Effects of autumn plowing on the movement and correlation of moisture, heat and nitrate nitrogen in seasonal freeze-thaw soil

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Abstract: A two-year experiment was established in northern Xinjiang to investigate the effects of autumn plowing methods on nitrate nitrogen accumulation, spring-sown soil conditions and cotton emergence rate, and to explore the response relationship between soil water, heat and nitrate nitrogen. The experiment included five autumn plowing treatments, namely, plough tillage (FG), no-tillage (MG), ridge and furrow alternation (LG), plough tillage with straw mulch (FJ) and plough tillage with activated charcoal mulch (FH). The results showed that both FH and FJ treatments were beneficial to promote the nitrate-nitrogen accumulation in topsoil, while FG, MG and LG treatments aggravated the nitrate nitrogen leaching in topsoil. During the freezing period, FH and FJ treatments were beneficial to reduce soil heat loss and facilitate the coordinated upward migration of soil water and nitrate nitrogen. In the thawing period, FH and FJ treatments favored suppressing the synergistic downward transport of soil water and nitrate-nitrogen and motivated the synergistic upward migration of heat and nitrate nitrogen in deep soil. Binary regression analysis suggested that the interaction between water, heat and nitrate nitrogen under FH and FJ treatments showed a highly significant correlation. FH and FJ treatments showed obvious advantages in regulating soil conditions and optimizing soil water, heat and nitrate nitrogen co-transport mechanism. During the spring sowing period, the FH and FJ treatments increased the average soil temperature by 0.99 ℃ and 1.29 ℃, and the average soil moisture content by 6.01% and 8.70%, and the average soil nitrate content by 10.20 mg/kg and 10.47 mg/kg, in the 0-25 cm soil layer, respectively. FH and FJ treatments significantly grew the emergence rate of cotton, which can be used as the main autumn tillage strategies in arid areas of northern Xinjiang.

Keywords: autumn plowing, seasonal freeze-thaw, nitrate nitrogen accumulation, water-heat-nitrogen interaction, Xinjiang
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1 Introduction

Nitrate nitrogen is one of the main forms of inorganic nitrogen in soil, and it is most easily absorbed by crops[1]. Studies have shown that the freeze-thaw process can facilitate organic nitrogen mineralization to produce nitrate nitrogen, which is conducive to alleviating the problem of available nitrogen deficiency[2,3]. However, other studies have also pointed out that the freeze-thaw process raises the risk of nitrate leaching, resulting in about 62% of nitrogen losses throughout the year[4,5]. Moreover, nitrate nitrogen is not easy to be retained by soil, and it is easy to loss with soil water or transform into N_2O gas[6,7]. This result in the destruction of the groundwater and atmospheric environment. Therefore, reducing nitrate nitrogen leaching in the seasonal freeze-thaw period is highly important not only for improving agricultural production but also for protecting the environment.

Soil tillage is an essential soil management measure in agricultural production activities, and it influences nitrate nitrogen leaching by regulating soil mineralization and water movement[8]. In addition, it changes the physical and chemical properties as well as the nitrogen cycle of the soil, which in turn affect nitrate nitrogen accumulation[9]. Plough tillage produces large surface areas and short diffusion paths in the soil, which then increases nitrate nitrogen leaching[10]. On the contrary, no-tillage has been reported to decrease the nitrate nitrogen leaching losses and erosion[11]. But other studies have shown that no-tillage aggravated soil nitrogen stratification and the uncertainty impact on the total agricultural environment[12,13]. So, how to steadily improve soil conditions by optimizing tillage methods has been widely concerned. Many scholars have confirmed that ridge furrow, straw returning and mulching have beneficial effects on protecting soil water and fertilizer and increasing crop yield[14-16]. In addition, straw mulching and activated carbon mulching can also effectively inhibit the leaching of nitrate nitrogen, which has positive significance for improving soil environment[17-19]. However, other studies have shown that the effect of crop straw returning on agronomic traits is not significant or even leads to crop yield reduction[20]. Hence, the regulation mechanism of tillage methods on soil regime is not clear.

At present, tillage as the main agronomic measures is widely used in crop growth period, but the application and research in seasonal freeze-thaw period is relatively less. Autumn plowing,

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as the main measure to protect soil fertility during seasonal freeze-thaw period, has obvious advantages in regulating nitrate nitrogen migration and maintaining soil status. Furthermore, it is also a necessary way to regulate soil conditions to explore the response relationship between nitrate nitrogen migration and soil hydrothermal movement in seasonal freeze-thaw period[21,22]. Thus, this study took the cotton field in northern Xinjiang as the research object and conducted in experimental plots during seasonal freeze-thaw period. This study aimed to examine the impact of autumn plowing practices on nitrate nitrogen accumulation and leaching and to make clear for the interaction among soil water, heat and nitrate nitrogen in seasonal freeze-thaw period.

2 Materials and methods

2.1 Field empirical

2.1.1 Experiment site

A field experiment was conducted over 2 seasonal freeze-thaw period from 2019 to 2021 in the Key Laboratory of Modern Water-saving Irrigation (85°57′49″E, 44°19′28″N), Shihezi, Xinjiang, China (Figure 1). The soil texture in this area is loam, with sand, silt and clay contents of 48.20%, 39.12% and 12.68%, respectively. The average dry bulk density of 0-100 cm soil layer is 1.56 g/cm^3, soil saturated water content is 28.8% and field water holding capacity is 21.6%. This area is a typical seasonal frozen soil region. The maximum frozen depth can reach 1.5 m. The precipitation during the seasonal freeze-thaw period in this area is mainly snowfall, and the seasonal fluctuation of daily average temperature is obvious (Figure 2). According to previous research[23], the seasonal freeze-thaw process can be divided into Pre-freezing period, stable freezing period and thawing period (Figure 3).

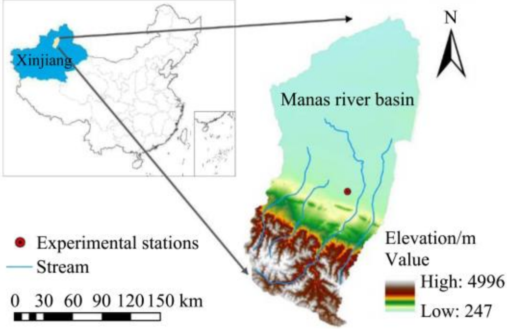
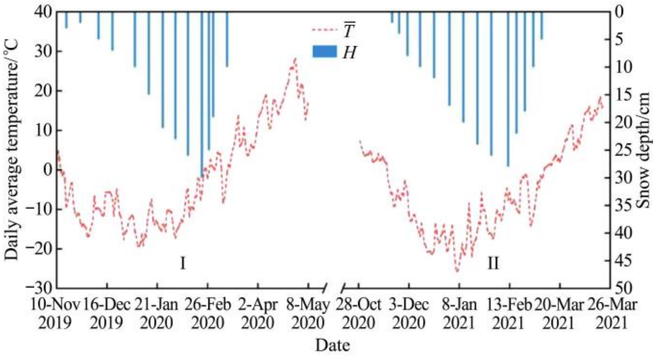
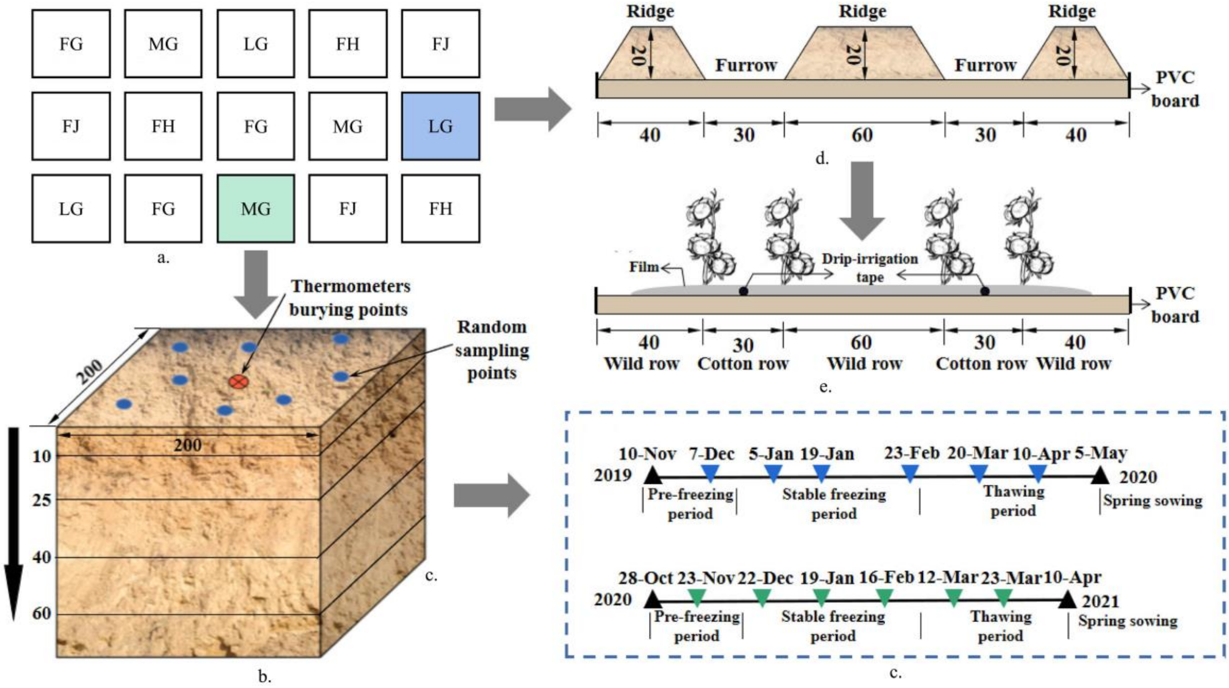


