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A Life Cycle Review of Cropping Patterns and Straw Returning on the Loess Plateau from the FEW Nexus Perspective

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Abstract. The Loess Plateau is a typical dryland farming region in China, where single-cropping per year is the dominant cropping system and straw returning serves as a core agricultural management practice. This review takes the Food-Energy-Water (FEW) nexus as the macro analytical framework and integrates it with Life Cycle Assessment (LCA) to systematically compare the differences in carbon footprint, nitrogen footprint, energy efficiency and water resource utilization between single-cropping and double-cropping systems with straw returning in the eastern Loess Plateau. The results show that the double-cropping system has a lower carbon footprint per unit yield but higher overall resource consumption, while the single-cropping system exhibits better sustainability in water resource utilization. Straw returning exerts significant water conservation and emission reduction effects in the dryland single-cropping region, whereas its effectiveness in the irrigated double-cropping region is closely dependent on water and nitrogen management practices. Current research in Shanxi Province faces prominent gaps, including the lack of direct comparative studies between southern and northern cropping systems and insufficient systematic assessments based on multi-indicator coupling. This study provides theoretical support for optimizing cropping structures and promoting the low-carbon and sustainable development of agriculture on the Loess Plateau.

Keywords: Loess Plateau, FEW nexus, cropping system, single-cropping system, double-cropping system, straw returning, life cycle assessment, carbon footprint, nitrogen footprint, energy efficiency analysis

1. Introduction

The Loess Plateau is a representative dryland farming region in China, where the planting industry is the core of local agricultural economy. Restricted by natural climatic conditions, the local cropping pattern is dominated by single-cropping per year, with a relatively simple crop structure centered on grain crops such as wheat and corn, which account for more than 80% of the total planting area [1]. This structural characteristic has become a key factor restricting the improvement of agricultural economic benefits in the region.

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Shanxi Province is located in the north-south transitional zone of the eastern Loess Plateau (110°15'—114°32'E, 34°35'—40°45'N), with a temperate continental monsoon climate showing obvious north-south differentiation and vertical variation. The region is divided into three climatic zones from north to south, corresponding to the northern dryland single-cropping region (mainly planting wheat and maize) and the southern irrigated double-cropping region (adopting winter wheat-summer maize rotation). This natural north-south transition of cropping patterns provides an ideal research platform for comparing the resource and environmental effects of different cropping systems [2]. From 2010 to 2020, the comprehensive agricultural evaluation value of Shanxi Province increased from 0.209 to 0.283, ranking fifth to sixth in China for a long time, indicating great potential for the high-quality development of local agriculture.

Straw returning is an important agronomic management practice on the Loess Plateau, which can significantly increase soil organic carbon and total nitrogen content, enhance soil fertility, promote crop yield increase, and play a positive role in increasing soil carbon sink and reducing farmland carbon emissions [3,4]. However, its negative environmental effects cannot be ignored: straw returning can promote soil denitrification and increase N_2O emissions, and under suitable hydrothermal conditions, it may exacerbate the release of greenhouse gases such as CH_4 [5], showing a "double-edged sword" effect. In Shanxi Province, the technical mode of straw returning is closely linked to the cropping system: the northern single-cropping region mainly adopts straw crushing and incorporation, while the southern double-cropping region is dominated by straw mulching, which means the environmental effects of straw returning must be evaluated in the specific context of different cropping systems.

Life Cycle Assessment (LCA) is a common method for accounting carbon and nitrogen footprints in agricultural systems, but traditional studies often focus on single environmental indicators and fail to reveal the intrinsic coupling relationships between grain production, energy consumption and water resource utilization. The emerging FEW nexus perspective provides a new analytical approach to solve this problem. At present, existing studies have separately explored the effects of cropping systems or straw returning on crop yield, carbon footprint and nitrogen footprint [6], but there is a lack of review studies that integrate the FEW nexus with LCA to systematically compare the regulatory effects of straw returning under different cropping systems. Based on this research gap, this study takes the FEW nexus as the framework and LCA as the quantitative tool to systematically analyze the resource and environmental coupling effects of cropping systems and straw returning in the eastern Loess Plateau, aiming to provide data support and theoretical reference for optimizing the regional cropping structure and promoting low-carbon agricultural management.

