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# Effect of a Ridge-Furrow Mulching System and Limited Supplementary Irrigation on $N_2O$ Emission Characteristics and Grain Yield of Winter Wheat (*Triticum aestivum* L.) Fields under Dryland Conditions

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**Abstract:** Knowledge of the characteristics of $N_2O$ emissions and the influential mechanism is of great significance to mitigate greenhouse gas emissions in semi-arid areas. In the present study, a three-year water-control study was conducted; three simulated rainfall amounts (heavy, normal, and light rainfall = 275, 200, and 125 mm, respectively), two wheat (*Triticum aestivum L.*) planting modes (RF (ridge–furrow mulching system) and TF (traditional flat planting)) and four supplementary irrigation amounts (150, 75, 37.5, and 0 mm) were set up. The effects of different cultivation methods and irrigation amounts on soil $N_2O$ emissions, the soil water content, available nitrogen content, and denitrifying enzyme activity were investigated to clarify the $N_2O$ emission mechanism in winter wheat fields (*Triticum aestivum L.*). The results obtained after three years showed that compared with TF, the $N_2O$ emissions under RF decreased by 21.62–30.72% ($p < 0.001$), whereas the soil water content increased by 6.26–8.82%, the available nitrogen content decreased by 1.71–16.24%, and the denitrifying enzyme activities increased by 0.2–24.16% under heavy rainfall conditions. Under conditions with normal and light rainfall, the $N_2O$ emission fluxes under RF increased by 3.66–12.46% and 6.08–15.57% ($p > 0.05$), while the soil water contents increased by 6.13–11.49% and 8.05–13.88%, the soil available nitrogen contents decreased by 11.0–21.42% and 19.93–34.44%, and the denitrifying enzyme activities increased by 0.01–24.08% and 0.03–20.79% compared with TF. Principal component analysis showed that the main factors related to $N_2O$ emissions under RF were the soil moisture content and available nitrogen content; these factors combined explained 94.37% the variation of the $N_2O$ emissions. However, the main factors under TF were the soil moisture content and denitrifying enzyme activity; these factors combined explained 85.81%. In the heavy and normal rainfall years, compared with TF, using RF and 75 mm irrigation achieved the goal of reducing water usage as well as decreasing the $N_2O$ emissions (or $N_2O$ increase was not significant). In light rainfall years, RF with 150 mm irrigation obtained significant reductions in water usage compared with TF but it also increased the $N_2O$ emission flux. Under different rainfall years, the yield of RF increased by 2.89–50.44% compared with the TF system, and the increase in wheat grain yield increased with decreasing rainfall.

**Keywords:** *Triticum aestivum L.*; saving water; $N_2O$ emission flux; grain yield; soil water content

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## 1. Introduction

$N_2O$ is an important greenhouse gas in the atmosphere and its comprehensive warming potential is 310 times higher than that of $CO_2$ [1,2]. Moreover, $N_2O$ can yield oxidation products such as nitric oxide (NO), which can destroy the ozone layer [3]. Due to global warming, unusual weather conditions have become more frequent, including extreme heat, droughts, and heavy rain [4]. Climate warming and extreme weather will have major impacts on the soil, which humans rely on for agricultural production and ensuring a reliable food supply. These problems are particularly important in China with a very large population [5].

Farmland soil is the main source of agricultural $N_2O$ emissions, where it accounts for about 80% of the total [6]. Therefore, reducing the $N_2O$ emissions from farmland is of great importance. Human activities can significantly change the $N_2O$ emissions from natural and artificially managed soils [7]. Cusack [8] showed that mulching can change parameters such as the soil moisture and nutrient status, thereby affecting soil microbial processes [9] and enzyme activities [10], which can then influence the $N_2O$ emissions. Previous studies have also indicated that the $N_2O$ emissions increase as the soil water content increases [11]. Different irrigation methods or amounts can affect nitrification and denitrification processes [12] in the soil by changing the soil moisture status, thereby influencing the amount of $N_2O$ generated and the $N_2O$ transport process to the atmosphere [13]. Many studies have investigated the effects of irrigation on $N_2O$ emissions but most focused on the actual emissions, differences in the emission coefficient, and the effects of environmental factors under different treatments [14,15]. In addition, most of these studies considered conventional irrigation methods, such as diffuse irrigation and drip irrigation [16,17]. In recent years, the ridge–furrow mulching (RF) system with supplementary irrigation has been applied widely in arid and semiarid areas with scarce water resources as a new water-saving and high-efficiency irrigation technique because it can significantly increase the soil temperature and moisture content [18–20]. Studies have demonstrated that the application of RF with supplementary irrigation can improve crop yields, but the changes in the soil water content and temperature as well as the use of plastic film also affect the $N_2O$ emissions from the soil.

Most previous studies of RF with supplementary irrigation focused on its effect on the soil moisture content and yield, but the changes in the $N_2O$ emissions and response to RF under different amounts of rainfall have not been reported. Thus, in the present study, in order to explore the field management measures to reduce $N_2O$ emissions under the premise of saving water and increasing production, we determined the effects of RF on the $N_2O$ emissions and related factors comprising the soil water content, soil available nitrogen content, and denitrifying enzyme activities under different amounts of rainfall and supplementary irrigation, where traditional flat planting (TF) was applied as the control. Principal component analysis and regression analysis were conducted to build a response model for $N_2O$ emissions. The results obtained in this study provide a scientific basis for reasonable farmland irrigation management strategies and a theoretical reference for developing irrigation techniques to reduce water usage and $N_2O$ emissions.

## 2. Materials and Methods

### *2.1. Study Site Description*

The research was performed at the crop water-control monitoring test site of the Institute of Water-saving Agriculture in Arid Areas of China (IWSA), Northwest A&F University, Xi'an, Shaanxi, China (108°04′ E, 34°20′ N). The experimental site is located 466.7 m above sea level in a semiarid area with an annual average temperature of 12.9 °C (the annual low and high temperatures are −17.4 and 42 °C). The annual average rainfall per year is 550–600 mm, and 60% occurs during July and September.

The crop water-control monitoring test site was a rain shelter measuring 3 m (hight) × 15 m (width) × 32 m (length) and contained planting pits with a 6.7 $m^2$ (3.15 × 2.13 m) area and 3 m depth. The bottom of the pit was covered with a filter layer (0.5-m-thick sand and stone), and a drain pipe was positioned to allow water to escape from the bottom of the pit. The original soil column comprising deep red soil, was collected from typical farmland in Yangling (Stratified old, manured loesial soil) and used to fill the pit layer by layer [21]. In the rooting depth of the soil (0–40 cm), the available NPK contents were 53.12 mg $kg^{-1}$, 22.34 mg $kg^{-1}$, and 97.37 mg $kg^{-1}$, and the total NPK contents were 1.31 g $kg^{-1}$, 0.83 g $kg^{-1}$, and 6.18 g $kg^{-1}$. The soil organic matter content was 10.91 g $kg^{-1}$, and the pH was 7.44. The mean soil bulk density was 1.25 g $cm^{-3}$.

