbon release from soil microbial heterotrophic respiration, calculated as $R_m = R_{as} \times 0.865$, where R_{as} is the total carbon emission from soil respiration during the crop growing season [19]. A positive NEP value indicates that the system acts as an atmospheric CO₂ absorption “sink,” while a negative value indicates an emission “source”. It is estimated that synthesizing 1 g of organic matter through photosynthesis requires absorbing 0.45 g of carbon, which allows calculation of the carbon fixation amount of primary productivity NPPC. According to existing research, NPPC/ R_{as} represents the carbon sequestration potential of the ecosystem soil, with higher values indicating stronger carbon sequestration potential.

1.4 Statistical Analysis Experimental data were organized and summarized using Microsoft Excel 2007, and significance tests were performed using SPSS 17.0 software.

Results

2.1 Seasonal Dynamics of Soil CO₂ Emission Flux in Wheat and Maize Monoculture and Intercropping Systems

2.1.1 Effects of Mulching and Planting Patterns on Seasonal Dynamics of Soil CO₂ Emission As shown in Figure 1 [Figure 1: see original paper], soil CO₂ emission flux throughout the entire growth period of monoculture wheat under standing stubble no-tillage (NTSSW), conventional tillage (CTW), and monoculture and intercropped maize exhibited a single-peak trend, while wheat strips under straw mulching no-tillage (NTSW), wheat-maize intercropping with standing stubble no-tillage and two-year film mulching (NTSSI2), and wheat-maize intercropping with straw mulching and two-year film mulching (NTSI2) showed a double-peak pattern. Wheat had the highest CO₂ emission flux at the flowering stage, with NTSSW and NTSW showing significantly lower emission fluxes than CTW, decreasing by 10.6% and 30.7%, respectively. The emission fluxes of wheat strips in NTSSI2 and NTSI2 were significantly lower than conventional tillage (CTI1), decreasing by 17.9% and 27.8%, respectively.

Both monoculture and intercropped maize had the highest CO₂ emission flux at the silking stage, with two-year film mulching in monoculture maize showing 14.3% lower emission flux than annual new film mulching. Emission fluxes in maize strips of NTSSI2 and NTSI2 were 6.1% and 5.6% lower than CTI1, respectively, reaching significant levels. This demonstrates that wheat straw return and two-year film mulching cultivation measures have the effect of reducing maximum farmland soil CO₂ emission flux.

Using the average of wheat and maize strip emission fluxes as the intercropping emission flux for comparison revealed that the average emission fluxes throughout the entire growth period of NTSSI2 and NTSI2 were 9.8% and 13.6% lower than CTI1, respectively. Compared with the average of corresponding monoculture emission fluxes throughout the entire growth period, NTSSI2, NTSI2, and CTI1 were 12.8%, 16.5%, and 3.3% lower, respectively. This indicates that integrating wheat straw no-tillage return and maize two-year film mulching cultivation measures into intercropping systems further enhances the emission reduction effect of intercropping.

2.1.2 Duration of High Emission Intensity Under Different Treatments Days with daily CO₂ emission flux higher than 5 mol · m⁻² · s⁻¹ were defined as high-emission days, while fluxes between 3-5 mol · m⁻² · s⁻¹ were defined as medium-emission days. The study found that CTW had 27 high-emission days, which was 18 and 27 days more than NTSSW and NTSW, respectively, but CTW had 15 and 24 fewer medium-emission days than NTSSW and NTSW, respectively. In intercropping systems, CTI1 had 15 more high-emission days (15 days) and 17-18 fewer medium-emission days (39 days) in wheat strips compared with NTSSI2 and NTSI2. The high-emission days of wheat strips in NTSSI2, NTSI2, and CTI1 were 27, 27, and 12 days fewer than CTW, respectively, indicating that intercropping and no-tillage straw mulching can reduce the duration of high-intensity CO₂ emission flux in wheat fields during the growth period.

Conventional tillage monoculture maize (SM1) had 60 high-emission days, which was 17 days more than no-tillage two-year film monoculture maize (SM2). SM1 had 45 medium-emission days, 7 days more than SM2, indicating that two-year film use can reduce the duration of high emissions. CTI1 had 13 and 17 more high-emission days in maize strips than NTSSI2 and NTSI2 (52 days), respectively, while CTI1 had 14 fewer medium-emission days (33 days) than NTSSI2 and 1 more than NTSI2. Compared with SM1, the maize strips of NTSSI2, NTSI2, and CTI1 had 20, 25, and 7 fewer high-emission days, respectively, demonstrating that intercropping and two-year film mulching cultivation measures can reduce the duration of high-intensity CO₂ emission flux in maize strips. Among different intercropping patterns, NTSSI2 and NTSI2 had 15 and 20 fewer high-emission days than CTI1, respectively. For medium-emission days, NTSSI2 had 11 more than CTI1, while NTSI2 had 2 fewer, indicating that wheat straw mulching, no-tillage, and two-year film mulching have advantages

in reducing intercropping CO₂ emissions.