2. Methodology

2.1. Literature search and screening

This review adopted a standardized literature search strategy to ensure the comprehensiveness and relevance of the included studies. The search was conducted in mainstream academic databases including CNKI, Web of Science, ScienceDirect and MDPI, with the search time range set from 2007 to 2025. The combined keywords included "Loess Plateau", "cropping system", "single-cropping", "double-cropping", "straw returning", "FEW nexus", "life cycle assessment", "carbon footprint" and "water use efficiency".

The inclusion criteria for literature were: (1) the research area was the eastern Loess Plateau or Shanxi Province; (2) the research object was single-cropping or double-cropping systems with straw returning measures; (3) the study provided measurable data on carbon footprint, nitrogen footprint,

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energy consumption or water use efficiency; (4) the literature type was peer-reviewed journal articles, doctoral dissertations or master's theses (excluding conference abstracts and non-academic reports). After strict screening, a total of 22 eligible studies were finally included for systematic analysis.

2.2. FEW-LCA coupling framework

The FEW nexus identified key nodes: food (yield, soil fertility), energy (agricultural input consumption, greenhouse gas emissions), and water (irrigation, water use efficiency). LCA quantified these nodes with "per unit area" and "per unit yield" as functional units, focusing on carbon footprint, nitrogen footprint, energy efficiency, and economic flow. The framework integrated FEW identification and LCA quantification to compare straw returning effects across cropping systems.

2.3. Data extraction and analysis

Data were extracted from selected literature, including study location, cropping system, straw returning method, nitrogen application rate, observation period, crop yield, changes in soil carbon and nitrogen content, greenhouse gas emissions, carbon footprint, nitrogen footprint, energy consumption, and water use. Descriptive statistics and comparative analysis were used to systematically summarize the moderating effects of straw returning under different cropping systems.

3. Comparison of cropping systems

3.1. Background differences

The Loess Plateau is located in the transitional zone between the eastern monsoon region and the northwestern arid region of China, spanning semi-humid and semi-arid climatic zones [7]. The mean annual temperature and precipitation show a gradual increasing trend from the northwest to the southeast [8], resulting in significant differences in regional aridity and thermal conditions. These complex climatic characteristics have led to the formation of distinctly different cropping systems in the northern and southern parts of the eastern Loess Plateau: the northern dryland region is dominated by single-cropping, with spring maize or winter wheat as the main crops; the southern irrigated region adopts double-cropping, with winter wheat-summer maize rotation as the main mode. This difference in cropping patterns not only affects the level of crop yield, but also leads to significant differences in resource consumption characteristics and greenhouse gas emission rules of farmland ecosystems.

3.2. Carbon footprint comparison

Single-cropping and double-cropping systems show significant differences in carbon footprint, which is closely related to cropping intensity and straw returning management measures.

For the double-cropping system (winter wheat-summer maize rotation), relevant studies have shown that the treatment of straw mulching combined with 120 kg $N \cdot hm^{-2}$ nitrogen application achieved the lowest carbon footprint, reaching -1613.92 kg CO_2-eq$\cdot hm^{-2} \cdot yr^{-1}$ [9], which is mainly due to the significant increase in soil organic carbon sequestration caused by straw mulching. A four-year field experiment in Yangling, southern Loess Plateau, found that the carbon footprint of

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the winter wheat-summer maize rotation system under different mulching measures ranged from 0.38 to 0.54 kg CO_2-eq·kg^{-1}, among which the straw mulching treatment had the lowest value (0.38 kg CO_2-eq·kg^{-1}) [10], which was significantly lower than the no-mulching and plastic film mulching treatments.