### *2.2. Experimental Design and Treatments*

The test crop was winter wheat (*Triticum aestivum L.*), and the selected variety was 'Xinong 979'. The trial was conducted for three consecutive years with annual sowing times of 15 October, 18 October, and 13 October, the harvest times were 15 June, 10 June, and 12 June of the following year. Artificial soil preparation, fertilization, tillage, and film mulching were conducted before sowing each year. The planting density was $2.25 \times 10^6$ seeds $ha^{-1}$. Fertilizer was applied at 225 kg $ha^{-1}$ N, 33 kg $ha^{-1}$ P, and 125 kg $ha^{-1}$ K at the time of sowing.

The experiment set up three kinds of rainfall according to the local precipitation characteristics in the winter wheat growth period [22]: heavy (P1: 275 mm), moderate (P2: 200 mm), and light (P3: 125 mm) rainfall levels, and two supplementary irrigation methods were set up under each precipitation: RF and TF (Figure 1). Each irrigation method was tested with four supplemental irrigation levels: 150 mm, 75 mm, 37.5 mm, and 0 mm, where half of the supplemental irrigation was supplied in the wintering stage and the other half in the jointing stage. The rainfall distribution is based on local rainfall patterns (Figure 2). That is to say, 24 treatments were tested in the experiment, where each was repeated three times. The trial was designed in completely randomized blocks. For identification, when the rainfall was 275 mm, the treatment names were $P1R_{150}$, $P1R_{75}$, $P1R_{37.5}$, and $P1R_0$, respectively, under the ridge–furrow mulching system. The treatment names were $P1F_{150}$, $P1F_{75}$, $P1F_{37.5}$, and $P1F_0$, respectively, under the traditional flat planting system. When the rainfall was 200 and 125 mm, treatments were named as stated above.

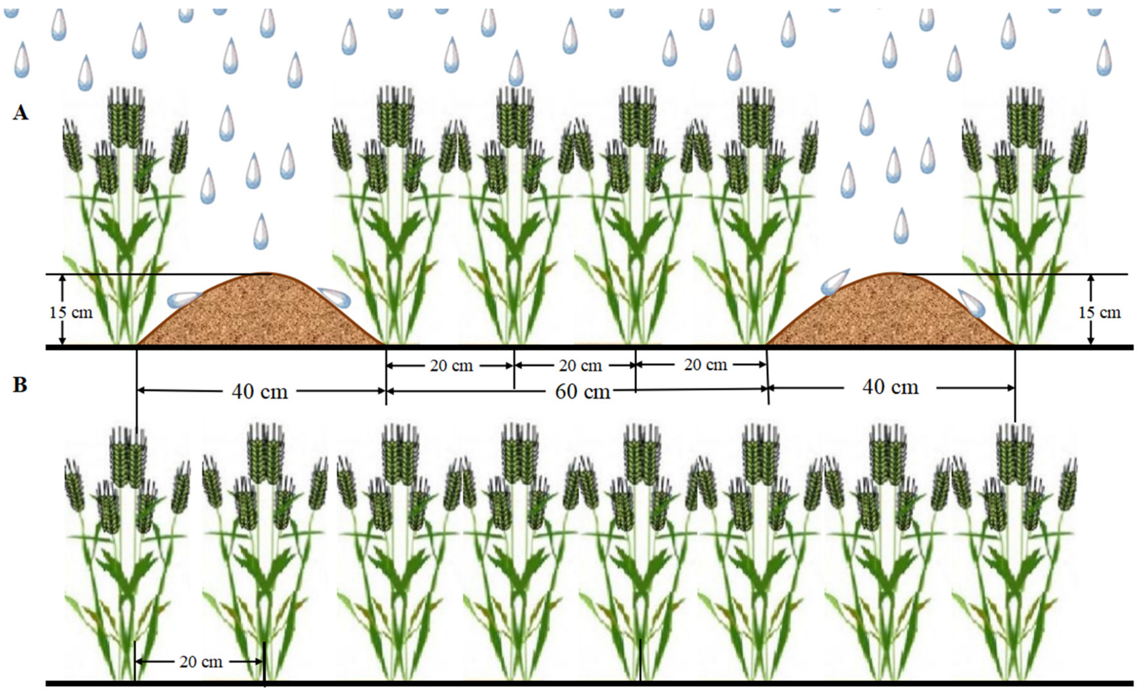


**Figure 1.** Schematic diagram of the field layout. (**A**) Ridge covered with plastic film mulch. (**B**) Traditional flat planting.

