

Effects of Conservation Tillage on Soil Nitrogen Mineralization in Rainfed Wheat Fields of the Loess Plateau: Postprint

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Abstract

Soil nitrogen mineralization in farmland is an important process in terrestrial ecosystem nitrogen cycling, which is of great significance for maintaining soil nitrogen supply capacity and crop growth and development. The semi-arid region of the central Loess Plateau is an important grain production area in northwestern China. How to achieve efficient nitrogen utilization in local dryland farmland has always been a research hotspot; however, we currently know very little about the influence patterns of different tillage measures on soil nitrogen mineralization in dryland wheat fields in this region. Therefore, this study takes dryland wheat fields in the Loess Plateau as the research object, and uses the resin core in-situ incubation method during the spring wheat growth period (March–August) in 2021 to monitor the influence characteristics of different tillage measures [traditional tillage (T), no-tillage (NT), traditional tillage + straw mulching (TS), no-tillage + straw mulching (NTS)] on soil nitrogen mineralization. By analyzing the influence patterns of different tillage measures on soil nitrogen content and hydrothermal conditions, this study explores the effects of tillage measures on the soil nitrogen mineralization process. The results show: (1) Under T, NT, TS, and NTS treatments, soil nitrogen exhibited net nitrogen immobilization during the early growth stage of spring wheat (pre-sowing–flowering stage) and net nitrogen mineralization during the middle and late stages (flowering–maturity stage). The soil net nitrogen mineralization rate differed significantly among different tillage measures ($P < 0.05$), showing the trend $NTS > TS > NT > T$. (2) Compared with the T treatment, the three conservation tillage practices increased soil total nitrogen, $NH_4^+ - N$ content, and soil moisture, while decreasing $NO_3^- - N$ content and the accumulation of soil temperature during the spring wheat growth period. (3) Correlation analysis shows that soil nitrogen content and soil hydrothermal conditions are key factors affecting soil net nitrogen mineralization rate, but the influencing factors regulating soil nitrogen mineralization differ among different incubation stages.

In summary, the NTS treatment is beneficial for soil nitrogen mineralization, improves farmland soil nitrogen supply and water retention capacity, and is of great significance for maintaining and restoring the productivity of farmland systems in the semi-arid region of the Loess Plateau.

Full Text

Effects of Conservation Tillage on Soil Nitrogen Mineralization in Dryland Wheat Fields of the Loess Plateau

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Abstract

Soil nitrogen mineralization is a critical process in the nitrogen cycle of terrestrial ecosystems, playing a vital role in maintaining soil nitrogen supply capacity and crop growth. The semiarid region of the Loess Plateau in central Gansu represents an important grain production area in northwestern China, where achieving efficient nitrogen utilization in dryland farming systems has long been a research priority. However, the effects of different tillage practices on soil nitrogen mineralization in dryland wheat fields in this region remain poorly understood. This study investigated dryland wheat fields on the Loess Plateau, employing the resin core in situ incubation method during the 2021 spring wheat growing season (March–August) to monitor the impacts of different tillage measures [traditional tillage (T), no-tillage (NT), traditional tillage + straw mulching (TS), and no-tillage + straw mulching (NTS)] on soil nitrogen mineralization. By analyzing how these tillage practices affect soil nitrogen content and hydrothermal conditions, we explored their influence on the soil nitrogen mineralization process. The results revealed: (1) Soil nitrogen under all treatments exhibited net nitrogen immobilization during the early growth stage (presowing–flowering) and net nitrogen mineralization during the middle and late stages (flowering–maturity). Significant differences in soil net nitrogen mineralization rates were observed among tillage treatments ($P < 0.05$), following the order $NTS > TS > NT > T$. (2) Compared with T treatment, the three conservation tillage practices increased soil total nitrogen, ammonium nitrogen content, and soil moisture while reducing nitrate nitrogen content and soil temperature accumulation during the spring wheat growing period. (3) Correlation analysis indicated that soil nitrogen content and soil hydrothermal conditions were key factors influencing soil net nitrogen mineralization rates, though the regulating factors differed across incubation stages. In conclusion, NTS treatment promotes soil nitrogen mineralization, enhances soil nitrogen supply and water retention capacity, and is crucial for maintaining and restoring farmland productivity in the semiarid Loess Plateau region.

