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Effects of Growth Stage-Based Limited Irrigation Management on Soil CO_2 and N_2O Emissions, Winter Wheat Yield and Nutritional Quality

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Abstract: Water scarcity and poor irrigation practices limit crop productivity and increase greenhouse gas (GHG) emissions in arid Northwest China. Therefore, we investigated the effects of five growth stage-based deficit irrigation strategies on the yield, quality, and greenhouse gas emissions of winter wheat. Across treatments, CO_2 emissions ranged from 3824.93 to 4659.05 kg ha^{-1} and N_2O emissions from 3.96 to 4.79 kg ha^{-1}. Compared with CK (irrigation in all growth stages), GHG emissions decreased significantly in T1, T2, T3, and T4 (p < 0.05). Water stress reduced the wheat yield, compared with CK, but the decrease depended on the stage without irrigation. Across treatments, the wheat yield was between 5610 and 6818 kg ha^{-1}. The grain protein content decreased in the order T4 > T3 > T1 > T2 > CK. On the basis of a catastrophe progression method evaluation, we recommend T1 as the irrigation practice for winter wheat, because it maintained a high grain yield and quality and reduced GHG emissions. Thus, in practice, soil moisture should be sufficient before sowing, and adequate water should be supplied during the heading and filling stages of winter wheat. This study provides a theoretical basis for exploring the irrigation strategies of high-yield, good-quality, and emission reduction of winter wheat.

Keywords: growth stage-based deficit irrigation; *Triticum aestivum*; greenhouse gas emissions; wheat yield; wheat grain protein content

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1. Introduction

The global annual wheat yield is approximately 730 million tons, and it provides approximately 20% of human dietary calories and protein demand [1]. Therefore, winter wheat is irreplaceable in maintaining global food security. The world population is expected to exceed 9 billion by 2050 [2], and the global demand for grain and crop protein is increasing rapidly. However, as global drought has increased in recent years, shortages of water resources have become a serious problem in wheat production [3]. Although the increasing demand for water resources is not compatible with sustainable development, high wheat yields and quality must be maintained in order to alleviate the pressure of food demand and ensure food security. However, when agricultural management measures, such as flood irrigation and excessive use of nitrogen fertilizer, are used to increase the wheat yield, the resulting environmental problems, such as greenhouse gas (GHG) emissions, are often ignored [4,5]. At present, with global warming becoming increasingly severe, the ecological and environmental problems are a serious threat to human survival and development [6]. Greenhouse gas emissions are one of the major causes of global warming, and emissions from farmlands have been gradually attracting global attention. Agricultural soils are the largest source of GHG emissions, and soil N_2O and CO_2 emissions during wheat production are important contributors to increasing the levels of global GHGs [7,8]. Increasing the grain yield at the expense of the environment is a poor strategy [9]. Therefore, reasonable and effective measures are needed to reduce emissions and mitigate global warming while ensuring the wheat yield and grain quality (protein content).

The Guanzhong Plain, a semiarid region in Northwest China, is one of the major winter wheat production areas in China. The spatial and temporal heterogeneity of precipitation is the primary factor limiting the sustainable development of winter wheat in the region [8]. Therefore, water management has important effects on the wheat yield and grain protein content, as well as GHG emissions [7,10]. In recent years, different types of new water-saving irrigation technologies have been used, including partial root zone irrigation [11], subsurface drip irrigation [12], and growth stage-based limited irrigation [13]. With growth stage-based limited irrigation, limited water resources are applied to the most water-sensitive period during crop growth in order to minimize the yield loss and optimize the water use. Xu et al. [3] showed that irrigation treatments increased the wheat yield compared with no irrigation after sowing treatment, and the highest yields were in those with irrigation at the wheat jointing and flowering stages. Flagella et al. [14] reported that late-reproductive stage water stress increased the grain protein content but decreased the grain yield compared with irrigation. These studies showed that drought in different growth periods has different effects on the crop quality and yield [10,15,16]. Previous studies on GHG emissions from farmlands in China have focused on the Northeast Plain [17], the North China Plain [18], and the Chengdu Plain [19]. Studies of GHG emissions from agricultural fields in the Guanzhong Plain are rare and mainly focus on the effects of mulch and nitrogen fertilizers [20]. In addition, studies on the effects of deficit irrigation on farmland GHG emissions are mainly based on a single gas [8]. Zhong et al. [18] found that deficit irrigation significantly reduced GHG emissions from wheat fields but simultaneously also decreased yields to varying degrees. Hou et al. [8] found that light water stress in the overwintering stage and ensuring irrigation during the jointing stage to the seed-filling period significantly reduced GHG emissions without significantly reducing the yield. As these studies suggest, how to balance reductions in water use and ensure grain yield and quality and control GHG emissions through rational irrigation has become a central concern in the development of water-saving agriculture.