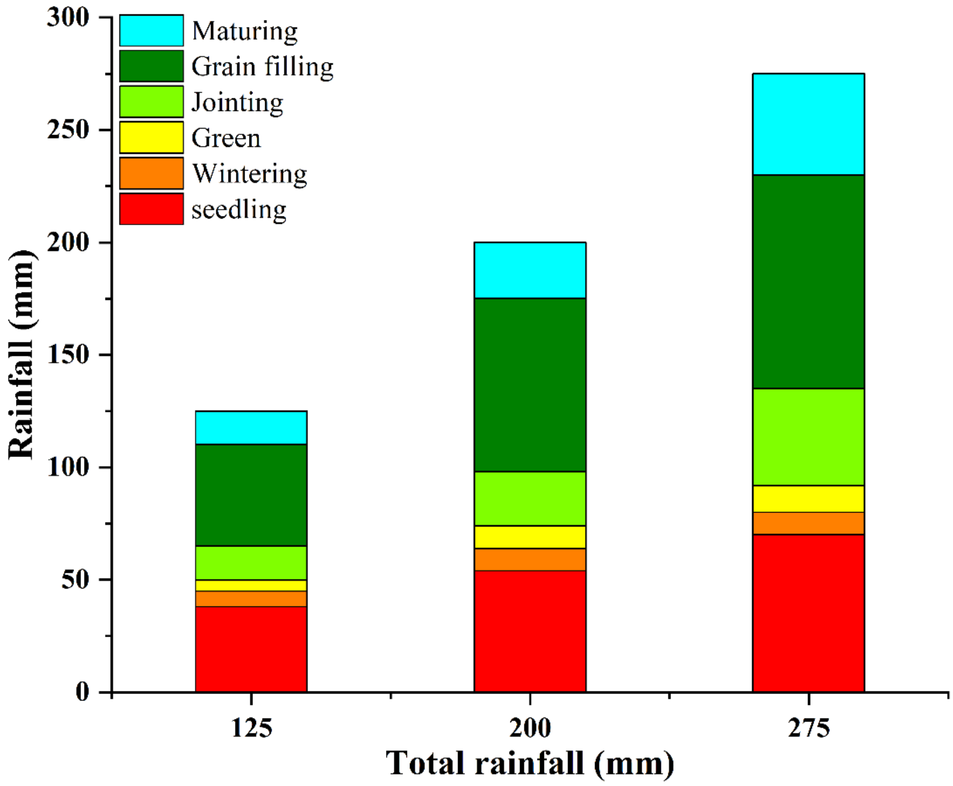


**Figure 2.** Distribution of simulated rainfall during the winter wheat growing seasons. Note: The seeding period is defined as the time of seed sowing, before seedling emergence; Wintering indicates the mean air temperature is stable at 0–1 °C, and wheat basically stops growing; Green: the temperature rises in the spring of the next year, the wheat leaves change color from green purple to bright green, and some heart leaves are exposed; Jointing: 1.5–2 cm above the ground between the stems of more than 50% of the plants in the field; Grain filling indicates that nutrients are quickly transported to the seeds and accumulate, the particles begin to deposit starch, and the endosperm is condensed milk; Maturing means the grains begin to harden.

## *2.3. Sample Collection and Analysis*

### 2.3.1. $N_2O$ Emission Fluxes

$N_2O$ emissions were sampled using a closed chamber-gas chromatography method [23]. The static box system comprised a closed top box (40 cm × 30 cm × 30 cm) and a base (40 cm × 30 cm × 15 cm). The top box and base were made of airtight, opaque material. The top box had two small holes: one for measuring temperature and the other for collecting $N_2O$, while ensuring air pressure balance between inside and outside of the box. After wheat sowing, we installed the base and ensured that the base covered the plant and row.

Sampling was carried out at the tillering stage, overwintering stage, greening stage, jointing stage, flowering stage, grain-filling stage, and during rainfall or irrigation events. Each sampling period lasted about one week until the gas emission was stable. During sampling, the box and base were sealed to prevent the exchange of $N_2O$ inside and outside. Samples were collected every 10 min with a 50-mL syringe, and the soil moisture and the temperature in the box were measured at the same time. The gas samples were transported to the laboratory, and the $N_2O$ emission flux was determined by a chromatographic system (GC-14B, Shimadzu, Kyoto, Japan). The gas emission rate was obtained by linear regression analysis based on the slope of the concentrations of four consecutive samples.

The $N_2O$ emission fluxes were calculated as follows:

$$f = k \cdot h \cdot \frac{\Delta c}{\Delta t} \times \frac{M \times 273}{22.41 \times (273 + \frac{T_1 + T_2}{2})} \times 60$$

where $f$ is the gas emission flux in mg (m$^2$ h)$^{-1}$, h is the height of the static box in m, $\Delta c/\Delta t$ is the variation in the concentration of the gas sample per unit time; $M$ is the molar mass N corresponding to 1 mol $N_2O$; $273/(273 + \frac{T_1+T_2}{2})$ is the correction coefficient for the absolute temperature, and $T_1$ and $T_2$ are the gas temperatures for the first and last samples, respectively, in the sampling box (°C).

#### 2.3.2. Soil Nitrate Nitrogen Content and Denitrifying Enzyme Activities

The sampling depths were 0–20 cm and 20–40 cm. At each sampling site, five points were selected according to an "S" shape in each treatment, and the five subsamples from the same soil layer were mixed to form a composite sample. Any detritus and stones were removed from the samples before placing them into aseptic bags and transporting them to the laboratory in a sampling box with ice. Visible animal and plant residues were removed in the laboratory before the fresh soil was screened through a 2 mm mesh and stored in a refrigerator at 4 °C to determine the soil denitrifying enzyme activities [24]. The soil available nitrogen content was determined using the alkali–dispersion method [25].

#### 2.3.3. Grain Yield

After wheat harvest, 2 m$^2$ samples were selected in each plot for individual harvest; the sample yield was calculated by measuring the number of wheat ears, spike number, and thousand-grain weight, which were converted to the yield per ha by unit (t·ha$^{-1}$).

### *2.4. Statistical Analysis*

The original data were analyzed using Microsoft Excel 2007. The differences in grain yield among different treatments were analyzed using the LSD test at the 5% level in SPSS 18.0 software. The analysis of correlations between $N_2O$ emissions, soil water contents, soil available nitrogen contents, and denitrifying enzyme activities was carried out using Origin 2019. Canoco 5 was used to conduct principal component analysis.

## 3. Results

### *3.1. $N_2O$ Emissions, Soil Water Contents, and Soil Available Nitrogen Contents under RF with Supplementary Irrigation*

During the growth of winter wheat, the $N_2O$ emission fluxes decreased initially under each treatment and then increased. The emission fluxes decreased slowly from the tillering stage to the jointing stage, before slowly increasing from the jointing stage to the grain filling stage and then stabilizing (Figure 3). Compared with TF, under RF with rainfall at 275 mm in the winter wheat growth period, the $N_2O$ emission fluxes decreased significantly by 21.62–30.72% ($p < 0.001$) during the same growth stages (Figure 3a). Under RF, the $N_2O$ emission fluxes with $P1R_{150}$ were 0.24–2.23 times higher than those with $P1R_{75}$, $P1R_{37\cdot5}$, and $P1R_0$ ($p < 0.05$) (Figure 3b). The $N_2O$ emission fluxes under RF with 200 mm rainfall were 3.66–12.46% higher ($p > 0.05$) compared with TF (Figure 3c), but the difference was not significant. Under RF, the $N_2O$ emission fluxes with $P2R_{150}$ were 7.05–69.33% higher than those with the other irrigation treatments, and the increase was greater as the irrigation amount decreased (Figure 3d). The $N_2O$ emission fluxes did not differ significantly between $P2R_{150}$ and $P2R_{75}$ ($p > 0.05$). Under rainfall at 125 mm, the $N_2O$ emission fluxes with RF were 6.08–15.57% higher compared with TF ($p > 0.05$). Under RF, the $N_2O$ emission fluxes with $P3R_{150}$ were 9.88–64.37% higher ($p < 0.05$) compared with the other treatments (Figure 3f).