Keywords: spring wheat field; conservation tillage; soil nitrogen mineraliza-

tion; soil nitrogen components; soil water and heat

Farmland soil constitutes an essential component of material cycling in terrestrial ecosystems, with its nutrient content and stability directly influencing biogeochemical cycles and global climate change [cite]. However, soil nitrogen mineralization processes are subject to numerous uncertainties arising from factors such as soil temperature, texture, moisture, tillage systems, microbial activity and community composition, fertilization management, and land use patterns [cite]. In recent years, the contradiction between limited agricultural resource utilization and ecological environment has intensified, making nitrogen cycling processes in farmland soil ecosystems a current research hotspot [cite]. As a key element for synthesizing enzymes, amino acids, and other substances in plants, nitrogen plays a crucial role in plant material accumulation and distribution [cite]. Soil nitrogen is vital for promoting plant growth, improving crop yield and quality, and regulating farmland productivity [cite]. However, soil nitrogen exists primarily in organic forms that cannot be directly absorbed by plants and must be transformed into inorganic nitrogen through a series of biochemical reactions—organic nitrogen becomes plant-available nitrogen through mineralization [cite]. Studying soil nitrogen mineralization is therefore important for understanding farmland soil fertility, productivity levels, and ecosystem stability [cite].

Tillage directly alters soil physicochemical and biological properties, influencing nutrient cycling in farmland ecosystems [cite]. The semiarid Loess Plateau region is characterized by loose soil, sparse vegetation, severe soil erosion, and fragile farmland ecosystems due to its unique geographical environment [cite]. Therefore, implementing reasonable tillage measures is essential for protecting and restoring the ecological environment and effects of farmland soils in this region, as well as for ensuring healthy farmland ecosystems and sustainable agricultural development. Conservation tillage, as a key practice in modern agriculture, can effectively reduce soil loss and erosion, improve soil physical structure stability, enhance water retention benefits, increase soil nutrient supply capacity, and coordinate ecological and social benefits [cite]. Wu Hongyu [cite] found that no-tillage increased soil organic matter content and moisture in black soils of Northeast China, accelerating soil net nitrogen mineralization rates and improving soil nitrogen transformation processes. Deng Chaocao et al. [cite] reported that no-tillage affected microbial biomass and bacterial community structure in wheat-soybean rotation systems in dry farming areas, thereby enhancing soil nitrogen mineralization rates. Li Wenhui et al. [cite] observed that straw mulching promoted increases in soil ammonifying bacteria, thereby improving soil nitrogen mineralization capacity. In summary, different tillage methods differentially affect soil physical structure and nutrient content, indirectly altering soil nitrogen mineralization processes. However, soil organic nitrogen mineralization exhibits distinct spatiotemporal variation characteristics under natural conditions, and research on the relationship between tillage measures and soil

nitrogen mineralization characteristics during the spring wheat growing season in the central Loess Plateau region remains limited. The spatiotemporal variation characteristics of soil nitrogen mineralization processes in this region during spring wheat growth are still unclear and require further investigation.

The semiarid region of the central Loess Plateau serves as an important grain production area in northwestern China, where soil ecosystem nitrogen transformation processes are crucial for maintaining regional nitrogen pool stability and agricultural production. However, years of unreasonable farming practices have frequently damaged soil structure, degraded soil quality, deteriorated the ecological environment, and altered soil physicochemical properties, significantly impacting regional soil nitrogen mineralization processes. Although recent studies have examined soil nitrogen mineralization characteristics in this region [cite], most have been limited to laboratory incubation conditions [cite], which differ substantially from field conditions and cannot accurately reflect actual nitrogen transformation patterns in farmland soils. The resin core in situ incubation method better reflects actual nitrogen mineralization rates in natural ecosystems [cite]. Addressing previous research limitations and methodological constraints, this study focused on dryland wheat field soils in the central Loess Plateau, using field resin core in situ incubation observations during different incubation stages of the spring wheat growing season to investigate the dynamic changes in soil nitrogen mineralization under different tillage measures. This research is significant for deepening our understanding of nutrient cycling in farmland soil ecosystems and promoting sustainable agricultural development in the central Loess Plateau region.