Figure 1 The experimental station location



Note: I is the first step of the experiment (Nov10, 2019 to May 8, 2020); II is the second step of the experiment (Oct 28, 2020 to Apr 10, 2021), the same as blow.

Figure 2 Dynamics of daily average air temperature ($\overline{T}$) and snow depth (H) during the test period



Note: (a) shows the experimental plot distribution under five autumn plowing methods (FG, MG, LG, FH, FJ), with three replicates; (b) is a diagram of the MG treatment, showing the system and its size, and indicating the thermometer burying points and random sampling points; (c) describes the sampling time from 2019 to 2021; (d) is a diagram of the LG treatment, showing ridge and furrow arrangement and specifications; (e) provides the cultivation pattern of the drip-irrigated cotton used in this study during spring sowing period; The units in the figure are cm.

Figure 3 Depiction of the filed experimental design

2.1.2 Experimental design

The experiment was established during the seasonal freeze-thaw period from 2019 to 2021 with five autumn plowing treatments, namely, plough tillage (FG), no-tillage (MG), ridge and furrow alternation (LG), plough tillage with straw mulch (FJ) and plough tillage with activated charcoal mulch (FH). The operation procedures for the five autumn plowing treatments are listed in Table 1.

The field was prepared in a randomized block design with 3 replicates. The plot (4 m^2) was 2 m long and 2 m wide, and separated from each other by a 0.4 m zone. In order to prevent soil water leakage, PVC plates were embedded around the inner wall of each field. Before spring sowing period, cotton was planted after rotary tillage and leveling on the test site. The sowing date was 8 May 2020 and 10 April 2021. The cotton variety is the main local variety in northern Xinjiang (Xinluzao 68). The planting pattern is drip irrigation under film. The details are shown in Figure 3.

Table 1 Operation procedure of the five autumn plowing treatments

Treatments	Operation procedure
FG	Shovel up, loosen and turn 0-28 cm soil layer into pit according to Xinjiang plough tillage standard.
MG	No soil disturbance.
LG	Taking the cotton planting pattern of drip irrigation in northern Xinjiang (one film, two pipes and four rows) as a reference, the position of the ditch was set at the cotton row, and the position of the ridge was at the wide row. The furrow is 20 cm deep and 40 cm wide, and the ridge is 20 cm high and 60 cm wide.
FJ	According to the cotton stalk production in the test area, the straw mulch amount was determined as 2.5 kg/m^2. The required cotton stalk was cut into short rods with a length of 3-5 cm, and evenly laid on the test area with a coverage thickness of 15 cm.
FH	Activated carbon was the large pore and small granular carbon particles formed by water cooling after insufficient combustion of cotton stalk. The amount of cotton stalk required for the preparation of activated carbon was consistent with that of straw cover. After the preparation of activated carbon, it was evenly spread on the test area, and the coating thickness was 5 cm.

2.2 Sampling and measurements

2.2.1 Meteorological data

Weather data from small automatic weather stations (Types: Spectrum Watchdog 2700; USA), and the observation period was 2019-2021. Before snowfall, a steel ruler with a measuring range of 1 m was buried on the flat ground of the test area. The snow depth was recorded every 10 d from the snowfall day, and the snow melting stage was monitored intensively until the complete melting stopped.

2.2.2 Soil Temperature, moisture and nitrate nitrogen content determination

The soil temperature of each treatment was automatically monitored by embedding button-type temperature recorders (Types: iButton DS1922L; Precision: ±0.1 ℃; USA) in 10 cm, 25 cm, 40 cm and 60 cm soil layers, and the recording interval was 1 h. The stratified soil samples of 10 cm, 25 cm, 40 cm and 60 cm were collected with a soil auger. Each plot selected 2 points, and two soil samples in the same plot were mixed with the same soil, into the plastic ziplock bag, refrigerated spare. In the sampling process, took a small amount of soil into the aluminum box at the same time, the samples were oven-dried at 105 ℃ for 24 h to determine the gravimetric soil water content. In the laboratory, the soil was sieved (2 mm) to extract impurities and then stored under cooled conditions (4 ℃). The sieved field-moist soil samples were extracted with 2 mol/L KCl for 1 h at a 1:5 soil-to-extract ratio, and the nitrate nitrogen concentration was determined by ultraviolet spectrophotometer (Types: UV1100; Germany).

2.2.3 Data calculation

The soil temperature gradient (G_t) was calculated using the following formula:

$$G_t = \frac{\partial T}{\partial Z} \approx \left(\frac{\Delta T_1}{\Delta Z_1} + \frac{\Delta T_2}{\Delta Z_2} + \dots + \frac{\Delta T_i}{\Delta Z_i}\right) / i \tag{1}$$

where, i is soil layer number; ΔT_i is the soil temperature difference in soil layer i, ℃; ΔZ_i is the depth difference in soil layer i, m.

The soil moisture gradient (G_m) was computed using the following formula:

$$G_m = \frac{\partial \theta}{\partial Z} \approx \left(\frac{\Delta \theta_1}{\Delta Z_1} + \frac{\Delta \theta_2}{\Delta Z_2} + \dots + \frac{\Delta \theta_i}{\Delta Z_i}\right) / i \tag{2}$$

where, $\Delta\theta_i$ is the soil moisture content difference in soil layer i, %.

The content of nitrate nitrogen (N) was counted using the following formula:

$$N = \frac{\rho \cdot V \cdot D}{\mathrm{m}} \tag{3}$$

where, ρ is the nitrate nitrogen concentration, mg/L; V is the volume of KCl leaching liquor, mL; D is dilution multiple; and m is soil quality, g.

The cotton emergence rate (α) was calculated using the following formula:

$$\alpha = \frac{n_1}{n} \times 100\% \tag{4}$$

where, n_1 is the number of cotton emergence; n is the total number of cotton seedlings.

The effect of temperature and moisture gradient binary factors on nitrate nitrogen content can be fitted by binary quadratic regression equation:

$$z = z_0 + ax + by + cx^2 + dy^2 + fxy \tag{5}$$

where, z is the soil nitrate nitrogen content; x is the soil temperature gradient; y is the soil humidity gradient; z_0, a, b, c, d, f are constant.