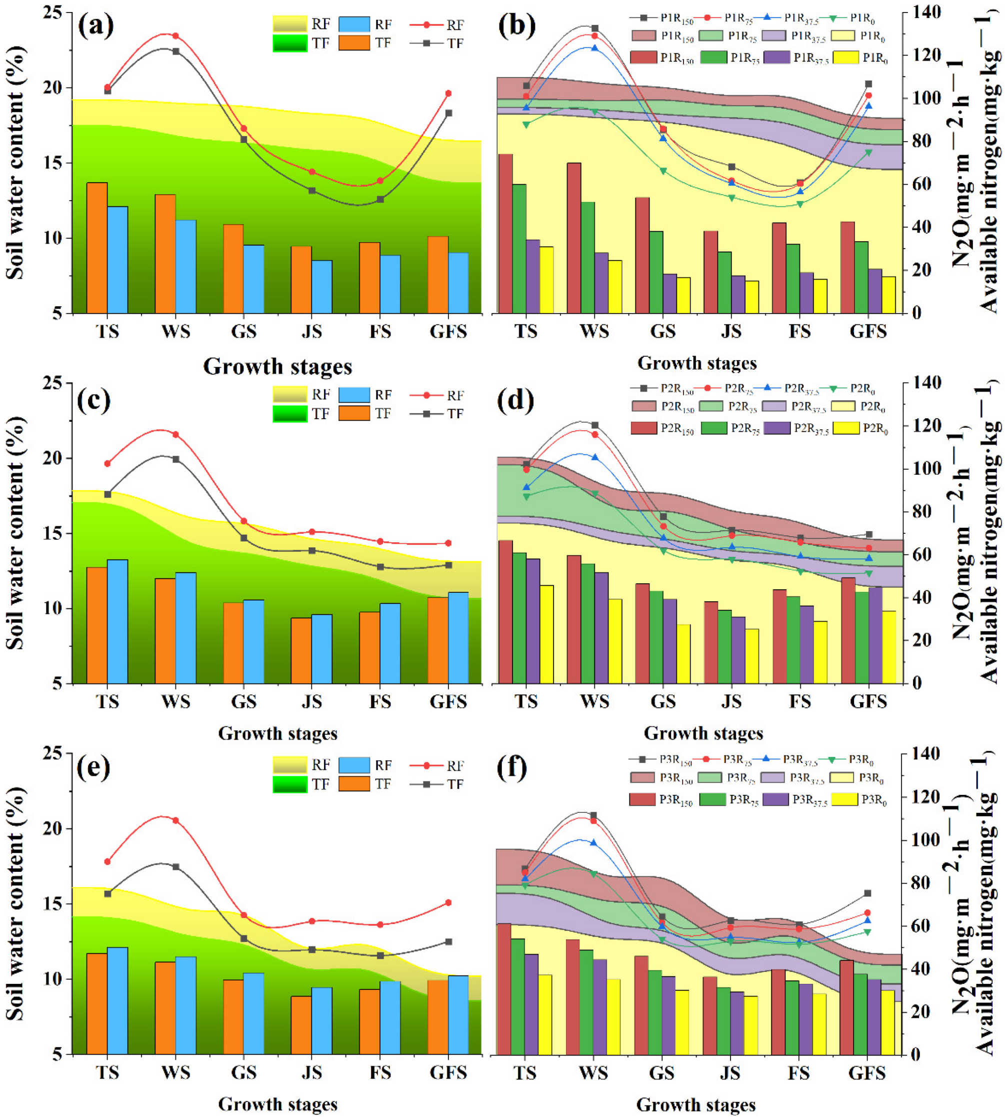


**Figure 3.** Effects of planting models and limited irrigation on the $N_2O$ rate, soil water content, and available nitrogen under simulated rainfall conditions during the winter wheat growing seasons. Note: The line represents the soil water content; the bar represents the $N_2O$ emission flux; the background represents available nitrogen. (**a**,**b**) represent P1: 275 mm rainfall; (**c**,**d**) represent P2: 200 mm rainfall; (**e**,**f**) represent P3: 125 mm rainfall. TF: traditional flat planting; RF: ridge–furrow mulching system. Four different irrigation amounts, 150 mm, 75 mm, 37.5 mm, and 0 mm were used. TS: tillering stage; RWS: re-wintering stage; GS: green stage: JS: jointing stage; FS: flowering stage; GFS: grain-filling stage.

The soil water contents (0–40 cm layer) increased, then decreased and stabilized. Compared with TF, under RF with rainfall at 275 mm in the winter wheat growth period, the soil water contents were 6.26–8.82% higher ($p > 0.05$) in the same growth stages, but the differences were not significant (Figure 3a). Under RF, the $N_2O$ emission fluxes in $P1R_{150}$ were 3.27–23.52% higher than those with $P1R_{75}$, $P1R_{37.5}$, and $P1R_0$, but the differences were only significant between $P1R_{150}$ and $P1R_0$ (Figure 3b). Under RF with rainfall at 200 mm, the soil water contents were 6.13–11.49% higher compared with TF (Figure 3c). Under RF, the soil water contents in $P2R_{150}$ were 2.66–28.22% higher than those in the other treatments, and those in $P2R_{75}$ were 7.2–24.90% higher than those in $P1R_{37.5}$ and $P1R_0$, but the difference was not significant between $P2R_{150}$ and $P2R_{75}$ (Figure 3d). With rainfall at 125 mm, the soil water contents were 8.05–13.88% higher under RF compared with TF

(Figure 3e). Under RF, the soil water contents in $P3R_{150}$ were significantly higher than those in $P3R_{75}$, $P3R_{37.5}$, and $P3R_0$ (6.67–14.65%, 18.81–28.27%, and 29.66–36.90% higher, respectively; $p < 0.05$) in different growth stages (Figure 3f). The differences in the soil water contents were more obvious as the amount of irrigation decreased.

Under RF and TF, the soil available nitrogen contents in the 0–40 cm soil layer tended to decrease during the growth of the winter wheat, and the differences between the two treatments were clearer in the later growth stages. With rainfall at 275 mm, the available nitrogen content under RF was 1.71–16.24% lower compared with TF ($p > 0.05$), but the difference was not significant (Figure 3a). Under RF, the soil available nitrogen contents in $P1R_{150}$ were higher than those in $P1R_{75}$, $P1R_{37.5}$, and $P1R_0$ (0.05–10.76%, 5.08–13.23%, and 19.11–42.10% higher, respectively). The soil available nitrogen contents differed significantly between $P1R_{150}$ and $P1R_0$ (Figure 3b). With rainfall at 200 and 125 mm, the soil available nitrogen contents under RF were 11.0–21.42% lower ($p > 0.05$) and 19.93–34.44% lower ($p > 0.05$), respectively, compared with TF during the winter wheat growth period (Figure 3c,e). Similar to RF with 275 mm rainfall, the difference between the soil available nitrogen contents with 200 and 125 mm was not significant when the irrigation amount $\geq$ 37.5 mm (Figure 3d,f).