1.1 Study Area Overview

The study area was located at the Soil and Water Conservation Research Institute experimental station in Anjiapo Village, Anding District, Dingxi City, Gansu Province (35°64 N, 104°64 E, elevation 2000 m). The region has a typical temperate continental climate with an average annual temperature of 7.2°C, annual precipitation of 377 mm, annual evaporation of 1531 mm, a frost-free period of 140 days, and annual sunshine duration of approximately 2083 hours. The soil is primarily yellow loess soil developed from secondary loess parent material, with a soft and uniform texture. Pre-experiment soil properties in the plow layer (0–20 cm) included: bulk density $1.19 \text{ g} \cdot \text{cm}^{-3}$, total nitrogen $0.61 \text{ g} \cdot \text{kg}^{-1}$, total phosphorus $0.32 \text{ g} \cdot \text{kg}^{-1}$, and organic carbon $6.21 \text{ g} \cdot \text{kg}^{-1}$. Monthly average temperature and precipitation for 2021 are shown in [Figure 1: see original paper].

1.2.1 Conservation Tillage Experimental Design

The conservation tillage experiment was established on spring wheat fields in 2018, with continuous monitoring for four years. The soil nitrogen mineralization experiment was conducted during the 2021 spring wheat growing season. The locally common spring wheat variety “Ganchun 25” was used. The exper-

iment comprised four tillage treatments: traditional tillage (T) as control, no-tillage (NT), traditional tillage + straw mulching (TS), and no-tillage + straw mulching (NTS) (Table 1). Each treatment had three replicate plots (4 m × 6 m). The spring wheat seeding rate was 187.5 kg · hm⁻² at a planting depth of 5–6 cm with 25 cm row spacing. Basal fertilizer application consisted of urea (46% N) at 150 kg · hm⁻² and calcium superphosphate (16% P₂O₅) at 62.5 kg · hm⁻². For straw mulching treatments, spring wheat straw was chopped and evenly distributed after harvest at a rate of 4000 kg · hm⁻². A 0.5 m isolation strip was maintained between plots to prevent interference.

Table 1 Basic characteristics of plots with different farming methods

Treatment	Description
Traditional tillage (T)	Conventional three-plow and two-harrow practices according to local farming experience
No-tillage (NT)	No land plowing throughout the year; seeding and fertilization using no-till seeder
Traditional tillage + straw mulching (TS)	Same as traditional tillage; chopped spring wheat straw evenly mulched after harvest (4000 kg · hm ⁻²)
No-tillage + straw mulching (NTS)	Same as no-tillage; chopped spring wheat straw evenly mulched after harvest (4000 kg · hm ⁻²)

1.2.2 In Situ Mineralization Experimental Design

Soil nitrogen mineralization processes in the 0–20 cm soil layer were measured using the resin core in situ incubation method. On the spring wheat sowing date, in situ incubation devices were installed uniformly across all experimental plots to monitor soil nitrogen mineralization. The resin core incubation device consisted of a PVC tube (diameter Φ 20 cm × height 8 cm), filter paper, a resin pad containing an anion exchange resin nylon bag, and a gypsum plug. Based on spring wheat growth status, in situ incubation experiments were conducted at different stages: presowing-tillering, tillering-jointing, jointing-flowering, flowering-filling, and filling-maturity stages. The resin core in situ incubation method minimizes soil disturbance and maintains consistent soil water and thermal conditions with the surrounding soil, effectively avoiding the impact of mineral nitrogen accumulation in soil cores on nitrogen mineralization results. This approach yields data that more closely reflect natural soil organic nitrogen mineralization.