2.2 Diurnal Variation Characteristics of Soil CO₂ Emission Flux in Wheat and Maize Monoculture and Intercropping Systems

2.2.1 Effects of Mulching Methods on Diurnal Variation of Soil CO₂ Emission Flux Throughout the crop growth period, soil CO₂ emission flux in farmland under different treatments showed an overall single-peak trend of low-high-low within the measurement period of 8:00–20:00 (Figure 2 [Figure 2: see original paper]). The average soil CO₂ emission flux of monoculture wheat peaked at 12:00, with conventional tillage showing the maximum emission flux of 4.60 mol · m⁻² · s⁻¹. For monoculture maize and intercropped wheat and maize, soil CO₂ emission flux peaked at 14:00, with conventional tillage showing the maximum emission fluxes of 5.19, 3.57, and 3.85 mol · m⁻² · s⁻¹, respectively.

2.2.2 Duration of Different Emission Flux Levels Within a Day Under Different Treatments Throughout the crop growth period, NTSSW and NTSW had 5 more hours of soil CO₂ emission flux higher than 4 mol · m⁻² · s⁻¹ within a day compared with CTW. The duration at 3–4 mol · m⁻² · s⁻¹ was 1.9 and 3.6 hours less than CTW, respectively. CTI1 had 0.6 hours less duration above 3 mol · m⁻² · s⁻¹ (1.9 hours) than NTSSI2 wheat strips, but 1.9 hours more than NTSI2 wheat strips. The duration above 3 mol · m⁻² · s⁻¹ in wheat strips of NTSSI2, NTSI2, and CTI1 was 9.5, 12.0, and 10.1 hours less than CTW, respectively, indicating that intercropping and no-tillage straw mulching measures can reduce the duration of high-intensity CO₂ emission flux in wheat strips within the same day.

SM1 had 1.8 more hours of duration above 4 mol · m⁻² · s⁻¹ (5.3 hours) than SM2, but 2.3 fewer hours at 3–4 mol · m⁻² · s⁻¹ (5.8 hours), indicating that two-year film mulching can reduce the duration of high CO₂ emission flux in maize farmland. The maize strips of CTI1 had 4.2 and 3.0 more hours of duration above 3 mol · m⁻² · s⁻¹ (8 hours) than NTSSI2 and NTSI2, respectively, but 4.2 and 3.0 fewer hours at 2–3 mol · m⁻² · s⁻¹ (4 hours). Compared with SM1, the maize strips of NTSSI2, NTSI2, and CTI1 had 5.4, 6.1, and 4.1 fewer hours of duration above 3 mol · m⁻² · s⁻¹, respectively, indicating that intercropping and two-year film mulching can reduce the duration of high-intensity CO₂ emission flux in maize strips within the same day. Among intercropping patterns, NTSSI2 and NTSI2 had 0.6 and 1.5 fewer hours of duration above 3 mol · m⁻² · s⁻¹ than CTI1, respectively, indicating that no-tillage straw mulching and two-year film mulching have advantages in reducing high CO₂ emissions from intercropping.

2.3 Total Soil CO₂ Emissions Under Different Treatments

2.3.1 Total Soil CO₂ Emissions Under Different Planting Patterns Intercropping reduced total farmland CO₂ emissions (Figure 3 [Figure 3: see original paper]). Before wheat harvest, the total carbon emissions from wheat strips in intercropping were significantly lower than CTW, and those from maize

strips were significantly lower than SM1, with reductions of 10.8%–34.1% and 8.4%–33.7%, respectively. The intercropping population reduced emissions by an average of 288–1,020 $\text{kg} \cdot \text{hm}^{-2}$ compared with conventional monoculture treatments, a reduction of 9.6%–34.0%. After wheat harvest, compared with CTW, the wheat strips in NTSI2 increased by 13.5%, while the total emissions of NTSSI2 and CTI1 decreased by an average of 73 $\text{kg} \cdot \text{hm}^{-2}$ and 70 $\text{kg} \cdot \text{hm}^{-2}$ compared with conventional monoculture treatments, representing reductions of 2.9% and 2.8%, respectively. However, NTSI2 increased by 143 $\text{kg} \cdot \text{hm}^{-2}$, an increase of 5.8%. Throughout the entire growth period, intercropping reduced total emissions by 279–876 $\text{kg} \cdot \text{hm}^{-2}$ compared with conventional monoculture, a reduction of 5.1%–16.0%, with significant differences.