There remains a lack of research on the effects of growth stage-based limited irrigation management on the crop yield and quality and GHG emissions. Even fewer studies include such a comprehensive analysis of winter wheat. Therefore, in this study, we investigated the effects of water stress treatments applied at different growth stages on the winter wheat yield and grain protein content and GHG emissions (CO_2 and N_2O). In addition, we used the catastrophe progression method in a comprehensive evaluation of multiple indicators to determine the most suitable irrigation scheme for the arid and semiarid regions of Northwest China. The goal was to identify scientifically sound production technology capable of producing high yields of high quality while reducing GHG emissions in winter wheat.

2. Material and Methods

2.1. Climate and Soil

From October 2020 to June 2021, a local variety of winter wheat (*Triticum aestivum* L. 'Xinong 979′) was grown in an experimental field under an automated rolling rainout shelter at the Water-saving Irrigation Experiment Station of Yangling Northwest A&F University in Shaanxi Province (34°20′ N, 108°04′ E), China. When it rained, the automated rolling rainout shelter was closed to avoid rainwater interfering with the experiment; otherwise, the shelter was open to allow winter wheat to receive sunlight. The study area had a typical warm temperate semi-humid monsoon climate, and the annual mean precipitation is 632 mm. Precipitation was unevenly distributed throughout the year, and there was less precipitation during the winter wheat reproductive period. The mean physicochemical properties of the soil at the top 80 cm of the test site were the following: field water-holding capacity, 0.26 cm^3 cm^{-3}; pH, 7.6; organic matter, 8.20 g kg^{-1}; and total nitrogen, 0.62 g kg^{-1}.

2.2. Experimental Design

Winter wheat was sown on 16 October 2020 and harvested on 4 June 2021. All plots were irrigated before sowing to create adequate soil moisture conditions, which ensured the uniform appearance of wheat seedlings. Traditional drill planting was used with row spacing of 25 cm and a density of 4 million plants per hectare. Before sowing, 140-kg N ha^{-1} and 70-kg P_2O_5 ha^{-1} were evenly distributed as the base fertilizer. No top fertilizer was applied during the growth period. The winter wheat phenology was divided into the overwintering, regreening, jointing, heading, and filling stages, according to the method of Zadoks et al. [21]. The experiment included five irrigation treatments, and these were irrigation at jointing, heading, and filling (T1); at overwintering, heading, and filling (T2); at overwintering, greening, and filling (T3); at overwintering, greening, and jointing (T4); and irrigation in all growth stages (CK). Each treatment had three replicates, for a total of 15 plots. Plots were rectangular and 8 m^2 (4 m long by 2 m wide). Each irrigation event delivered 80 mm of irrigation water using conventional border irrigation. A water meter was used to accurately control the amount.

2.3. Main Indices and Methods

2.3.1. Grain Yield and Protein Content

After harvest, the wheat was air-dried to a grain moisture fraction of 13% and weighed to determine the yield. The grain nitrogen content was determined by the Kjeldahl analysis, and then, the concentration of protein in the wheat grains was calculated by multiplying the nitrogen content by the constant 5.7 [1,22].

2.3.2. Gas Collection and Determination

Gas chromatography was used to measure soil gas emission fluxes under different irrigation treatments during the winter wheat growing season. Measurements were every 15 d before the jointing stage and every 10 d after the jointing stage, with additional samples collected after irrigation events. Gases were collected from static closed chambers made of opaque polyvinyl chloride panels that were 0.5 m in length, 0.5 m in width, and 0.5 m in height. To prevent drastic temperature changes inside the chambers due to sunlight exposure during a sampling period, the exteriors were wrapped in thermal insulation. To ensure uniformity of the air inside chambers, a small fan was installed at the top of the chambers to mix the air. Separate bases of static closed chambers were buried in the center of a plot before sowing to reduce the soil disturbance. There was a 5-cm-deep recess in the top of the bases to accommodate static closed chambers. The recess was filled with water before sampling the isolate gas exchange between inside and outside of the static closed chambers.