For the single-cropping system (dryland winter wheat), a three-year field experiment in Wenxi, Shanxi, showed that the carbon footprint of winter wheat under different film mulching and sowing methods was 1.14~3.60 kg CO_2-eq·kg^{-1} [11]. The carbon footprint of the film mulching combined with conventional drilling treatment was 1.04~1.24, 1.80~2.14 and 1.29~1.54 kg CO_2-eq·kg^{-1} in the three years respectively, showing the characteristics of lower values in wet and normal years and higher values in dry years, which is mainly affected by the impact of precipitation on crop yield and soil carbon sequestration capacity.

Overall comparison shows that although the double-cropping system has higher total annual carbon emissions due to its high multiple cropping index, its carbon footprint per unit yield is significantly lower. The optimized double-cropping treatment has a carbon footprint per unit yield of 0.38 kg CO_2-eq·kg^{-1} [10], while the optimized single-cropping treatment is 1.14 kg CO_2-eq·kg^{-1} [11]. The effect of straw returning on carbon footprint is significantly different between the two systems: in the double-cropping system [12,13], straw mulching combined with reduced nitrogen application can achieve a negative carbon footprint (carbon sequestration exceeds emissions); in the single-cropping system, straw returning can reduce the carbon footprint, but the value remains positive.

3.3. Energy perspective comparison

Single-cropping and double-cropping systems have significant differences in water use efficiency and water demand characteristics, and the water-saving effect of straw returning shows obvious regional differentiation.

For the double-cropping system (winter wheat-summer maize rotation), the effect of straw mulching on water use efficiency is closely related to irrigation conditions [14]. Under full irrigation conditions, the annual water use efficiency of the straw mulching treatment is 2.15~2.28 kg·m^{-3}, which has no significant advantage compared with the no-mulching control (2.29~2.42 kg·m^{-3}); while combining with integrated management measures such as deficit irrigation, the annual water use efficiency of the straw mulching treatment can be increased by 7.4%.

For the single-cropping system (dryland spring maize), a study in Shouyang, Shanxi, showed that straw mulching significantly improved crop water use efficiency [15]. The grain water use efficiency of the straw mulching treatment averaged 23.01~27.01 kg·ha^{-1}·mm^{-1} in two growing seasons, an increase of 15.5% compared with the no-mulching control; the biomass water use efficiency was 51.86~55.04 kg·ha^{-1}·mm^{-1}, an average increase of 9.55%. At the same time, straw mulching reduced soil ineffective evaporation by 13% compared with the control, which is the main mechanism for improving water use efficiency.

Comprehensive comparison in table 1 shows that straw returning has a positive effect on water use efficiency in both cropping systems, but the improvement intensity is quite different. The reason for this difference is closely related to the total water consumption of the systems: the double-cropping system has high total water consumption due to the successive planting of two crops, which partially offsets the water-saving effect of straw mulching; the single-cropping system has low total water consumption and is subject to drought stress for a long time, so the evaporation reduction effect of straw mulching is more prominent. From the perspective of the FEW nexus,

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straw returning as a water-saving and efficiency-enhancing measure plays a more significant role in the dryland single-cropping region.

Table 1. Comparison of key indicators between single-cropping and double-cropping systems

Cropping System	Single-Cropping (Dryland)	Double-Cropping (Irrigated)
Carbon footprint per unit yield (kg CO_2-eq·kg^{-1})	1.14-3.60 (straw mulching with no-till lower than rotary tillage)	0.38-0.54 (lowest with straw mulching, can be negative)
Main sources of energy consumption	Fertilizer production, diesel for machinery	Fertilizer production, electricity for irrigation, diesel for machinery
Increase in water use efficiency	Grain:15.5%, Biomass: 9.55%, Soil evaporation reduced by 13%	Annual increase of 7.4% (straw mulching +integrated management)
Water demand	Low, relies on natural precipitation, no irrigation	High, requires full irrigation, high water consumption
Core effect of straw returning	Significant water conservation and emission reduction, reduced carbon footprint, improved soil fertility	Effect depends on water and nitrogen regulation; with reduced nitrogen, lowers fertilizer energy consumption; improves water use efficiency

4. Water resource perspective comparison

Straw returning exerts complex regulatory effects on farmland agroecosystems by affecting soil carbon and nitrogen cycling and farmland water-heat balance. On the one hand, straw as an organic carbon source increases soil carbon sequestration, improves soil fertility, and reduces soil evaporation through mulching to optimize soil water status; on the other hand, straw returning stimulates soil microbial activity, promotes soil denitrification process, and increases the emission of greenhouse gases such as N_2O and CO_2. The coexistence of positive and negative effects makes the regulatory effect of straw returning highly dependent on the cropping system and field management conditions.