2.3.2 Effects of Mulching Methods on Total Soil CO_2 Emissions Comparing total soil CO_2 emissions under different mulching methods within the same planting pattern revealed that before wheat harvest, monoculture wheat under NTSSW and NTSW treatments reduced total soil CO_2 emissions by 648 $\text{kg} \cdot \text{hm}^{-2}$ and 966 $\text{kg} \cdot \text{hm}^{-2}$ compared with CTW treatment, representing reductions of 21.3% and 31.8%, respectively, reaching significant levels (Figure 3). In intercropping patterns, NTSSI2 and NTSI2 reduced emissions by 481 $\text{kg} \cdot \text{hm}^{-2}$ and 711 $\text{kg} \cdot \text{hm}^{-2}$ in wheat strips compared with CTI1, representing reductions of 17.7% and 26.2%, respectively. In maize strips, emissions were reduced by 454 $\text{kg} \cdot \text{hm}^{-2}$ and 752 $\text{kg} \cdot \text{hm}^{-2}$, representing reductions of 16.7% and 27.7%, respectively. The intercropping populations reduced emissions by 468 $\text{kg} \cdot \text{hm}^{-2}$ and 731 $\text{kg} \cdot \text{hm}^{-2}$, representing reductions of 17.2% and 26.9%, respectively, all reaching significant levels. After wheat harvest, straw mulching treatments in both monoculture and intercropped wheat were higher than conventional tillage, while differences in maize strips were not significant.

Throughout the entire growth period, SM2 reduced emissions by 632 $\text{kg} \cdot \text{hm}^{-2}$ compared with SM1, a reduction of 10.0%. NTSSI2 and NTSI2 reduced emissions by 471 $\text{kg} \cdot \text{hm}^{-2}$ and 518 $\text{kg} \cdot \text{hm}^{-2}$ compared with CTI1, representing reductions of 9.2% and 10.1%, respectively, both reaching significant differences. This indicates that wheat straw no-tillage mulching, two-year film mulching cultivation measures, and their integrated patterns all have advantages in reducing total farmland soil CO_2 emissions, with NTSI2 showing the greatest carbon reduction potential.

2.4 Carbon Budget Characteristics of Farmland Under Different Treatments

Under no-tillage straw mulching and two-year film mulching cultivation measures, all treatments showed positive NEP values, indicating that the farmland ecosystem could fix atmospheric CO_2 and function as an absorption “sink” (Table 2). The NEP values of NTSSI2, NTSI2, and CTI1 were 43.1%, 43.6%, and 33.9% higher than conventional monoculture treatments on average, respectively, reaching significant differences. This demonstrates that integrated

no-tillage straw mulching and two-year film mulching cultivation measures exhibit strong carbon sink potential. Among intercropping patterns, NTSI2 had the highest NPPC/Ras value, which was 21.7% higher than CTI1, indicating the strongest carbon sequestration potential. Therefore, no-tillage straw mulching combined with two-year film mulching has the effect of enhancing farmland soil carbon sinks and represents a suitable cultivation measure for the study area.

Discussion

3.1 Response of Soil Carbon Emissions to Different Planting Patterns

Intercropping, through the staggered combination of different crops in morphology, ecotype, and growth period, forms ecological niche complementarity in time, space, and growth period, which can increase soil organic carbon content and reduce farmland carbon emissions compared with monoculture patterns. For example, Chai et al. [7] demonstrated that farmland carbon emissions in wheat-maize intercropping systems were significantly reduced by 24% compared with monoculture maize. This study confirmed these findings, showing that intercropping reduced farmland carbon emissions by 20% compared with monoculture maize. Additionally, in wheat-maize intercropping patterns, maize as a highly productive C_4 crop has significantly higher total carbon emissions during its growth period than wheat under monoculture conditions. When maize is combined with wheat in intercropping (C_4 and C_3 crop combination), interspecific interactions in the intercropping community partially suppress maize growth, significantly reducing soil respiration rates in the maize strip and resulting in obvious emission reduction effects for both intercropped wheat and maize compared with corresponding monocultures, consistent with Qin et al. [20]. Since intercropping serves as a widespread cultivation pattern for improving crop production efficiency and reducing farmland carbon emissions, more systematic research on the mechanisms of farmland carbon emissions in intercropping patterns is essential for farmland carbon reduction.