### *3.2. Denitrifying Enzyme (Nitrate Reductase and Nitrite Reductase) Activities under RF and Supplementary Irrigation*

The nitrate reductase and nitrite reductase activities under different treatments tended to increase initially and then decreased, where the peak occurred in the jointing stage. With rainfall at 275 mm during the winter wheat growth period, the summed nitrate reductase and nitrite reductase activities (S) under RF were 0.2–24.16% higher compared with TF, and the differences were significant in the wintering and greening stages (Figure 4a). Under RF, the values of S in $P1R_{150}$ were 0.81–13.83% higher ($p > 0.05$) compared with the other irrigation treatments, but the differences were not significant (Figure 4d). With rainfall at 200 mm, the S values under RF were 0.01–24.08% higher than those under TF during the same stages, and the differences were significant during the wintering stage (Figure 4b). Under RF, the S values in $P2R_{150}$ were 1.80–14.84% higher ($p > 0.05$) than those in the other irrigation treatments, but the differences between the treatments were not significant (Figure 4e). With rainfall at 125 mm, the S values under RF were 0.03–20.79% higher compared with TF, as also found under the other rainfall conditions, and the difference between the two treatments was only significant during the wintering stage (Figure 4c). Under RF, the S values in $PIR_{150}$ were 3.40–12.73% higher ($p > 0.05$) compared with the other supplemental irrigation treatments (Figure 4f).

### *3.3. Relationships among N2O Emissions, Soil Water Contents, Soil Available Nitrogen Contents, and Denitrifying Enzyme Activities under RF and TF*

Principal component analysis was conducted on the $N_2O$ emission fluxes, soil water contents, soil available nitrogen contents, soil denitrifying enzyme activities (nitrate reductase and nitrite reductase), and the S values under RF and TF (Figure 5). The results showed that the combined contribution of the first (S) and second (soil water content) principal components under TF was greater than 85%, where the first two principal components included five indexes. In particular, the first principal component had the highest contribution, i.e., 65.18%, and the contributions of principal components 3–5 were very small. In order to represent as much information as possible with the fewest indicators, the first two factors were selected as the principal components to explain the variations in the $N_2O$ emission flux. Under RF, the cumulative contribution of the first, second, and third principal components was 94.37%. Hence, these three factors were selected to explain the variations in the $N_2O$ emission flux.

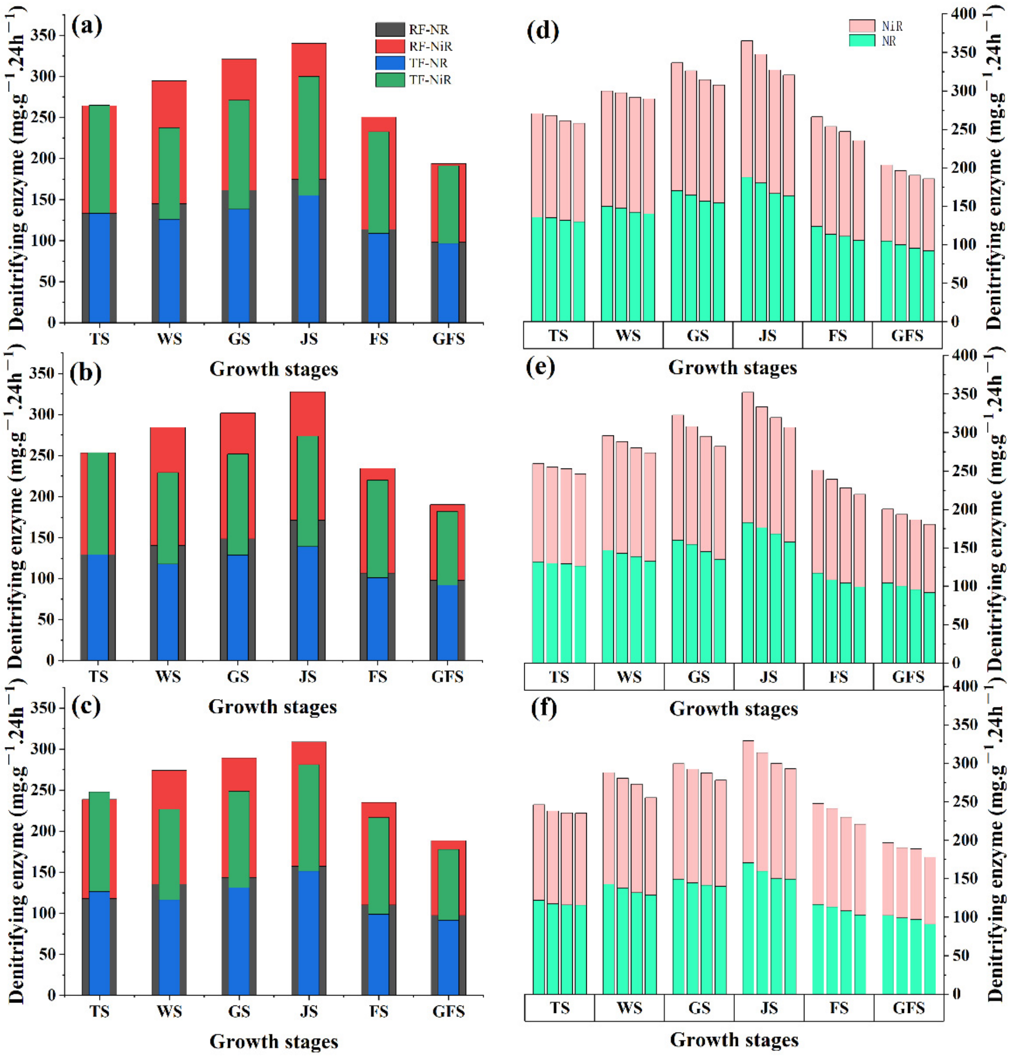


**Figure 4.** Effects of planting models and limited irrigation on denitrifying enzymes under simulated rainfall conditions during the winter wheat growing seasons. (**a**,**d**) represent Note: P1: 275 mm rainfall; (**b**,**e**) represent P2: 200 mm rainfall; (**c**,**f**) represent P3: 125 mm rainfall. TF: traditional flat planting; RF: ridge–furrow mulching system. Four different irrigation amounts, 150 mm, 75 mm, 37.5 mm, and 0 mm were used. TS: tillering stage; RWS: re-wintering stage; GS: green stage: JS: jointing stage; FS: flowering stage; GFS: grain filling stage.