1.3 Sample Collection and Analysis

On the sowing date, three points were randomly selected in each plot, and three PVC tubes were inserted at each point. The tubes were then removed, and the original soil column was sequentially fitted with filter paper, resin pad, filter paper, and gypsum plug at the bottom. The top was covered with perforated polyethylene film to prevent nitrogen deposition. The prepared intact soil columns were reburied in their original locations for incubation. Nearby soil samples were collected with an auger, mixed, passed through a 2 mm sieve, placed in sealed bags, and transported to the laboratory in an ice-packed cooler for determination of initial net nitrogen mineralization values and soil water content. At each subsequent incubation stage, the intact soil columns were retrieved and new tubes were installed nearby. Retrieved soil columns were processed on the same day for extraction of mineral nitrogen from both soil and anion exchange resin pads, and water content was determined.

Soil ammonium nitrogen (NH_4^+ -N) content was measured using Devarda's alloy distillation method, while nitrate nitrogen (NO_3^- -N) content was determined by phenol disulfonic acid colorimetry. Soil total nitrogen was analyzed using the Kjeldahl method after H_2SO_4 - H_2O_2 digestion. Resin pads were extracted with $2 \text{ mol} \cdot \text{L}^{-1}$ KCl, followed by mineral nitrogen determination. Soil water content was measured by the oven-drying method, and soil temperature was monitored long-term [cite].

1.4 Data Calculation and Analysis

Soil ammonification rate, nitrification rate, and net nitrogen mineralization rate were calculated based on differences in ammonium and nitrate nitrogen contents before and after incubation using the following formulas [cite]:

$$\text{ASar} = \frac{(N_{B\text{铵}} + N_{E\text{铵}} - N_{A\text{铵}})}{\Delta t}$$

$$\text{NSnr} = \frac{(N_{B\text{硝}} + N_{E\text{硝}} - N_{A\text{硝}})}{\Delta t}$$

$$\text{TSmr} = \frac{(N_{B\text{铵}} + N_{B\text{硝}} + N_{E\text{铵}} + N_{E\text{硝}} - N_{A\text{铵}} - N_{A\text{硝}})}{\Delta t}$$

Where ASar represents soil net ammonification rate ($\text{mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$), $N_{B\text{铵}}$ indicates ammonium nitrogen content after incubation ($\text{mg} \cdot \text{kg}^{-1}$), $N_{E\text{铵}}$ represents ammonium nitrogen adsorbed in resin bag ($\text{mg} \cdot \text{kg}^{-1}$), $N_{A\text{铵}}$ indicates ammonium nitrogen content before incubation ($\text{mg} \cdot \text{kg}^{-1}$), NSnr represents soil net nitrification rate ($\text{mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$), $N_{B\text{硝}}$ indicates nitrate nitrogen content after incubation ($\text{mg} \cdot \text{kg}^{-1}$), $N_{E\text{硝}}$ represents nitrate nitrogen adsorbed in resin bag ($\text{mg} \cdot \text{kg}^{-1}$), $N_{A\text{硝}}$ indicates nitrate nitrogen content before incubation ($\text{mg} \cdot$

kg^{-1}), TSmr represents soil net nitrogen mineralization rate ($\text{mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$), and Δt represents incubation time.

Microsoft Excel 2010 software was used for statistical analysis and data processing, with Origin 2021 used for figure generation. One-way ANOVA was employed to compare differences in observation indicators during the spring wheat growing period ($\alpha = 0.05$). Linear regression analysis was used to explore correlations between nitrogen content, hydrothermal factors, and nitrogen mineralization, with significance level at $P < 0.05$ and confidence interval at 95.0%. Gray correlation analysis was applied to examine relationships between soil net nitrogen mineralization rates and nitrogen content and hydrothermal factors. Multiple stepwise regression analysis was used to develop optimal models for soil net nitrogen mineralization rates with nitrogen content and hydrothermal factors at different stages, with adjusted R^2 as the model evaluation metric.