2.3 Statistical analysis

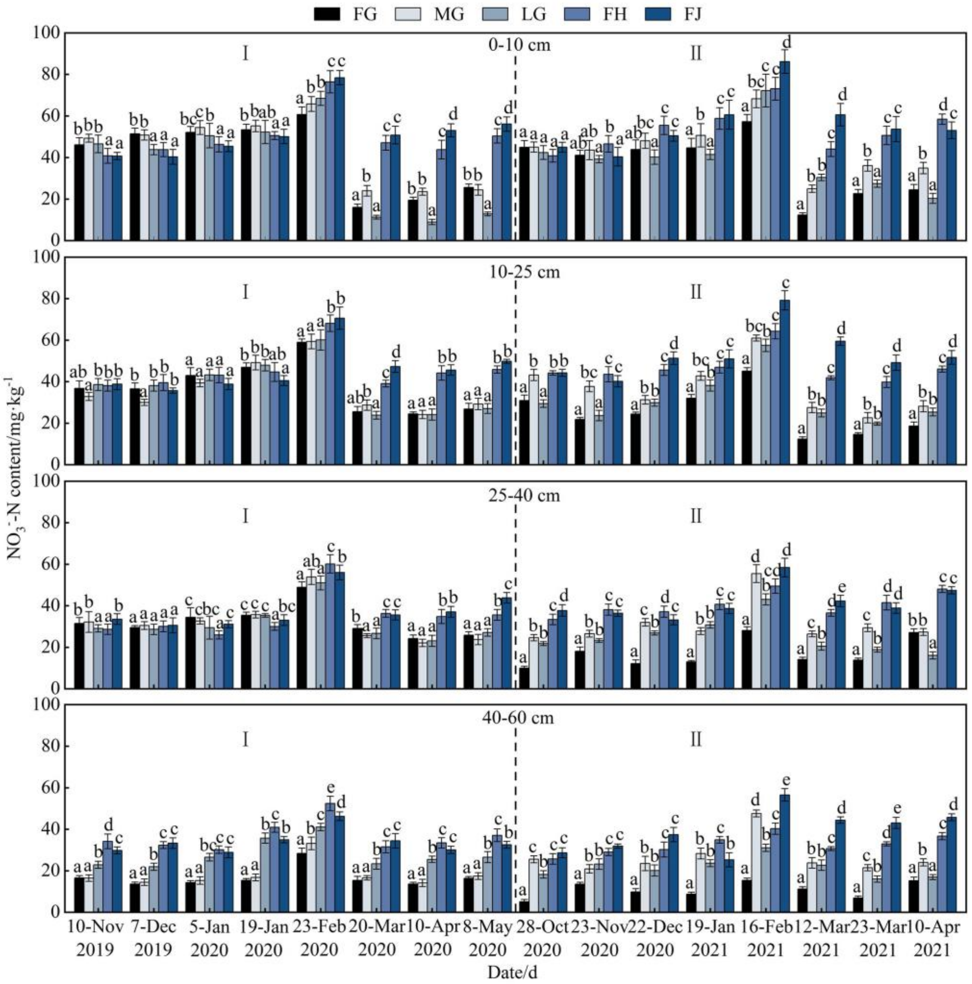
Statistical analysis was performed using IBM SPSS Version 26.0 (IBM, USA). All data presented are means of three replicates. Differences between means were analysed by analysis of variance (ANOVA). The least significant difference test was used to compare differences in means among treatments at the 0.05 probability level.

3 Results

3.1 Effects of different autumn plowing treatments on soil nitrate nitrogen content at seasonal freeze-thaw period

Figure 4 shows temporal-spatial variation of nitrate nitrogen in both seasonal freeze-thaw period. The distribution of soil nitrate nitrogen content in different treatments was similar in the whole profile: the soil nitrate nitrogen content in the range of 0-60 cm showed a sine curve trend with time, and gradually stabilized with the increase of soil depth.

Combined with Table 2, the average nitrification rates of 0-60 cm soil layer in MG, LG, FH and FJ increased by 0.02, 0.04, 0.11, 0.10 mg/kg·d from 2019 to 2020 and improved by 0.05, 0.09, 0.13, 0.16 mg/kg·d from 2020 to 2021, respectively, compared with those in FG. This indicated that the effects of different treatments on promoting soil nitrate nitrogen accumulation of 0-60 cm soil layer was in a descending order of FJ, FH, LG, MG and FG. The leaching loss rates of nitrate nitrogen in 0-60 cm soil layer under MG, FH and FJ reduced by 7.27%-7.54%, 17.62%-21.82% and 21.29%-29.32% in both thawing period, respectively, compared with those under FG treatment. However, LG enhanced nitrate nitrogen leaching loss compared to FG treatment. Over the course of two seasonal freeze-thaw period, nitrate nitrogen accumulation of FJ and FH were significantly higher than those of LG, MG and FG. This indicated that FJ and FH could significantly retain soil fertility in seasonal freeze-thaw period.



Note: Different lowercase letters indicate significant differences between different treatments at the same time ($P<0.05$), the same below.

Figure 4 Temporal-spatial changes of soil nitrate nitrogen content under different treatments

Table 2 Statistical characteristics of nitrate nitrogen content in 0-60 cm soil layer

Year	Treatments	ANR/mg kg^{-1} d^{-1}	LLR/%	NNI/mg kg^{-1}
2019-2020	FG	0.16	54.85	–9.09
	MG	0.18	47.68	–8.22
	LG	0.20	59.65	–10.89
	FH	0.27	37.23	6.80
	FJ	0.26	32.56	9.84
2020-2021	FG	0.12	55.24	–10.36
	MG	0.17	47.70	–8.49
	LG	0.21	58.39	–10.54
	FH	0.25	33.42	8.52
	FJ	0.28	25.92	10.60

Note: NNR is the average nitrification rate during freezing period; LLR is the leaching loss rate during thawing period; NNI is the Nitrate nitrogen increment of the whole period.

3.2 Effects of different autumn plowing treatments on the relationship between soil water, heat and nitrate nitrogen in seasonal freeze-thaw period

3.2.1 Response relationship between soil nitrate nitrogen content and soil temperature

The soil temperature gradient reflects the change of soil temperature in the unit vertical distance. When the soil temperature gradient is positive, the heat transmits upward, and when the soil temperature gradient is negative, the heat transfers downward. The soil heat of each treatment was dissipated upward in the freezing period, and the heat dissipation intensity was in a descending order of FG, MG, LG, FH, and FJ. The duration of soil heat loss in MG, LG, FH and FJ was shortened by 1, 3, 5, 8 days from 2019 to 2020, and abbreviated by 2, 5, 9, 14 days from 2020 to 2021, respectively, compared with those in FG. During the thawing period, the positive and negative alternation of soil temperature gradients occurred in FH and FJ. This indicated that FH and FJ were conducive to promoting the conduction and accumulation of heat from deep soil to shallow soil. However, FG, MG and LG promoted the continuous heat transfer to deep soil (Figure 5).