The principal components with the main contributions and the $N_2O$ emission fluxes were fitted as shown in Figure 6. Under TF, the main factors that affected the $N_2O$ emission flux (y) were the soil water content ($\chi_1$) and denitrifying enzyme activities ($\chi_2$), where regression analysis obtained the following equation: $y = 3.361\chi_1 - 0.115\chi_2 + 21.610$ ($R^2 = 0.586$). As shown in Figure 6, the $N_2O$ emission fluxes increased sharply when the soil water content exceeded 15%. The main factors that affected the $N_2O$ emission fluxes (y) under RF were the soil denitrifying enzyme activities ($\chi_1$) and soil available nitrogen contents ($\chi_2$), where regression analysis obtained the following equation: $y = 0.375\chi_1 - 0.016\chi_2 + 14.015$ ($R^2 = 0.599$). Thus, the $N_2O$ emission fluxes increased sharply when the soil denitrifying enzyme activities exceeded 240 μg $m^{-2}$ $h^{-1}$.

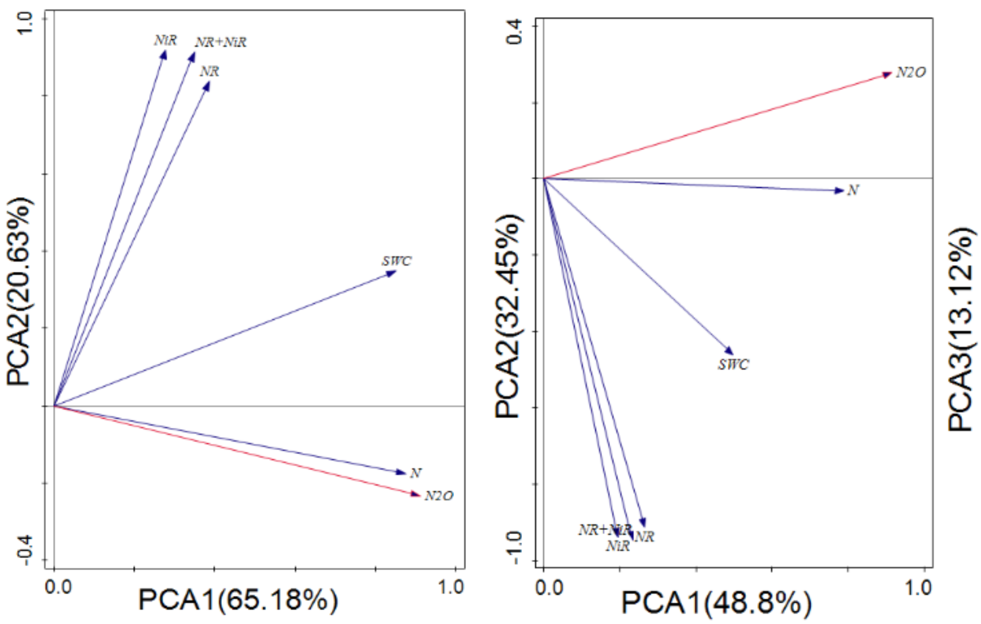


**Figure 5.** Principal component analysis (PCA) of $N_2O$ emission flux with different indexes under RF and TF. Note: The left is TF, the right is RF.

### *3.4. Effect of the Ridge-Furrow Mulching System on Grain Yield*

Grain yield increased with rainfall and supplementary irrigation amount (Table 1). In the heavy rainfall period of winter wheat, when the supplementary irrigation was the same, the grain yield of RF increased by 9.80–28.92% compared with TF (the differences among $P1R_{150}$, $P1R_{75}$, and $P1T_{150}$ were not significant, and these values were significantly higher than those of the other treatments). In the normal rainfall period of winter wheat, compared with TF, the yield of RF increased by 9.77–50.44%. Similar to heavy rainfall years in winter wheat, the differences among $P2R_{150}$, $P2R_{75}$, and $P2T_{150}$ were not significant, and these values were significantly higher than those in the other treatments. In the light rainfall period of winter wheat, in the treatment with the same supplementary irrigation amount, the yield of RF increased by 2.89–40.58% compared with TF, and the increase was greater with the decrease in the amount of supplementary irrigation.

**Table 1.** Effects of planting models and limited irrigation on grain yield.

| Treatments | Grain Yield ($t{\cdot}ha^{-1}$) | Treatments | Grain Yield ($t{\cdot}ha^{-1}$) | Treatments | Grain Yield ($t{\cdot}ha^{-1}$) |
|---|---|---|---|---|---|
| $P1R_{150}$ | 7.73 ± 0.52a | $P2R_{150}$ | 7.30 ± 0.30a | $P3R_{150}$ | 4.42 ± 0.83de |
| $P1R_{75}$ | 7.38 ± 0.84a | $P2R_{75}$ | 6.89 ± 1.15b | $P3R_{75}$ | 3.70 ± 0.27ef |
| $P1R_{37\cdot5}$ | 6.82 ± 0.39ab | $P2R_{37\cdot5}$ | 6.02 ± 0.65c | $P3R_{37\cdot5}$ | 3.20 ± 1.83f |
| $P1R_0$ | 5.33 ± 0.39cd | $P2R_0$ | 4.49 ± 1.69de | $P3R_0$ | 2.91 ± 0.11fg |
| $P1T_{150}$ | 7.04 ± 0.70ab | $P2T_{150}$ | 6.65 ± 0.28b | $P3T_{150}$ | 4.17 ± 1.03e |
| $P1T_{75}$ | 6.15 ± 0.52bc | $P2T_{75}$ | 4.58 ± 1.18de | $P3T_{75}$ | 3.14 ± 0.56f |
| $P1T_{37\cdot5}$ | 5.29 ± 1.06cd | $P2T_{37\cdot5}$ | 4.21 ± 0.85e | $P3T_{37\cdot5}$ | 3.11 ± 1.68f |
| $P1T_0$ | 4.75 ± 0.78de | $P2T_0$ | 3.17 ± 1.12f | $P3T_0$ | 2.07 ± 2.16g |

Note: P1: 275 mm rainfall; P2: 200 mm rainfall; P3: 125 mm rainfall. TF: traditional flat planting; RF: ridge–furrow mulching system. Four different irrigation amounts, 150 mm, 75 mm, 37.5 mm, and 0 mm, were used. Different lowercase letters denote significant differences between different supplemental irrigation modes and amounts ($p < 0.05$).