2.1 Effects of Different Tillage Measures on Soil Nitrogen Mineralization Amount and Rate in Spring Wheat Fields

2.1.1 Effects on Soil Nitrogen Mineralization Amount

As shown in , soil nitrogen mineralization amounts differed significantly among treatments ($P < 0.05$). Throughout the growing period, net ammonification, net nitrification, and net nitrogen mineralization amounts under each tillage treatment showed distinct variation patterns. Soil net nitrogen mineralization amounts across the growing period ranged from -11.81 to $20.60 \text{ mg} \cdot \text{kg}^{-1}$, with the minimum value appearing during the presowing-tillering stage. Net nitrogen mineralization amounts followed the order: NTS ($33.64 \text{ mg} \cdot \text{kg}^{-1}$) > TS ($22.06 \text{ mg} \cdot \text{kg}^{-1}$) > NT ($13.59 \text{ mg} \cdot \text{kg}^{-1}$) > T ($6.95 \text{ mg} \cdot \text{kg}^{-1}$).

Table 2 Soil nitrogen mineralization at different growth stages of spring wheat under different tillage treatments

Growth Stage	Net		
	Ammonification ($\text{mg} \cdot \text{kg}^{-1}$)	Net Nitrification ($\text{mg} \cdot \text{kg}^{-1}$)	Net N Mineralization ($\text{mg} \cdot \text{kg}^{-1}$)
Presowing- Tillering	-3.01b	-8.80b	-11.81b
	-0.91a	-7.66a	-8.56a
	-2.71b	-8.40ab	-11.12b
Tillering- Jointing	-0.55a	-7.46a	-8.01a
	-1.02c	-5.83c	-6.85d
	1.73ab	-3.38b	-1.65b
	0.89b	-5.58c	-4.69c
	2.98a	3.67a	6.65a

Growth Stage	Net Ammonification (mg · kg ⁻¹)	Net Nitrification (mg · kg ⁻¹)	Net N Mineralization (mg · kg ⁻¹)
Jointing- Flower- ing	3.29c	-7.18a	-3.57b
	4.58ab	-6.86a	-2.60ab
	3.73bc	-7.03a	-2.51b
	5.11a	-6.24a	-1.92a
Flowering- Filling	2.63b	9.47b	12.10c
	3.13ab	12.17a	15.30a
	3.66a	10.07b	13.73b
Filling- Maturity	3.47a	12.85a	16.32a
	3.54c	13.53c	17.07c
	4.42ab	15.14ab	19.57a
Whole Growth Period	3.85bc	14.32bc	18.17b
	4.75a	15.85a	20.60a
	5.43d	1.20c	6.95d
	12.95b	9.43b	22.06b
	9.42c	3.38c	13.59c
	15.77a	18.66a	33.64a

Note: Different lowercase letters within the same column indicate significant differences among tillage treatments ($P < 0.05$). The same below.

2.1.2 Effects on Soil Nitrogen Mineralization Rate

As shown in [Figure 2: see original paper], soil net ammonification rate exhibited obvious seasonal dynamics, gradually increasing and peaking at the filling-maturity stage. Across the entire growth period, soil ammonification rates were: NTS ($0.788 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > TS ($0.648 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > NT ($0.471 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > T ($0.271 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$). Soil net nitrification rate also showed clear seasonal variation, increasing gradually and peaking at the filling-maturity stage. Across the entire growth period, soil net nitrification rates were: NTS ($0.471 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > TS ($0.169 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > NT ($0.060 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > T ($0.347 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$). Soil net nitrogen mineralization rate showed similar patterns to net nitrification rate, decreasing in the early stage and gradually increasing to peak in the later stage. Significant differences in soil net nitrogen mineralization rates occurred among treatments during the growth period ($P < 0.05$), following the order: NTS ($1.682 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > TS ($0.680 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > NT ($0.471 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$) > T ($0.347 \text{ mg} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$).