Soil CO_2 or N_2O emission fluxes and cumulative soil CO_2 or N_2O emissions during the entire growth period of winter wheat were calculated using the following equations [8]:

$$F = \rho \cdot h \cdot \frac{273}{(273 + T)} \cdot \frac{d_c}{d_t} \tag{1}$$

$$M = \sum_{i=0}^{n} \frac{(F_{i+1} + F_i) \times (t_{i+1} - t_i) \times 24}{2 \times 100} \tag{2}$$

where F is the CO_2 gas emission flux (mg m^{-2} h^{-1}) or N_2O gas emission flux (μg m^{-2} h^{-1}), ρ is the gas density at the standard conditions (g cm^{-3}), h is the height of the static closed chamber (0.5 m), T is the temperature inside the static closed chamber at the time of sampling (°C), dc/dt is the rate of change in the gas concentration inside a static closed chamber with time, M is the total amount of soil CO_2 or N_2O emissions (kg ha^{-1}), i is the sampling order, n is the number of samples, and t is the sampling time (d).

2.4. Basic Principle of the Catastrophe Progression Method

The basic concept of the catastrophe progression method is to decompose the evaluation indicators of the system under study into an inverted dendritic structure. Then, starting from the bottom of the dendritic structure, the mutation level is evaluated upwards to obtain the comprehensive catastrophe membership function value of the evaluation system [23–25]. The main steps of the mutation level method are as follows (Figure 1a):

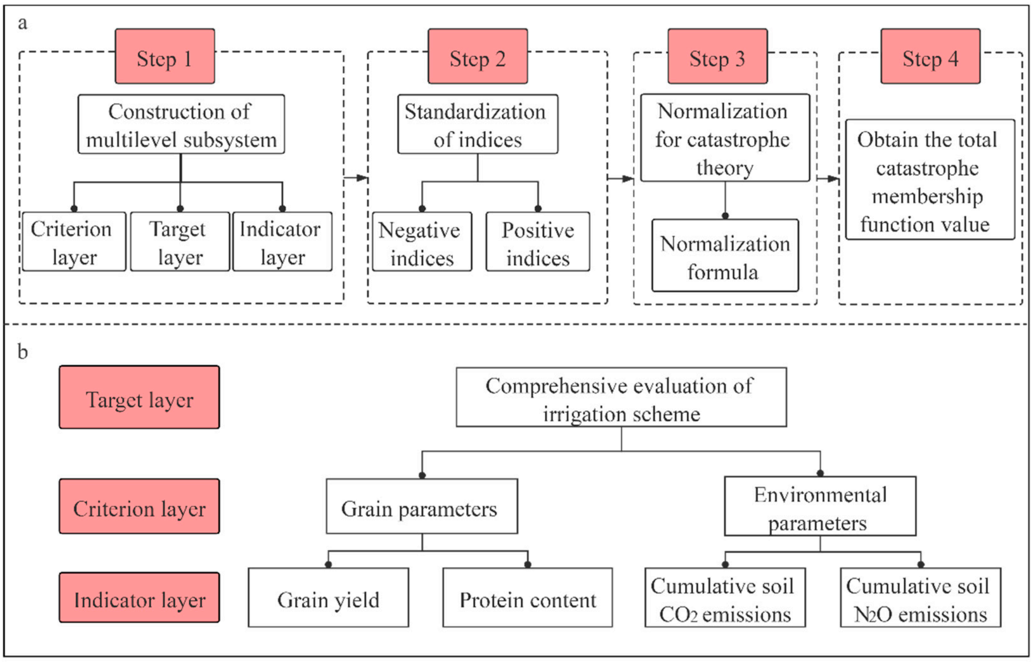

Figure 1. Main steps in the catastrophe progression method (**a**) and evaluation indices of irrigation treatments used in the catastrophe progression method (**b**).

The study analyzed the evaluation system, decomposed the total indicators into a multilayer indicator system, and constructed an evaluation indicator system. The evaluation indices in this study were divided into two categories: grain parameters (yield and grain protein content) and environmental parameters (total CO_2 emissions and total N_2O emissions; Figure 1b).

The underlying indicators were standardized, and the raw data were processed using the formula, such that the range of the raw data after it was converted into dimensionless data conformed to 0–1. Equations (3) and (4) were used to standardize the indices. In this study, when the grain parameter indicators belonged to positive-type indicators, Formula (3) was used, and when the environmental parameter indicators belonged to negative-type indicators, Formula (4) was used. Equations (3) and (4) are calculated as follows:

$$S_j = (x_j - x_{j\min}) / (x_{j\max} - x_{j\min}) \tag{3}$$

$$S_j = (x_{j\max} - x_j) / (x_{j\max} - x_{j\min}) \tag{4}$$

where S_j is the standard value of index j, x_j is the original data of j, and $x_{j\max}$ and $x_{j\min}$ are maximum and minimum values, respectively, of the original variable x_j.