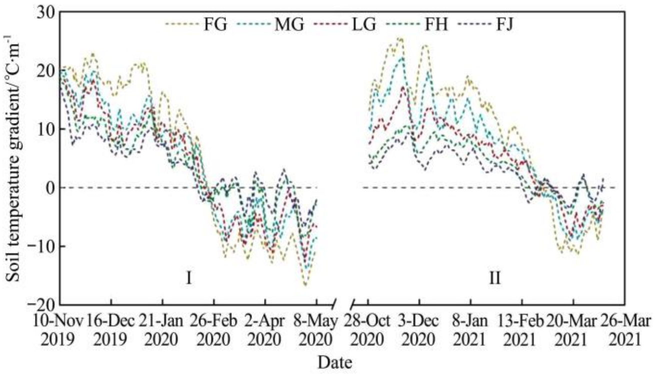
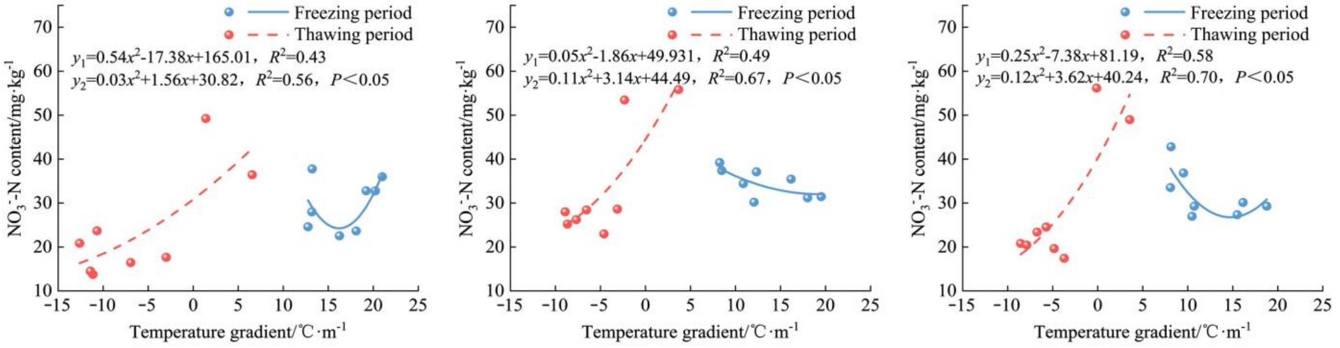
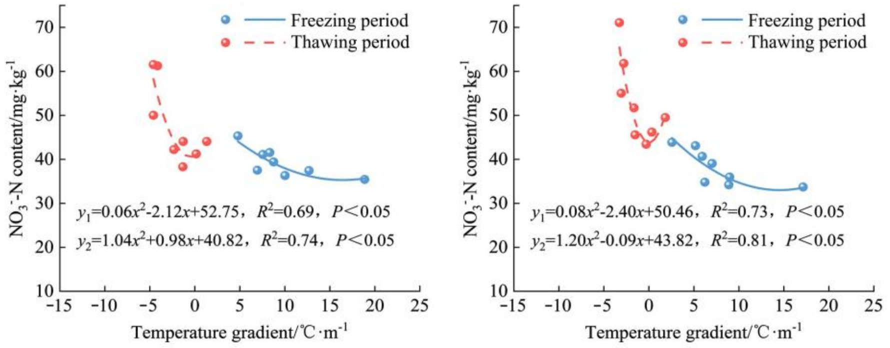


Figure 5 Variation of soil temperature gradient in 0-60 cm soil layer under different autumn plowing treatments

Figure 6 showed the response relationship between soil nitrate nitrogen content and soil temperature gradient in 0-60 cm soil layer. In the freeze period, there was no significant correlation between soil nitrate nitrogen content and soil temperature gradient in FG, MG and LG ($p>0.05$), while there was significant negative correlation between soil nitrate nitrogen content and soil temperature gradient in FH and FJ ($p<0.05$). FH and FJ weakened the soil heat loss intensity, which was more favorable to promoting the accumulation of nitrate nitrogen. During the thawing period, there was a significant positive correlation between soil nitrate nitrogen content and soil temperature gradient in FG, MG and LG ($p<0.05$), which accelerated the migration of soil nitrate nitrogen to deep soil with heat. However, When the soil temperature gradient was negative, the soil nitrate nitrogen content in FH and FJ was significantly negatively correlated with the soil temperature gradient ($p<0.05$). On the contrary, when the soil temperature gradient was positive, the soil nitrate nitrogen content was significantly positively correlated with the soil temperature gradient ($p<0.05$). Therefore, FH and FJ not only inhibited the downward movement of soil nitrate nitrogen and soil heat, but also promoted the upward movement of soil nitrate nitrogen and soil heat. This indicated that FH and FJ had obvious advantages in improving soil temperature and nutrient conditions during seasonal freeze-thaw period.



a. FG b. MG c. LG



d. FH e. FJ

Note: y_1 is the soil nitrate nitrogen content in freezing period; y_2 is the soil nitrate nitrogen content in melting period; x is the soil temperature gradient.

Figure 6 The response relationship between soil nitrate nitrogen content and soil temperature gradient

3.2.2 Response relationship between soil nitrate nitrogen content and soil moisture

The soil humidity gradient reflects the change of soil moisture migration in the unit vertical distance. When the soil humidity gradient is positive, the soil water moves uphill, and when the soil humidity gradient is negative, the soil water moves decurrently. During the freezing period, the soil moisture of each treatment moves upward. Compared with FG treatment, the soil moisture migration intensity of MG, LG, FH and FJ treatments enhanced by 1.16, 1.57, 1.73, 2.07 times from 2019 to 2020, and elevated by 2.06, 2.86, 4.81, 5.42 times from 2020 to 2021, respectively. The soil humidity gradient of FG, MG and LG in thawing period showed the characteristics of negative to positive, while the soil humidity gradient of FH and FJ was minus, and the water migration intensity decreased significantly. This showed that FJ and FH not only delayed the infiltration process of snowmelt water but also hindered the upward evaporation of soil moisture, which was more advantageous to the accumulation of soil moisture in the tillage layer (Figure 7).

Figure 8 showed the response relationship between soil nitrate nitrogen content and soil humidity gradient in 0-60 cm soil layer. During freezing period, there was no significant correlation between soil nitrate nitrogen content and soil humidity gradient in FG and MG, while there was significant positive correlation between soil nitrate nitrogen content and soil humidity gradient in LG, FH and FJ ($p<0.05$). This indicated that LG, FH and FJ were

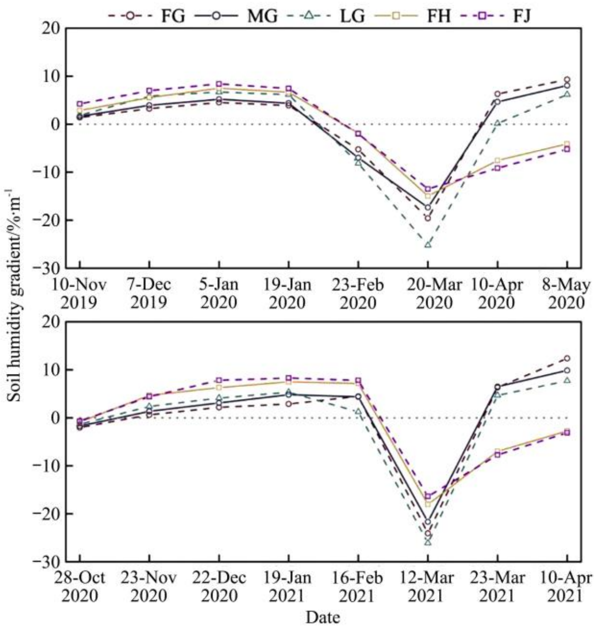
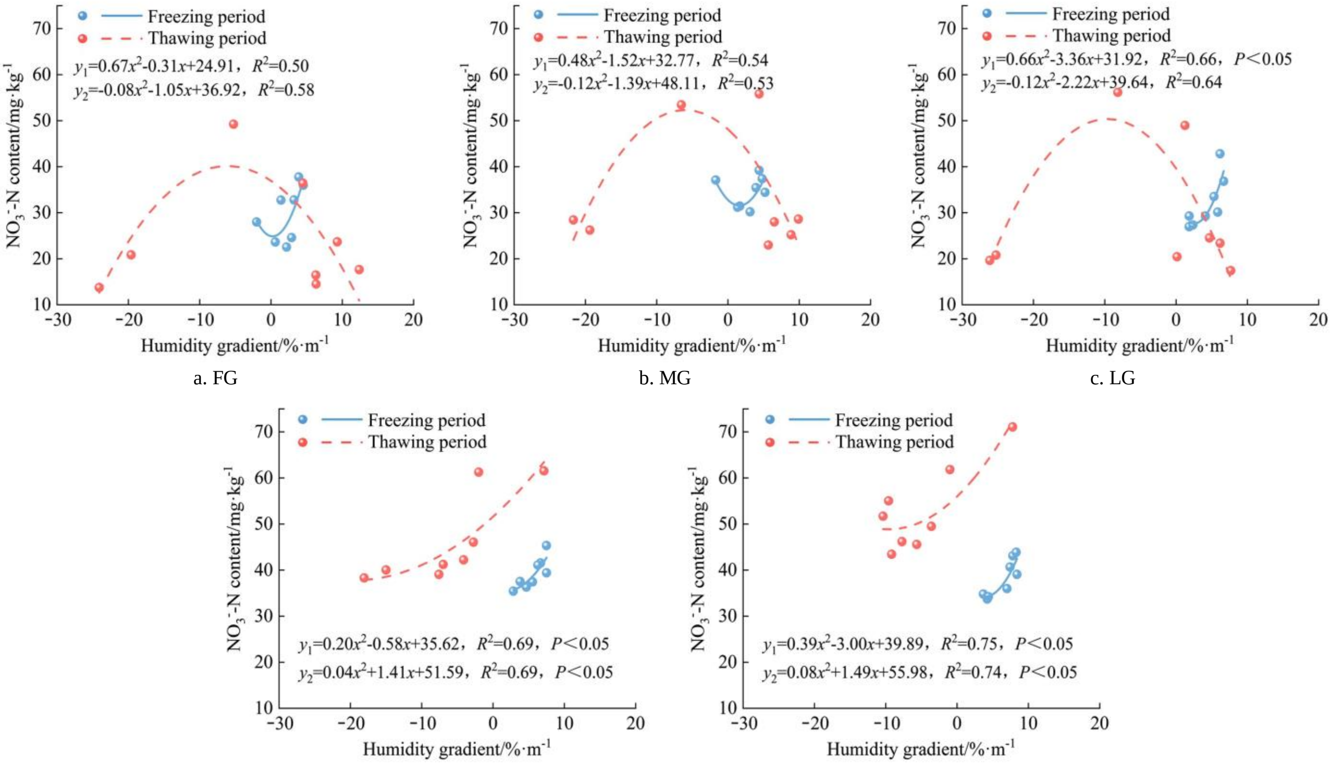