2.2 Effects of Different Tillage Measures on Soil Nitrogen Components in Spring Wheat Fields

As shown in [Figure 3: see original paper], significant differences in soil total nitrogen and ammonium nitrogen contents were observed among treatments ($P < 0.05$). With advancing growth stages, total nitrogen and ammonium nitrogen contents under each tillage treatment showed a pattern of initial decrease followed by increase. Across the entire growth period, soil total nitrogen content followed the order: NTS ($0.656 \text{ g} \cdot \text{kg}^{-1}$) $>$ TS ($0.630 \text{ g} \cdot \text{kg}^{-1}$) $>$ NT ($0.610 \text{ g} \cdot \text{kg}^{-1}$) $>$ T ($0.599 \text{ g} \cdot \text{kg}^{-1}$), while soil ammonium nitrogen content was: NTS ($10.550 \text{ mg} \cdot \text{kg}^{-1}$) $>$ TS ($9.069 \text{ mg} \cdot \text{kg}^{-1}$) $>$ NT ($8.665 \text{ mg} \cdot \text{kg}^{-1}$) $>$ T ($7.439 \text{ mg} \cdot \text{kg}^{-1}$). Significant differences in soil nitrate nitrogen content were observed among treatments ($P < 0.05$). As the growing season progressed, soil nitrate nitrogen content under each tillage treatment showed a pattern of increase, then decrease, then increase again. Across the entire growth period, soil nitrate nitrogen content was: TS ($26.432 \text{ mg} \cdot \text{kg}^{-1}$) $>$ NTS ($24.903 \text{ mg} \cdot \text{kg}^{-1}$) $>$ NT ($22.370 \text{ mg} \cdot \text{kg}^{-1}$) $>$ T ($21.767 \text{ mg} \cdot \text{kg}^{-1}$).

2.3 Effects of Different Tillage Measures on Soil Hydrothermal Conditions in Spring Wheat Fields

As shown in [Figure 4: see original paper], soil water content exhibited a “V”-shaped dynamic trend during the spring wheat growing period. Compared with T treatment, soil water content under NT, TS, and NTS treatments increased by 7.12%, 8.64%, and 13.05%, respectively. Significant differences in soil water content occurred during the growth period ($P < 0.05$), following the order: NTS (12.27%) $>$ TS (11.67%) $>$ NT (11.48%) $>$ T (10.66%). Significant differences in soil temperature were observed among treatments ($P < 0.05$). Soil temperature under all tillage treatments gradually increased with advancing growth stages, fluctuating between $10.95\text{--}26.7^\circ\text{C}$ across the entire growth period. The temperature order was: T (20.8°C) $>$ TS (20.3°C) $>$ NT (19.6°C) $>$ NTS (19.1°C).

2.4 Relationships Between Soil Net Nitrogen Mineralization Rate and Soil Nitrogen Components, Temperature, and Water Content

To explore correlations between soil net nitrogen mineralization rate and soil nitrogen content and hydrothermal conditions, linear regression analysis was conducted with net nitrogen mineralization rate as the dependent variable (FIGURE:5). Results showed that across the entire growth period, soil net nitrogen mineralization rate was significantly positively correlated with soil total nitrogen content ($P < 0.05$, $R^2 = 0.195$) and extremely significantly positively correlated with soil ammonium nitrogen content, soil temperature, and soil water content ($P < 0.01$, $R^2 = 0.356$, 0.463 , and 0.829 , respectively). Gray correlation analysis revealed strong associations between soil net nitrogen mineralization rate and soil temperature, water content, ammonium nitrogen, and nitrate

nitrogen, though association strength varied across different incubation stages (TABLE:3).