In the dryland single-cropping system, straw returning mainly shows positive synergistic effects. A study on dryland winter wheat in Linfen, Shanxi, found that compared with straw returning with rotary tillage, straw mulching with no-till reduced soil N_2O emissions by 19.2% [13]; the total carbon footprint was reduced by 11.0% and 6.9% in two years, and the carbon footprint per unit yield was reduced by 37.2% and 18.5% respectively. The study on dryland spring maize in Shouyang, Shanxi, also showed that straw mulching reduced soil evaporation by 13% [15] and significantly improved crop yield. The above results indicate that under dryland single-cropping conditions, straw returning realizes the synergistic improvement of resource use efficiency through multiple effects such as water conservation, emission reduction and yield increase.

In the irrigated double-cropping system, the effect of straw returning is conditional and dependent on water and nitrogen management measures (table 2). Relevant studies have shown that the nitrogen fertilizer application rate is significantly positively correlated with the carbon footprint of the double-cropping system, and nitrogen reduction combined with straw returning can effectively reduce the energy consumption caused by fertilizer production [12]. Under full irrigation conditions, the effect of straw mulching on improving annual water use efficiency is not significant, while combining with deficit irrigation and other management measures can significantly improve the water use efficiency of the double-cropping system [16]. This shows that the effectiveness of straw

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returning in the double-cropping system is jointly regulated by irrigation intensity and nitrogen application rate.

Table 2. Comparison of mechanisms underlying the moderating effects of straw returning under different cropping systems

Cropping System	Single-Cropping (Dryland)	Double-Cropping (Irrigated)
Core Mechanism	Water conservation + emission reduction + fertility improvement	Carbon sequestration + efficiency enhancement + condition dependence
Key Influencing Factors	Water conditions (dominant drought stress), soil aeration	Water management (irrigation intensity), nitrogen application rate
Main effect characteristics	Synergistic benefits in water conservation, carbon sequestration, and emission reduction	Dependent on water and fertilizer management practices

The direction of the effect of straw returning primarily depends on three key factors: first, water conditions—the water conservation effect is prominent under dryland conditions but weakens under irrigated conditions; second, soil aeration—long-term no-till improves soil structure and can inhibit denitrification; third, nitrogen management—excessive nitrogen application can amplify the N_2O emission effect of straw returning. Therefore, the effect of straw returning is not fixed; optimizing management practices within a specific cropping system is necessary to realize its positive effects.

5. Shanxi: current research status and research gaps

Shanxi Province is located in the north-south transitional zone of the eastern Loess Plateau [17], where dryland single-cropping and irrigated double-cropping systems coexist. This unique geographical and agricultural context provides favorable conditions for comparing the resource and environmental effects of different cropping systems. While a foundation of relevant research has been established in Shanxi, several issues still require further investigation.

5.1. Current research status

In the field of dryland agricultural research, existing studies have analyzed the temporal and spatial variation characteristics of the carbon footprint of corn and wheat production in Shanxi Province [18,19], and identified fertilizer production, field N_2O emissions and agricultural machinery fuel consumption as the main carbon emission sources. Research on water use efficiency [15] has focused on the regulatory effects of different mulching measures on soil evaporation and crop transpiration, and confirmed that straw mulching is an effective measure to reduce soil ineffective evaporation and improve water use efficiency. In addition, relevant studies have also clarified the positive effect of straw returning combined with nitrogen fertilizer application on soil organic carbon accumulation, providing a theoretical basis for the improvement of dryland soil fertility.