Figure 7 Variation of soil humidity gradient in 0-60 cm soil layer under different autumn plowing treatments

conducive to promoting the synergistic upward migration of soil moisture and nitrate nitrogen. In thawing period, there was a significant quadratic function relationship between soil nitrate nitrogen content and soil moisture gradient in FG, MG and LG ($p<0.05$), while there was a significant positive correlation between soil nitrate nitrogen content and soil moisture gradient in FH and FJ ($p<0.05$). Overall, FJ and FH showed obvious advantages in water storage and fertilizer fixation, which was more conducive to improving soil moisture in spring sowing.

3.2.3 Interaction relationship of soil water, heat and nitrate nitrogen

Binary regression analysis was carried out with soil temperature gradient and soil humidity gradient as independent variables and soil nitrate nitrogen content as dependent variable (Table 3). It was found that the interaction between soil temperature gradient and humidity gradient in the freezing period and the thawing period of each treatment could explain 84%-93% and 87%-96% of the variation of soil nitrate nitrogen content, respectively. The dual effect of soil temperature gradient and soil humidity gradient were significantly stronger than that of single factor, indicating that soil moisture and soil temperature movement had a certain interaction effect on the change of soil nitrate nitrogen content. The R^2 values of the binary regression equation of each treatment in the thawing period were greater than in the freezing period, which manifested that the intensity of soil water, heat and nitrate nitrogen cooperative migration in thawing period was stronger than that in freezing period. The R^2 values of the binary regression equation of different treatments appeared a descending order as FJ, FH, LG, MG and FG throughout the whole experiment. FJ and FH significantly strengthened the response degree between soil nitrate nitrogen content, soil temperature gradient and soil humidity gradient ($p<0.01$). As a whole, FJ and FH had obvious advantages in controlling water, heat and nitrate nitrogen coordinated migration.



a. FG b. MG c. LG

d. FH e. FJ

Note: y_1 is the soil nitrate nitrogen content in freezing period; y_2 is the soil nitrate nitrogen content in melting period; x is the soil humidity gradient.

Figure 8 The response relationship between soil nitrate nitrogen content and soil temperature gradient

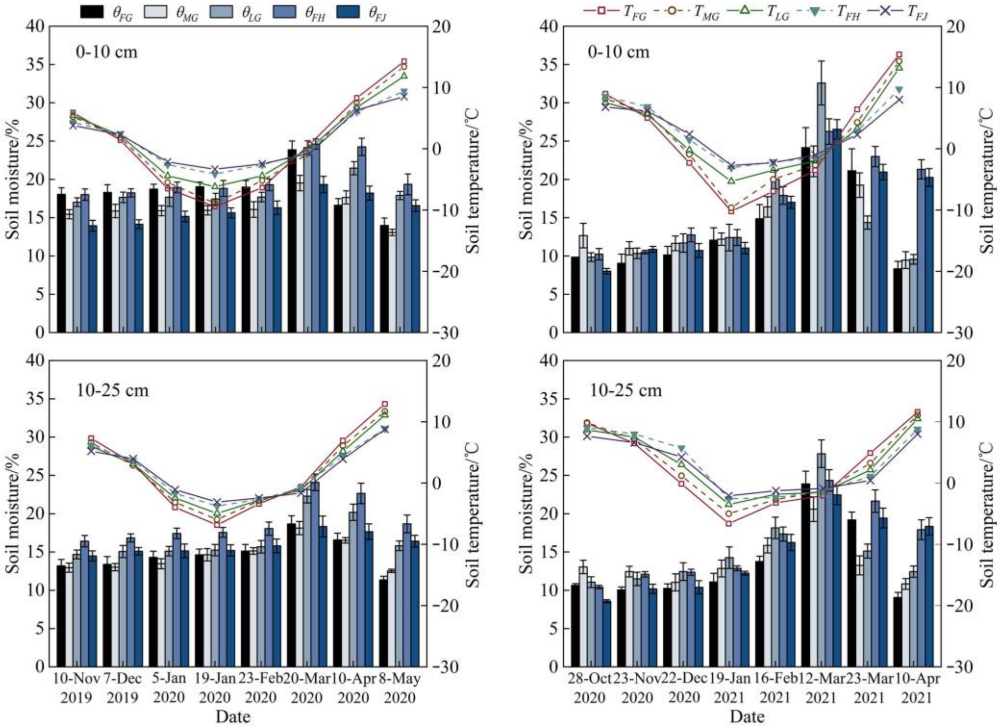
Table 3 Binary regression analysis of soil nitrate nitrogen content, soil temperature gradient and soil humidity gradient under different treatments

Treatment	Binary regression equation	R^2	Significance
FG	$z_1=106.16+10.74x+17.89y+0.47x^2+2.85y^2–1.56xy$	0.84	$P<0.05$
	$z_2=44.14+2.80x–2.20y+0.15x^2–0.07y^2–0.22xy$	0.87	$p<0.05$
MG	$z_1=138.82–13.42x–12.65y+0.39x^2+0.68y^2+0.86xy$	0.88	$p<0.01$
	$z_2=55.81+5.69x–2.81y+0.31x^2–0.06y^2–0.40xy$	0.94	$p<0.05$
LG	$z_1=74.91–7.43x+5.18y+0.27x^2+0.62y^2+0.55xy$	0.88	$p<0.01$
	$z_2=54.66+3.89x–2.32y–0.45x^2–0.13y^2+0.22xy$	0.91	$p<0.05$
FH	$z_1=109.08-12.57x–3.42y+0.38x^2–0.31y^2+0.79xy$	0.92	$p<0.01$
	$z_2=65.97+20.41x–2.03y+6.90x^2+0.27y^2–2.91xy$	0.93	$p<0.01$
FJ	$z_1=92.65–10.81x–2.98y+0.29x^2+0.29y^2+0.80xy$	0.93	$p<0.01$
	$z_2=48.20–2.86x–3.03y+3.88x^2–0.05y^2–1.02xy$	0.96	$p<0.01$

Note: z_1 is the soil nitrate nitrogen content in freezing period; z_2 is the soil nitrate nitrogen content in thawing period; x is the soil temperature gradient; y is the soil humidity gradient.