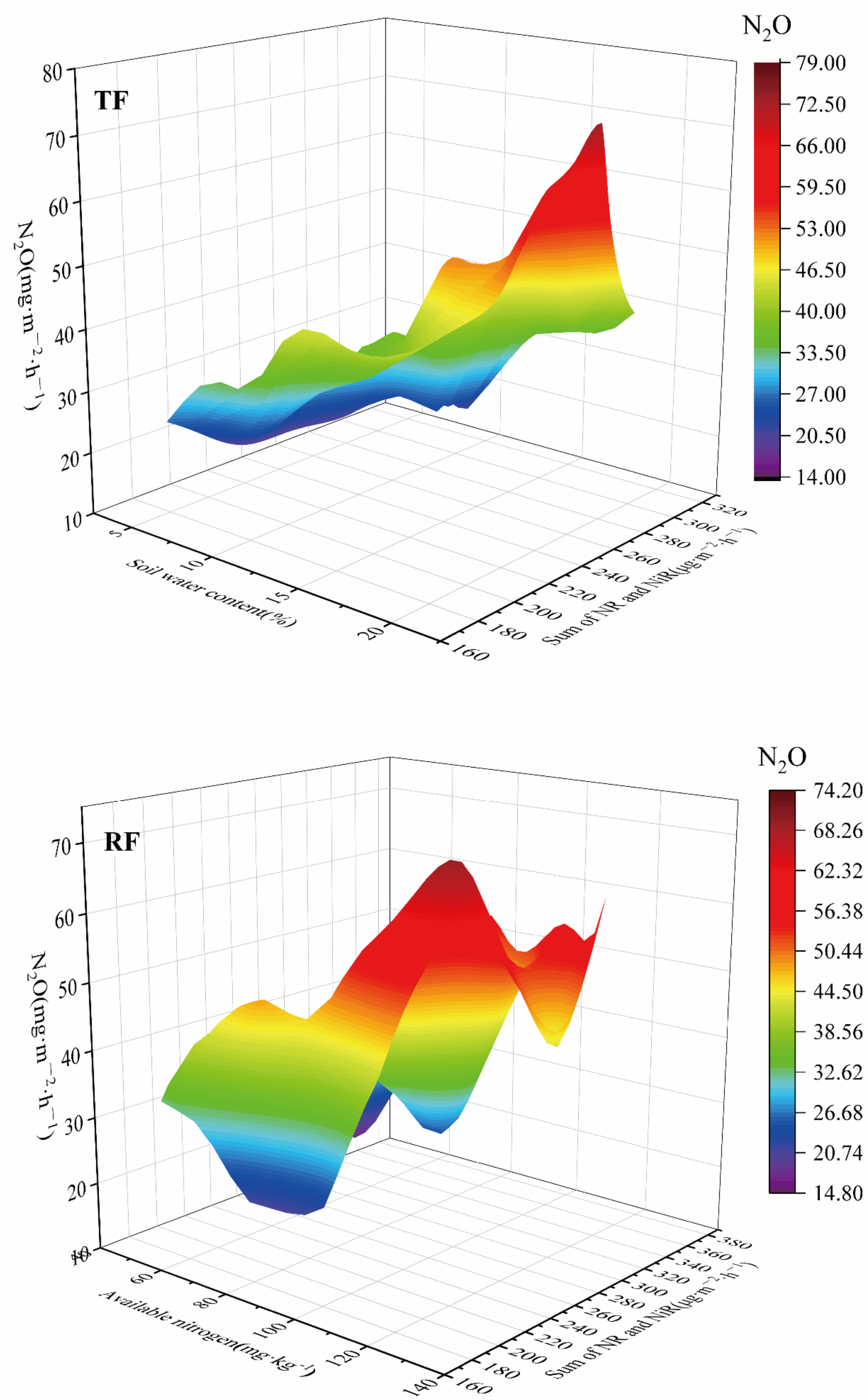


**Figure 6.** Fitting of principal components to $N_2O$ emission flux under RF and TF.

## 4. Discussion

### *4.1. $N_2O$ Emissions and Grain Yield from Winter Wheat Fields under RF with Different Amounts of Rainfall and Supplementary Irrigation*

The emissions of $N_2O$ from farmland soil are governed by a series of microorganisms that participate in the nitrogen cycle. The main nitrification and denitrification processes performed by microorganisms utilize inorganic nitrogen in the form of ammonium nitrogen and nitrate nitrogen [26,27]. Under general soil conditions, nitrification and denitrification occur simultaneously, and the release of $N_2O$ is the due to the combination of these two processes [27,28]. In the present study, the $N_2O$ emissions fluxes from the soil were higher in the early growth period than the later period, possibly because the soil nitrogen content remained high after the application of nitrogen fertilizer before sowing, and the availability and nitrification of the nitrogen matrix increased, so the $N_2O$ emission fluxes were higher due to the mineralization of nitrogen in this stage [29]. During the winter wheat growth process, the $N_2O$ emissions tended to decrease in each treatment because of nitrogen leaching due to irrigation as well as the uptake and fixation of nitrogen by the crop [30]. Our results showed that under the conditions with 200 mm and 125 mm rainfall during the winter wheat growth period, the $N_2O$ emissions fluxes were higher under RF than under TF in different stages, probably because the soil water contents were higher under RF compared with TF [31]. The higher soil water contents accelerated the mineralization or denitrification of nitrogen to enhance the soil $N_2O$ emissions [32]. Amha et al., Ref. [33] also found a significant positive correlation between denitrification and the soil water content by studying the relationships between denitrification, the soil pH, nitrogen, carbon, and water. We obtained the opposite results under the conditions with rainfall at 275 mm, possibly because the excessive supplementary application of irrigation under conditions with sufficient soil water created an anaerobic state in the soil [34] and affected the microbial activity levels, thereby influencing nitrification and denitrification, and finally the formation and emission of $N_2O$ [32,35].