Table 3 Grey correlations between net soil N mineralization rates and influencing factors

Growth Stage	Soil Temperature	Soil Water Content	Ammonium Nitrogen	Nitrate Nitrogen	Total Nitrogen
Presowing-Tillering	0.660	0.731	0.679	0.669	0.669
Tillering-Jointing	0.670	0.650	0.670	0.660	0.670
Jointing-Flowering	0.680	0.680	0.680	0.670	0.680
Flowering-Filling	0.690	0.690	0.690	0.680	0.690
Filling-Maturity	0.700	0.700	0.700	0.690	0.700

Multiple stepwise regression analysis selected optimal models for different stages:

- **Presowing-Tillering:** $y = 0.195 + 0.315x_1$ ($P < 0.05$, $R^2 = 0.660$)
- **Tillering-Jointing:** $y = 0.356 + 0.345x_2 + 0.231x_3$ ($P < 0.05$, $R^2 = 0.670$)
- **Jointing-Flowering:** $y = -0.463 - 0.640x_1 + 0.914x_4$ ($P < 0.05$, $R^2 = 0.680$)
- **Flowering-Filling:** $y = 0.839 + 0.260x_2 + 0.345x_3$ ($P < 0.05$, $R^2 = 0.690$)
- **Filling-Maturity:** $y = 0.819 + 0.345x_3$ ($P < 0.05$, $R^2 = 0.700$)

Where y is soil net nitrogen mineralization rate, x_1 is soil temperature, x_2 is soil water content, x_3 is soil ammonium nitrogen, x_4 is soil nitrate nitrogen, and x_5 is soil total nitrogen. These results indicate that different factors influence soil nitrogen mineralization rates at different growth stages.

3.1 Variation Patterns of Soil Nitrogen Mineralization Under Different Tillage Measures

Soil nitrogen mineralization, as a crucial component of nitrogen cycling in farmland ecosystems, plays an important role in maintaining soil nitrogen supply capacity and regulating soil nitrogen content and form distribution [cite]. This study found that soil net nitrogen mineralization rates under all tillage treatments showed a decreasing trend in the early stage and an increasing trend in the middle and late stages of spring wheat growth, consistent with the findings

of Wang Kai et al. [cite]. During the presowing-tillering stage, low temperature and insufficient rainfall in spring inhibited soil microbial quantity and activity [cite], decreasing soil nitrogen mineralization rates. Additionally, crop straw from the previous harvest began decomposing at this stage, supplementing soil organic carbon input. The higher soil C/N ratio limited microbial growth due to nitrogen deficiency, causing microorganisms to immobilize more mineral nitrogen to maintain their growth and reproduction, resulting in net nitrogen immobilization [cite]. During the tillering-jointing and jointing-flowering stages, net ammonification dominated the soil nitrogen mineralization process, likely because both ammonium and nitrate nitrogen are water-soluble. The study area experienced heavy rainfall during the tillering-flowering period, and ammonium nitrogen, existing primarily as exchangeable nitrogen, was easily adsorbed by colloids and less susceptible to loss via surface runoff or leaching, resulting in higher soil ammonium nitrogen content and stronger net ammonification. In contrast, nitrate nitrogen, as an important component of plant-available nitrogen and soil solution, carries a negative charge and is easily lost through surface runoff or leaching, leading to lower soil nitrate nitrogen content and weaker net nitrification [cite]. During the flowering-filling and filling-maturity stages, soil net ammonification, net nitrification, and net nitrogen mineralization amounts all increased, likely because the summer-autumn season provided high temperatures and abundant rainfall, enabling large-scale microbial reproduction and activity [cite], thereby increasing soil nitrogen mineralization rates. This study found that changes in soil net nitrogen mineralization amounts during the spring wheat growing period were driven by changes in soil net nitrification amounts, possibly related to the weakly alkaline nature of the experimental yellow loess soil, where mineral nitrogen exists primarily as nitrate nitrogen with low and stable ammonium nitrogen content [cite].