In the field of irrigated agricultural research, the research on the southern double-cropping region is mainly focused on the winter wheat-summer maize rotation system [12]. Some studies have investigated the effects of long-term straw returning and organic fertilizer application on crop yield and nitrogen use efficiency [20], and confirmed the synergistic effect of straw returning on improving yield and fertilizer use efficiency. Research on the physicochemical properties of irrigated farmland soil has also shown that straw returning can significantly improve soil structure, increase soil nutrient content and optimize the soil micro-ecological environment.

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5.2. Research gaps

First, there is a lack of direct comparative studies between southern and northern cropping systems. Existing studies mostly focus on a single cropping system: the northern single-cropping region focuses on carbon footprint, water use efficiency and soil improvement, while the southern double-cropping region focuses on crop yield, nitrogen use efficiency and soil microbiology [12,13,15,20]. There is a lack of direct comparative research on the resource and environmental effects of the two cropping systems, and the natural north-south transitional characteristic of Shanxi's cropping patterns has not been fully utilized.

Second, insufficient systematic assessments based on multi-indicator coupling. Most existing studies focus on a single environmental indicator or crop response indicator [15,19], and there are few comprehensive evaluation studies that integrate carbon footprint, water use efficiency, energy consumption and nitrogen efficiency into a unified analytical framework. The introduction of the FEW nexus perspective can provide a new research idea for solving this problem and realize the multi-dimensional comprehensive assessment of agricultural systems.

Third, the comparative research on the effects of different straw returning methods is insufficient. In Shanxi Province, the northern single-cropping region mainly adopts straw crushing and incorporation, while the southern double-cropping region is dominated by straw mulching [21]. However, there is no systematic comparative research on the differences in resource and environmental effects of these two straw returning methods under different cropping systems, and the optimal matching mode of straw returning methods and cropping systems has not been clarified.

In summary, the existing research in Shanxi Province has provided a multi-faceted basic dataset for understanding the effects of straw returning under dryland and irrigated conditions, but the systematic comparison and multi-dimensional assessment of southern and northern cropping systems from the perspective of the FEW nexus still need further in-depth research.

6. Conclusion

Based on the FEW nexus perspective and with the help of LCA quantitative analysis method, this study systematically examined the resource and environmental coupling effects of straw returning under single-cropping and double-cropping systems in the eastern Loess Plateau, and clarified the current research status and gaps in Shanxi Province. The main conclusions are as follows:

1.There are significant differences in resource and environmental characteristics between single-cropping and double-cropping systems. The double-cropping system has the advantages of high per unit area yield and low carbon footprint per unit yield, but its total resource consumption (energy, water) and carbon emissions per unit area are significantly higher; the single-cropping system has low total energy consumption, no irrigation demand, and strong water resource sustainability, and its energy consumption can be further reduced through conservation tillage measures such as no-till.

2.Straw returning has different regulatory effects in different cropping systems. Under dryland single-cropping conditions, straw returning achieves water conservation, emission reduction and yield increase by reducing soil evaporation, inhibiting N_2O emissions and reducing mechanical energy consumption, and significantly improves the comprehensive resource use efficiency of the farmland system; under irrigated double-cropping conditions, the effect of straw returning is closely dependent on water and nitrogen management, and it is necessary to combine with reduced nitrogen application and deficit irrigation to exert its positive effects of reducing energy consumption and improving water use efficiency.

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3.The research on cropping systems and straw returning in Shanxi Province has laid a certain foundation, but there are prominent research gaps: the lack of direct comparative studies between southern and northern cropping systems, insufficient multi-indicator coupled systematic assessments, and the absence of comparative research on the effects of different straw returning methods. These gaps restrict the in-depth understanding of the interaction between cropping systems and straw returning in the region.

4.From the perspective of the FEW nexus, future research should fully leverage the geographical advantage of Shanxi's north-south cropping pattern transition to carry out comparative research on different cropping systems; integrate carbon footprint, nitrogen footprint, water use efficiency and energy consumption into a unified analytical framework to realize multi-dimensional systematic assessment; optimize the straw returning technical mode according to the characteristics of different cropping systems, so as to realize the coordinated development of grain production, resource conservation and environmental protection on the Loess Plateau..

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