3.2 Correlation Between Tillage Measures, Mulching Methods and Soil Carbon Emissions

As farmland soil represents the largest carbon pool in terrestrial carbon cycles, soil respiration constitutes the primary pathway for carbon input from farmland carbon pools to atmospheric carbon pools, with changes in soil respiration rates significantly impacting global climate warming. Therefore, in-depth research on the effects of soil tillage measures and mulching methods on soil respiration emission characteristics is crucial for developing scientifically effective soil tillage methods and carbon regulation management measures. Studies have shown that tillage methods and straw mulching significantly affect farmland soil respiration. Compared with conservation tillage, conventional tillage, due to frequent soil disturbance, enhances soil aeration and microbial activity, resulting in significantly higher farmland soil respiration rates than rotary tillage and no-tillage, while subsoiling shows significantly higher rates than plowing. Straw incorporation

can increase soil respiration rates, and with increasing straw return amounts, soil carbon emission flux increases significantly, whereas straw mulching reduces soil respiration rates.

Additionally, although wheat-maize intercropping can reduce farmland carbon emissions, carbon emissions from maize strips remain significantly higher than adjacent wheat strips because plastic film mulching in maize strips significantly increases soil CO₂ release. Adopting conservation tillage represents a feasible approach for reducing carbon emissions. Therefore, this study applied no-tillage two-year film mulching cultivation measures to both monoculture maize and wheat-maize intercropping patterns, investigating the effects of different straw and two-year film mulching methods on carbon emissions in monoculture and intercropping farmland. The results demonstrated that no-tillage straw mulching and two-year film mulching significantly reduced total CO₂ emissions from monoculture farmland, with even more prominent emission reduction effects when integrated into intercropping patterns. The intercropping system in this study employed different mulching measures in strips, effectively coordinating the application of conservation tillage in different strips and achieving organic integration of intercropping with conservation tillage, showing obvious effects on coordinating system emission reduction and consumption reduction, which deserves researchers' attention.

3.3 Integration Effects of Straw Mulching, Two-Year Film Use and Intercropping on Soil Carbon Emissions

Previous studies have shown that the integrated application of no-tillage and straw return measures plays an important role in coordinating yield increase and carbon emission reduction in wheat-maize intercropping systems, serving not only as an effective guarantee for increasing yield but also as a powerful measure for reducing carbon emissions. Among these, wheat straw no-tillage mulching integrated into intercropping patterns shows the greatest carbon reduction effect and has become the main measure for integrating conservation tillage technology in wheat-maize intercropping systems in this region to ensure yield increase while reducing emissions and minimizing negative environmental impacts of agricultural production. Research has indicated that soil temperature directly affects the activity of microbial and plant respiratory enzymes, thereby influencing soil respiration rates. No-tillage straw mulching technology effectively improves soil structure and reduces soil temperature, consequently reducing soil CO₂ emission flux.

This study integrated no-tillage wheat straw mulching and two-year film mulching into an intercropping pattern, inevitably causing differences in soil temperature and crop growth and development in different strips, with adaptive characteristics changing according to environmental variations, inevitably leading to differences in soil respiration, mainly manifested in seasonal and diurnal variation differences in carbon emission flux. The results showed that the integrated straw mulching and two-year film mulching intercropping signif-

icantly reduced total farmland carbon emissions compared with conventional intercropping patterns, primarily because the integrated pattern reduced the duration of high-intensity CO₂ emission flux during the crop growth period and the duration within the same day. Since standing stubble in NTSSI2 cannot directly form a straw physical barrier on the soil surface or topsoil layer, its effect on reducing soil temperature is not obvious, thus its effect on inhibiting soil respiration and reducing soil carbon emissions is slightly weaker than NTSI. Therefore, the NTSI treatment shows the most effective emission reduction effect.

Conclusion

Wheat-maize intercropping can reduce total farmland soil CO₂ emissions, with average reductions of 279–829 kg·hm⁻² compared with conventional monoculture, representing a reduction of 5.1%–16.0%. The intercropping pattern integrating no-tillage straw mulching and two-year film mulching measures showed even more obvious emission reduction effects, reducing emissions by 9.2% (NTSSI2) and 10.1% (NTSI2) compared with conventional intercropping, with emission reductions of 471 kg·hm⁻² and 518 kg·hm⁻², respectively. The main reason for reduced CO₂ emissions when integrating wheat straw mulching, no-tillage, and two-year film mulching into intercropping patterns is the reduction in the duration of high CO₂ emission flux days and the duration of high emission intensity within a day. Both no-tillage wheat straw mulching and two-year film mulching cultivation measures exhibit “carbon sink” characteristics, with their integration into intercropping patterns showing more prominent emission reduction potential and carbon sink effects. Compared with conventional intercropping, their NPPC/Ras values were 19.1% (NTSSI2) and 21.7% (NTSI2) higher, respectively. Therefore, integrating no-tillage straw mulching and two-year film mulching into intercropping can serve as an efficient farming system model for carbon emission reduction and carbon sink enhancement in arid oasis irrigation regions.

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