3.3 Effects of different autumn plowing treatments on soil moisture status and cotton emergence rate during spring sowing period

Seasonal freeze-thaw period is a critical stage for the transition of farmland from fallow period to spring sowing period, and the change of soil water, heat and fertilizer conditions in 0-25 cm soil layer during this period plays a key role in crop emergence. Compared with FG, the fluctuation amplitude of soil temperature in MG, LG, FH and FJ all decreased (Figure 9). Compared with FG, the average soil temperatures in 0-25 cm soil layer of MG, LG, FH and FJ aggrandized by 0.37 ℃, 0.52 ℃, 1.04 ℃, 1.32 ℃ from 2019 to 2020, and increased by 0.27 ℃, 0.56 ℃, 0.94 ℃, 1.26 ℃ from 2020 to 2021, respectively. The soil water content in 0-25 cm soil layer of LG, FH and FJ all enhanced obviously throughout the two experimental stages. The soil moisture increments of LG, FH and FJ were 1.17%, 3.23%, 4.88% from 2019 to 2020, and were 1.90%, 8.79%, 12.51%, from 2020 to 2021, respectively. However, both FG and MG aggravated the loss of soil moisture in the 0-25 cm soil layer. In different autumn plowing methods, FH and FJ significantly promoted the accumulation of nitrate nitrogen in 0-25 cm soil layer, while FG, MG and LG aggravated the leaching of nitrate nitrogen in 0-25 cm soil layer (Figure 4). In 2019-2020, the content of nitrate nitrogen in 0-25 cm soil layer of FH and FJ augmented by 8.68 and 13.18 mg/kg, and lifted by 11.71 and 7.76 mg/kg in 2020-2021, respectively. The cotton emergence rates of each treatment during spring sowing period manifested as a descending order of FJ, FH, LG, MG and FG in both experimental stages (Table 4). In general, FH and FJ had significant advantages in improving soil moisture status and promoting cotton emergence during spring sowing period.



Note: θ_{FG}, θ_{MG}, θ_{LG}, θ_{FH}, θ_{FJ} are soil water content of FG, MG, LG, FH, FJ respectively. T_{FG}, T_{MG}, T_{LG}, T_{FH}, T_{FJ} are the daily average soil temperature of FG, MG, LG, FH, FJ respectively.

Figure 9 Temporal-spatial variation characteristics of soil temperature and soil water content in 0-25 cm soil layer under different autumn plowing treatments

Table 4 Cotton seedling emergence rate under different autumn plowing treatments

Years	Treatments	Cotton seedling emergence rate/%
2019-2020	FG	86.84±0.98a
	MG	89.02±0.59ab
	LG	91.02±0.42b
	FH	96.25±1.92c
	FJ	96.29±2.58c
2020-2021	FG	88.61±1.08a
	MG	90.36±1.64a
	LG	92.86±1.13b
	FH	96.51±0.70c
	FJ	97.56±0.62c

4 Discussion

4.1 Effect of autumn plowing on nitrate nitrogen leaching and accumulation in seasonal freeze-thaw period

Different autumn plowing treatments have different regulatory effects on soil nitrate nitrogen content in plough layer. In the present papers, FJ and FH had the best effect on promoting the accumulation of nitrate nitrogen in the topsoil during the freezing period. This was due to the warm-keeping function of the surface cover will delay the freezing process of the soil, so that the deep soil nitrate nitrogen had sufficient time to migrate upward with soil water. FG would increase soil porosity[24] and then accelerates the infiltration of snowmelt water. LG has strong water storage capacity[25,26] and then expedites the infiltration of snowmelt water. Therefore, this study found that FG and LG increased the leaching loss of nitrate nitrogen, while FH and FJ significantly reduced the leaching loss of nitrate nitrogen. The reason was that the surface mulching hindered the process of soil nitrate leaching down with the infiltration of snowmelt water. At the same time, activated carbon can adsorb nitrate nitrogen in soil[27,28] and straw decomposition can input nutrients to the soil[29,30] which further improved the content of nitrate nitrogen in topsoil. Traversed the whole seasonal freeze-thaw period, the variation of soil nitrate nitrogen in FG, MG and LG showed leaching > accumulation, and the variation of soil nitrate nitrogen in FH and FJ presented as accumulation > leaching, which was consistent with the results of previous studies[31-33]. The feasibility of regulating soil fertility by changing autumn plowing methods was further proved. Hu et al.[34] found that no-tillage significantly reduced the risk of soil nitrate nitrogen leaching. However, in our study, soil nitrate nitrogen in 0-60 cm soil layer under MG still had serious leaching loss. This was due to the soil conditions in different regions were different, which severely affected the migration of soil water. Moreover, our study had found that soil mulching significantly reduced the leaching process of soil nitrate nitrogen to deep soil compared with the non-mulching treatment, and the water and fertilizer status of tillage soil layer significantly improved, which was inconsistent with the results of Yin et al.[35]. This was due to the few amount of rainfall during our experiment and the external supply of soil water was only snow melting water, which severely affected the infiltration process of soil water under the surface coating.

4.2 The regulation mechanism of autumn plowing on the synergistic relationship between soil water, heat and nitrate nitrogen in seasonal freeze-thaw period

Nitrate nitrogen is homogeneous with soil colloid and easy to leach with soil water[36]. Therefore, the leaching and accumulation of nitrate nitrogen in soil is closely related to soil water movement. Zhao et al.[37] found that the content of nitrate nitrogen in soil was positively correlated with soil water. However, our study found that soil nitrate nitrogen and soil humidity gradient in FG, MG and LG showed significant quadratic function relationship during thawing period ($p<0.05$). This proposed that FG, MG, and LG changed the soil water diffusion path, causing leaching of soil nitrate nitrogen. In addition, our study found that soil nitrate nitrogen had a significantly positive correlation with soil moisture gradient in FH and FJ ($p<0.05$). FH and FJ significantly improved the status of soil water and nutrients during the whole seasonal freeze-thaw period. This was attributed to the ground cover prevented the leaching of nitrate nitrogen to deep soil, and inhibited the invalid evaporation of soil water. Therefore, FH and FJ significantly promoted the migration of soil moisture and nitrate nitrogen from deep soil to topsoil. This was consistent with the results of Hou et al.[38]

Soil temperature is also an important factor affecting the migration of nitrate nitrogen. The rise of soil temperature would improve the activity of microorganisms, promote the mineralization and nitrification of organic nitrogen, so as to change the content of nitrate nitrogen in soil[39,40]. Soil temperature gradient is the driving force of soil water migration, and soil water is the carrier of nitrate nitrogen migration[41]. Therefore, soil temperature can also affect the transportation of nitrate nitrogen while changing soil water migration. In our study, we focused on the response relationship between soil nitrate nitrogen and soil temperature gradient under five autumn plowing treatments. The results showed that there was a significant negative correlation between soil nitrate nitrogen content and soil temperature gradient in FH and FJ during freezing period ($p<0.05$), and a significant quadratic function relationship during thawing period ($p<0.05$). FH and FJ had obvious advantages in promoting the synergistic migration of soil nitrate nitrogen and soil temperature, and improving the heat and nutrient conditions of spring sowing soil, which was consistent with the existing research results[42,43].