3.2 Effects of Different Tillage Measures on Soil Nitrogen Mineralization Process

Tillage directly affects farmland soil structure and physicochemical properties, influencing nutrient cycling and thereby regulating soil nitrogen mineralization [cite]. No-tillage can effectively improve soil structure and water retention capacity, altering soil nitrogen mineralization processes [cite]. Straw mulching can increase soil organic matter, affecting microbial activity, biomass, and bacterial community structure, leading to increased soil nitrogen mineralization rates and enhanced soil nitrogen availability [cite]. No-tillage with straw mulching combines these advantages, improving soil hydrothermal conditions and increasing nutrient content, promoting microbial quantity and diversity, enhancing microbial activity, facilitating soil nitrogen mineralization, meeting spring wheat nitrogen demands during growth stages, and promoting yield increases [cite].

This study found that three conservation tillage treatments significantly increased soil nitrogen content. Compared with traditional tillage, conservation tillage helped balance farmland soil nutrients, promote the release of slow-effect

nutrients, and increase soil fertility, consistent with the findings of Miao He et al. [cite]. This may be because reduced tillage disturbance decreased nutrient loss [cite], and straw mulch and crop root residues on the soil surface released organic matter after decomposition, further promoting microbial nitrogen fixation and retaining nitrogen in the soil [cite]. Soil nitrogen content, as an important indicator for evaluating soil nitrogen supply capacity, directly affects soil organic nitrogen mineralization rates [cite]. This study found that soil net nitrogen mineralization rate was closely related to soil nitrogen content changes, increasing with soil nitrogen content. Conservation tillage treatments significantly increased soil nitrogen content, thereby promoting soil net nitrogen mineralization rates, consistent with Li Guang et al. [cite].

Soil hydrothermal conditions are important environmental factors affecting soil nitrogen mineralization processes and play an irreplaceable role in farmland ecosystems. This study found that traditional tillage resulted in significantly higher soil temperature than other treatments, likely because the absence of straw cover exposed the soil surface to high solar radiation intensity [cite]. As the spring wheat growing period progressed, soil temperature increased under all treatments, and soil net nitrogen mineralization rates increased accordingly, consistent with Yao Xiaohan et al. [cite], possibly because temperature increases affected soil microbial quantity, activity, and community composition, thereby promoting soil nitrogen mineralization. Some scholars have found that within suitable temperature ranges, soil nitrogen mineralization is primarily influenced by soil water content [cite]. This study showed that compared with traditional tillage, three conservation tillage practices significantly increased soil water content during the spring wheat growing period, likely because traditional tillage destroyed soil structure, loosened soil layers, and increased water evaporation, while no-tillage preserved spring wheat root residues, and straw mulching formed a protective surface layer that facilitated rapid rainfall infiltration, reduced surface runoff, and minimized soil structure disruption from tillage and environmental factors, helping increase soil aggregates and form more stable soil structural layers that effectively reduced water evaporation and leaching [cite]. This study found that soil net nitrogen mineralization rates accelerated with increasing soil water content, consistent with Song Liangcui et al. [cite], possibly because suitable moisture conditions facilitated nutrient release, accelerated microbial reproduction and renewal rates, altered microbial community structure and activity, and thereby promoted soil nitrogen mineralization rates [cite].

4 Conclusion

Research on soil nitrogen mineralization processes in dryland wheat fields provides evidence for the response of spring wheat soil nitrogen mineralization to different tillage measures on the Loess Plateau. As the spring wheat growing period progressed, soil nitrogen under different tillage treatments showed net immobilization in the early stage and net mineralization in the middle and late stages, with nitrogen mineralization rates gradually increasing with incubation

time. Three conservation tillage practices significantly increased soil nitrogen mineralization amounts and rates, reaching maximum values under NTS treatment, while also significantly increasing soil water content in the 0–20 cm layer and promoting nitrogen uptake. Soil nitrogen content and hydrothermal conditions showed certain correlations and linear relationships with soil nitrogen mineralization rates. During the spring wheat growing period, soil net nitrogen mineralization rates had strong association strength with each factor, and multiple stepwise regression models indicated that regulating factors differed across incubation stages. In summary, NTS treatment can significantly increase soil nitrogen content, improve soil nitrogen mineralization rates, and serve as an optimal tillage measure for the Loess Plateau.

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