Ridge–furrow mulching systems cause a banded distribution of wheat in the fields; the wheat near the ridge has an edge advantage, and yield factors play a positive effect [36]. Therefore, compared with the traditional flat planting, under the condition of reducing the planting area, ridge–furrow mulching systems increase the number of spikes, grains, and grain weight of winter wheat, compensating for the yield loss caused by the decrease in the planting area [37,38]. The results of this study showed that the ridge–furrow mulching system increased the crop yield compared with traditional flat planting in years with different amounts of rainfall. This study also found that the increase in crop yield was more obvious in light rainfall years compared with heavy and normal years ("light, normal, and heavy rainfall" represent three different types of rainfall according to the local precipitation characteristics in the winter wheat growth period). This showed that the ridge–furrow mulching technology has a good effect in dry farmland areas [39]. In addition, limited irrigation in the key growth period of farmland with certain irrigation conditions can not only improve the effect of soil water storage but can also improve the water use efficiency of crops [40]. This result expands the scope of the popularization of ridge–furrow mulching technology.

### *4.2. Relationships among Soil $N_2O$ Emissions Fluxes, Soil Water Contents, Soil Available Nitrogen Contents, and Denitrifying Enzyme Activities under RF and TF*

In natural and artificially managed soils, nitrification and denitrification are the main pathways responsible for $N_2O$ emissions, and they account for about 70% of global $N_2O$ emissions [41,42]. Therefore, the factors that affect nitrification and denitrification processes may influence $N_2O$ emissions [43,44]. Among these factors, the water status generally directly affects both nitrification and denitrification because nitrification is an aerobic process whereas denitrification is an anaerobic process [22], and the partial pressure of oxygen in the soil is determined by the soil water status [45]. In the current study, the $N_2O$ emission fluxes were higher under RF than TF in the winter wheat growth period during the years with normal and light rainfall [46], possibly because RF increased the soil moisture content, thereby accelerating the rates of nitrification and denitrification [47] to increase the production of $N_2O$. The opposite results were obtained in the year with heavy rainfall probably because the wetter soil environment was in an anaerobic state, which inhibited the denitrification process [48]. Braker and Conrad [49] showed that $N_2O$ emissions were mainly due to nitrification when the soil water contents ranged from 30–60/70% [50], whereas the $N_2O$ emissions were mainly caused by denitrification when the soil water contents were 80–90%. In the present study, the soil water content was about 30% under RF in the heavy rainfall year, and thus nitrification may have mainly determined the $N_2O$ emission fluxes.

The available nitrogen in the soil is utilized as a substrate for nitrification and denitrification, and thus it significantly affects the $N_2O$ emissions from soil [51]. Wang et al., [52] found that the soil available nitrogen could enhance the denitrification rate but also inhibit the reduction of $N_2O$ to $N_2$, and the available nitrogen content in the soil surface had a highly significant positive correlation with $N_2O$ emissions. Thus, the available nitrogen is an important factor that affects soil $N_2O$ emissions. In the present study, the available nitrogen contents were higher under RF than TF under different rainfall conditions, possibly because the high soil water with RF promoted the rapid conversion of ammonium nitrogen to nitrate nitrogen to enhance the denitrification rate and increase the $N_2O$ emissions [53]. This may also explain why the $N_2O$ emissions fluxes were higher under RF than TF during the years with normal and light rainfall. However, in the year with heavy rainfall, the available nitrogen content was higher under RF than TF, but mulching may have affected the $N_2O$ emissions by changing the soil conditions.

Nitrate reductase and nitrite reductase are obligate enzymes that participate in the reduction of soil nitrate nitrogen, and they are important biological factors that affect denitrification in the soil and $N_2O$ emissions [54]. Shi [55] found that the nitrate reductase activity in the soil changed with the soil moisture conditions and it was also affected by rainfall. Moreover, studies have shown that the soil nitrate reductase and nitrate reductase activities have important effects on the forms of nitrogen present in the soil and $N_2O$ emissions [56]. In the present study, the nitrate reductase and nitrate reductase activities differed according to the seasons. Under the three rainfall conditions, the summed nitrate reductase and nitrate reductase activities were higher under RF than TF, and the difference was significant in the winter. Our results indicated that RF with supplementary irrigation increased the activity levels of denitrifying enzymes, possibly because this treatment increased the soil organic matter content [57], and organic matter can increase the activity of denitrifying enzymes in the soil [58]. Zhu et al., Ref. [59] found that the soil microbial volume increased after mulching, and thus the activities of denitrifying bacteria also increased, with higher denitrifying enzyme activities [60].

We quantified the relationships among the soil water contents, soil available nitrogen contents, soil denitrifying enzyme activities, and $N_2O$ emission fluxes under RF and TF by conducting regression analysis. Considering the overlap between different variables in the model, principal component analysis was performed based on the two irrigation modes in order to reduce the number of variables. We found that the $N_2O$ emissions under different supplemental irrigation methods were affected by different factors. Under RF, the main factors that affected the $N_2O$ emissions were the soil water content and soil available nitrogen content. However, under TF, the main factors were the soil available nitrogen content and denitrifying enzyme activities. The main factors may have differed because the application of irrigation and film mulching could have changed the soil conditions [61,62]. Xiang et al., Ref. [63] showed that the effects of different amounts of irrigation on the soil $N_2O$ emissions were mainly governed by changes in the soil moisture conditions, which affected the amount of $N_2O$ generated in the soil and the $N_2O$ transport process to the atmosphere. Numerous studies have also demonstrated that mulching can increase the number of microorganisms in the soil [64] as well as the soil temperature and water content [65] to promote microbial growth, reproduction, and metabolism. These changes will also directly or indirectly influence the $N_2O$ emissions.

## 5. Conclusions

In the year with heavy rainfall, RF with supplementary irrigation at 75 mm significantly reduced the water usage compared with TF and it decreased the $N_2O$ emissions in the winter wheat growth period. In the normal rainfall year, RF with irrigation at 75 mm increased the soil water content compared with TF, but without significantly increasing the $N_2O$ emissions. In the year with light rainfall, RF with supplementary irrigation at 150 mm increased the soil moisture during the winter wheat growth period, but it also increased the $N_2O$ emissions. Under heavy, normal and light rainfall years, the yield of RF increased by 9.80–28.92%, 9.77–50.44%, and 2.89–40.58%, respectively, compared with the TF system, and the increase became larger with the decrease in rainfall. Under TF, the main factors that affected the $N_2O$ emissions were the soil moisture content and denitrifying enzyme activities, which together explained 85.81% of the variation in the $N_2O$ emission fluxes, and the following function was obtained: $y = 3.361\chi_1 - 0.115\chi_2 + 21.610$ ($R^2 = 0.586$). Under RF, the main factors that affected the $N_2O$ emissions were the soil denitrifying enzyme activities and available nitrogen contents, which together explained 94.37% of the variation in the $N_2O$ emissions fluxes, and the following function was obtained: $y = 0.375\chi_1 - 0.016\chi_2 + 14.015$ ($R^2 = 0.599$).

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