The change of soil nitrate nitrogen content is not only related to the single factor of soil temperature and water, but also closely related to the synergistic movement of water and heat. There were significant interactions among soil water, heat and nitrate nitrogen under different autumn plowing methods. The interaction among water, heat and nitrate nitrogen in FH and FJ was the most significant, and the ability of warming, water storage and fertilizer fixation was the strongest. Overall, FH and FJ can improve soil moisture status during seasonal freeze-thaw period by optimizing the synergistic relationship between soil water, heat and nitrate nitrogen, which has practical guiding significance for agricultural production in northern Xinjiang.

4.3 The regulation mechanism of autumn plowing on soil water and heat status and nitrate nitrogen content in spring sowing soil

The changes of soil water and heat status and nitrate nitrogen content during seasonal freeze-thaw period have significant impacts on soil moisture, crop seed germination and early crop growth in spring sowing next year[44]. Studies showed that different tillage treatments can change soil surface conditions and heat flow, thereby affecting soil moisture migration and nutrient content[45,46]. FG and MG were not conducive to the maintenance of soil water and heat resources, and reduced the content of soil organic matter and nitrogen in the tillage layer[47,48]. This was consistent with the results of our experiments. Therefore, in order to improve the soil conditions during the spring sowing period, it was necessary to change the traditional autumn plowing method in northern Xinjiang. Other studies proposed that LG can enhance the ability of soil water storage and fertilizer capacity[49,50]. This may be due to the different specifications of ridge and furrow, or the low soil microbial activity in the seasonal freeze-thaw period, which was not availed to the accumulation of soil nitrate nitrogen. In addition, our experimental results showed that the soil moisture of FH and FJ was the best during spring sowing, and the emergence of spring sowing crops was the best, too. This was because the ground cover provided good water and heat conditions, and the tillage treatment improved soil permeability, which are beneficial to promote the decomposition of soil organic matter and the accumulation of soil nutrients[51,52].

5 Conclusions

Based on data collected over two seasonal freeze-thaw period in the field, we found that FG and MG had the worst effect on regulating the conditions of soil water, heat and nitrate nitrogen during seasonal freeze-thaw period. LG was conducive to improving soil water and heat conditions, but was not in favor of the accumulation of soil nitrate nitrogen. FH and FJ had the best effect in all aspects. FH and FJ on the one hand inhibit the downward migration of soil water, heat and nitrate nitrogen, on the other hand, FH and FJ can promote the migration of soil water, heat and nitrate nitrogen from the deep soil layer to the plough layer. Moreover, FH and FJ significantly heightened the reciprocity among soil nitrate nitrogen content, temperature gradient and humidity gradient ($p<0.01$), and optimized the synergistic migration mechanism of soil water, heat and nitrate nitrogen, which was more helpful in maintaining soil water and heat resources and retaining soil nutrients. FH and FJ lessened the loss of soil moisture, heat and nitrate nitrogen during seasonal freeze-thaw period. In addition, FH and FJ significantly boosted the soil temperature, water content and nitrate nitrogen content in 0-25 cm soil layer during spring sowing period, and promoted the rate of cotton emergence. Considering the superiority of FH and FJ in regulating soil water, heat and nitrate nitrogen, it was suggested to popularize this in the arid area of northern Xinjiang.

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[References]

[1] Liu Z J, Chen Z J, Ma P Y, Meng Y, Zhou J B. Effects of tillage, mulching and N management on yield, water productivity, N uptake and residual soil nitrate in a long-term wheat-summer maize cropping system. Field Crops Research, 2017; 213: 154–164.

[2] Ouyang W, Chen S Y, Cai G Q, Hao F H. Dryland soil hydrological processes and their impacts on the nitrogen balance in a soil-maize system of a freeze-thawing agricultural area. PLoS One, 2017; 9(7): 282–293.

[3] Elliott A C, Henry H A L. Freeze-thaw cycle amplitude and freezing rate

effects on extractable nitrogen in a temperate old field soil. Biology and Fertility of Soils, 2009; 45(5): 469–476.

[4] Gou X L, Wu F Z, Yang W Q, Tan B, Xu Z F, Liu J L, et al. Effect of changes in seasonal freeze-thaw pattern on nitrogen loss from leaching in the alpine forest soil. Acta Scientiae Circumstantiae, 2014; 34(2): 439–448. (in Chinese)

[5] Joesph G, Henry H A. Soil nitrogen leaching losses in response tofreeze-thaw cycles and pulsed warming in a temperate old field. Soil Biology & Biochemistry, 2008; 40(7): 1947–1953.

[6] Wertz S, Goyer C, Zebarth B J, Tatti E, Burton D L, Chantigny M H, et al. The amplitude of soil freeze-thaw cycles influences temporal dynamics of N_2O emissions and denitrifier transcriptional activity and community composition. Biology and Fertility of Soils, 2016; 52(8): 1149–1162.

[7] Ros G H, Hoffland E, Kessel C V, Temminghoff J M. Extractable and dissolved soil organic nitrogen- A quantitative assessment. Soil Biology & Biochemistry, 2009; 41(6): 1029–1039.

[8] Wang H G, Guo Z J, Shi Y, Zhang Y L, Yu Z W. Impact of tillage practices on nitrogen accumulation and translocation in wheat and soil nitrate-nitrogen leaching in drylands. Soil & Tillage Research, 2015; 153: 20–27.

[9] Dong Q, Dang T H, Guo S L, Hao M D. Effect of different mulching measures on nitrate nitrogen leaching in spring maize planting system in south of Loess Plateau. Agricultural Water Management, 2019; 213:654–658.

[10] Matthews A M, Armstrong A C, Leeds-Harrison P B, Harris G L, Catt J A. Development and testing of a model for predicting tillage effects on nitrate leaching from cracked clay soils. Soil & Tillage Research, 2000; 53: 245–254.

[11] Issaka F, Zhang Z, Li Y T, Zhao Z Q, Asenso E, Kanu A S, et al. Zero tillage improves soil properties, reduces nitrogen loss and increases productivity in a rice farmland in Ghana. Agronomy, 2019; 9(10): 641–654.

[12] López-Fando C, Pardo M T. Use of a partial-width tillage system maintains benefits of no-tillage in increasing total soil nitrogen. Soil & Tillage Research, 2011; 118: 32–39.

[13] Habtegebrial K, Singh B R, Haile M. Impact of tillage and nitrogen fertilization on yield, nitrogen use efficiency of tef (Eragrostis tef (Zucc.) Trotter) and soil properties. Soil & Tillage Research, 2007; 94: 55–63.

[14] Clay D E, Schumacher T E, Brix-Davis K A. Carbon and nitrogen mineralization in row and interrow areas of chisel and ridge tillage systems. Soil & Tillage Research, 1995; 35(3): 167–174.

[15] Fan L L, Shi H B, Li R P, Miao Q F, Wang S N, Pei W W. Effects of straw mulching on soil water-salt transportation and water use efficiency of maize under furrow irrigation. Transactions of the CSAM, 2021; 52(2): 283–293, 319. (in Chinese).

[16] Sadiq M, Li Q, Rahim N, Tahir M M. Effect of conservation tillage on yield of spring wheat (Triticum aestivum L.) and soil mineral nitrogen and carbon content. International Agrophys, 2021; 35: 83–95.

[17] Li F, Han X, Ma X L, Wang L J, Song T Q, Wang Y Y. Straw mulch control runoff and nitrogen and phosphorus loss from slope farmland in black soil region of northeast. Journal of Soil and Water Conservation, 2020; 34(4): 37–42. (in Chinese)

[18] Reverchon F, Flicker R C, Yang H, Yan G J, Xu Z H, Chen C R. Changes in δ15N in a soil–plant system under different biochar feedstocks and application rates. Biology & Fertility of Soils, 2014; 50(2): 275–283.

[19] William H, Philip R, James W. Effects of three different biochars on aggregate stability, organic carbon mobility and micronutrient bioaviliability. Journal of Environmental Management, 2016; 181: 770–778.

[20] Brennan J, Hackett R, McCabe T, Grant J, Fortune R A, Forristal P D. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. European Journal of Agronomy, 2014; 54: 61–69.

[21] Lei T, Gu Q Q, Guo X H, Ma J J, Zhang Y, Sun X H. Urease activity and urea hydrolysis rate under coupling effects of moisture content, temperature, and nitrogen application rate. International Journal of Agricultural and Biological Engineering, 2018; 11(2): 132–138.

[22] Zhang X D, Zhao J, Yang L C, Kamran M, Xue X K, Dong Z Y, et al. Ridge-furrow mulching system regulates diurnal temperature amplitude and wetting-drying alternation behavior in soil to promote maize growth and water use in a semiarid region. Field Crops Research, 2019; 233: 121–130.

[23] Sun K, Wang C X, Lan M J, Liang F. Effect of autumn tillage on soil thermal conditions during the seasonal freeze-thaw period in the north Xinjiang. Journal of Soil and Water Conservation, 2021; 35(5): 63–71. (in Chinese)

[24] Hu H N, Lu C Y, Wang Q J, Li H W, He J, Xu D J, et al. Influences of wide-narrow seeding on soil properties and winter wheat yields under conservation tillage in North China Plain. Int J Agric & Biol Eng, 2018; 11(4): 74–80.

[25] Yin M H, Li Y N, Zhang T L, Xu Y B, Gu X B, Wang X Y. Effects of different rainwater harvesting patterns on soil hydrothermal regimes and water use efficiency of summer maize. Transactions of the CSAM, 2015; 46(12): 194–203, 211. (in Chinese)

[26] Hu X J, Liang A Z, Yao Q, Liu Z X, Yu Z H, Wang G H, et al. Ridge tillage improves soil properties, sustains diazotrophic communities, and enhances extensively cooperative interactions among diazotrophs in a clay loam soil. Frontiers in Microbiology, 2020; 11(8): 1333–1344.

[27] Gao D C, Zhang L, Liu Q, Rong X M, Zhang Y P, Tian C. Application of biochar in dryland soil decreasing loss of nitrogen and improving nitrogen using rate. Transactions of the CSAE, 2014; 30(6): 54–61. (in Chinese)

[28] Mizuta K, Matsumoto T, Hatate Y, Nishihara K, Nakanishi T. Removal of nitrate-nitrogen from drinking water using bamboo powder charcoal. Bioresource Technology, 2004; 95(3): 255–257.

[29] Dalal R C, Strong W M, Cooper J E, King A J. No-tillage and nitrogen application affects the decomposition of 15N-labelled wheat straw and the levels of mineral nitrogen and organic carbon in a Vertisol. Australian Journal of Experimental Agriculture, 2007; 47(7): 862–868.

[30] Chen X W, Zhao H B, Liu J F, Mao A R. Winter wheat nitrogen utilization under different mulching practices on the Loess Plateau. Agronomy Journal, 2020; 112(2): 1391–1405.

[31] Alvarez R, Steinbach H S. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil & Tillage Research, 2009; 104(1): 1–15.

[32] Dempster D N, Jones D L, Murphy D V. Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. Soil Research, 2012; 50(3): 216–221.

[33] Fu Q, Yan J W, Li H, Li T X, Hou R J, Liu D, et al. Effects of biochar amendment on nitrogen mineralization in black soil with different moisture contents under freeze-thaw cycles. Geoderma, 2019; 353: 459–467.

[34] Hu L F, Hu C S, An Z M, Zhang A J, Chen F. Effects of different tillage patterns on crop yields and nitrate leaching in soil. Journal of Soil and Water Conservation, 2005; 19(6): 188–191. (in Chinese)

[35] Yin T, He W Q, Yan C R, Liu S, Liu E K. Effects of plastic mulching on surface of no-till straw mulching on soil water and temperature. Transactions of the CSAE, 2014; 30(19): 78–87. (in Chinese)

[36] Mo F, Wang J Y, Ren H X, Sun G J, Kavagi L, Zhou H, et al. Environmental and economic benefits of micro–field rain–harvesting farming system at maize (Zea mays L.) field scale in semiarid east African Plateau. Agricultural Water Management, 2018; 206: 102–112.

[37] Zhao L H, Li C Z, Kang D, Ren C J, Han X H, Tong X G, et al. Dynamic change in soil soluble nitrogen under farmland converted to forest in the Loess Hilly Region. Acta Ecologica Sinica, 2018; 38(2): 689–697. (in Chinese)

[38] Hou X Q, Li R. Effects of autumn tillage with mulching on soil water, temperature and nutrient and potato growth. Transactions of the CSAM, 2020; 51(12): 262–275. (in Chinese)

[39] Pajuste K, Frey J. Nitrogen mineralization in podzol soils under boreal Scots pine and Norway spruce stands. Plant and Soil, 2003; 257(1): 237–247.

[40] Herrmann A, Witter E. Sources of C and N contributing to the flush in mineralization upon freeze-thaw cycles in soils. Soil Biology and Biochemistry, 2002; 34(10): 1495–1505.

[41] Yao B L, Li G Y, Wang F. Effects of winter irrigation and soil surface mulching during freezing-thawing period on soil water-heat-salt for cotton fields in south Xinjiang. Transactions of the CSAE, 2016; 32(7): 114–120. (in Chinese)

[42] Wang X K, Li Z B, Xing Y Y. Effects of mulching and nitrogen on soil temperature, water content, nitrate-N content and maize yield in the Loess Plateau of China. Agricultural Water Management, 2015; 161: 53–64.

[43] Zhang J J, Li X Y, Peng Z Y, Guo Y, Ding Z J, Leng X. The distribution of soil water, temperature, nitrogen and salinity under biofilm mulching in Hetao sunflower field. Ecology and Environmental Sciences, 2018; 27(6): 1067–1075. (in Chinese)

[44] Wang H L, Zhang X C, Yu X F, Hou H Z, Fang Y J, Ma Y F. Effects of

annual whole-film mulching on freezing-thawing characteristics, moisture, and temperature distribution of maize soil in semi-arid area. Chinese Journal of Applied Ecology, 2020; 31(4): 1146–1154. (in Chinese)

[45] Sarkar S, Singh S R. Interactive effect of tillage depth and mulch on soil temperature, productivity and water use pattern of rainfed barley (*Hordium vulgare* L). Soil & Tillage Research, 2007; 92: 79–86.

[46] Yang Y H, Ding J L, Zhang Y H, Wu J C, Zhang J M, Pan X Y, et al. Effects of tillage and mulching measures on soil moisture and temperature, photosynthetic characteristics and yield of winter wheat. Agricultural Water Management, 2018; 201(1): 299–308.

[47] Qiu Y, Wang X. Effects of tillage patterns on soil moisture and soybean yield in sloping fields. Transactions of the CSAE, 2018; 34(22): 128–137. (in Chinese)

[48] Zhang J L, Sikander K T, Wen X X, Chen Y X, Gao M B, Liu Y, et al. Soil respiration and its affecting factors in dry-land maize field under different tillage systems. Transactions of the CSAE, 2012; 28(18): 192–199. (in Chinese)

[49] Zhang G X, Mo F, Shah F, Meng W H, Liao Y C, Han J. Ridge-furrow configuration significantly improves soil water availability, crop water use efficiency, and grain yield in dryland agroecosystems of the Loess Plateau. Agricultural Water Management, 2020; 245: 657–666.

[50] Zhao H, Wang R Y, Ma B L, Xiong Y C, Qiang S L, Wang C L, et al. Ridge-furrow with full plastic film mulching improves water use efficiency and tuber yields of potato in a semiarid rainfed ecosystem. Field Crops Research, 2014; 161: 137–148.

[51] Chen J F, Zheng X Q, Qin Z D, Liu P, Zang H F, Sun M. Effects of maize straw mulch on spatiotemporal variation of soil profile moisture and temperature during freeze-thaw period. Transactions of the CSAE, 2013; 29(20): 102–110. (in Chinese)

[52] Hou X Q, Li R. Potato tuber yields in semi-arid environments are increased by tillage and mulching practices. Agronomy Journal, 2018; 110(6): 2641–2651.