The catastrophe evaluation model of the subsystem was determined, the calculations were carried out according to the normalization formula, and the catastrophe membership function value of the corresponding subsystem was obtained. The catastrophe model used in this study is shown in Table 1 [23–25].

Table 1. Normalization formulas for catastrophe theory.

Name	Control Variable	State Variable	Normalization Formula
Cusp model	2	1	$x_a = a^{1/2}$ and $x_b = b^{1/3}$

Note: x is the state variable, and a and b are control variables.

The abrupt membership function value was calculated layer by layer, and finally, the comprehensive abrupt membership function value was obtained for evaluation. The catastrophe progression method was used to comprehensively evaluate different irrigation modes and identify the best irrigation treatment. A high comprehensive catastrophe membership function value indicated that an irrigation treatment maintained a high yield and high-quality grain of winter wheat and reduced GHG emissions.

2.5. Statistical Analyses

SPSS 18.0 (IBM, Inc., Armonk, NY, USA) was used to conduct an ANOVA and following the least-significant difference (LSD) multiple comparison test. Significance was accepted at $p < 0.05$. GraphPad Prism 8 was used to prepare figures (GraphPad Software, San Diego, CA, USA).

3. Results

3.1. Greenhouse Gas Emissions from Winter Wheat Soils under Different Irrigation Treatments

3.1.1. Seasonal Emission Fluxes and Cumulative Emissions of Soil CO_2 under Different Irrigation Treatments

Figure 2 shows changes in the soil CO_2 emission fluxes under different irrigation treatments. The emission fluxes of CO_2 changed seasonally during the whole growth period of winter wheat and across treatments, first decreasing and then increasing. The fluxes decreased significantly to 22.78–50.49 mg m^{-2} h^{-1} 120 d after sowing ($p < 0.05$) from the initial values of 144.06–156.57 mg m^{-2} h^{-1}. Several peaks in the CO_2 emissions were observed after the irrigation events. The highest CO_2 emissions occurred at 185 d after planting, with 178.92 mg m^{-2} h^{-1} in CK, 161.66 mg m^{-2} h^{-1} in T1, 87.91 mg m^{-2} h^{-1} in T2, 93.75 mg m^{-2} h^{-1} in T3, and 173.37 mg m^{-2} h^{-1} in T4.

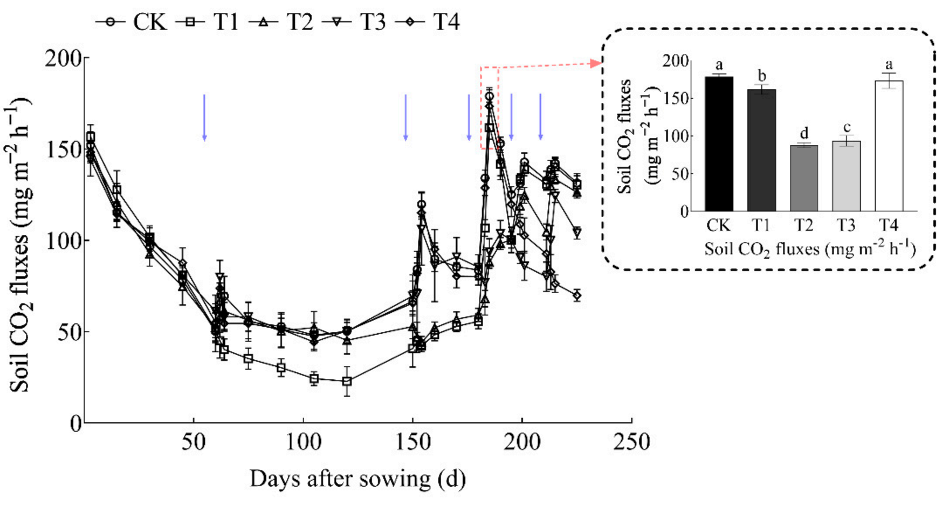

Figure 2. Changes in soil CO_2 fluxes (mg m^{-2} h^{-1}) under different irrigation treatments during a winter wheat growing season. The blue arrows denote irrigation; vertical bars represent standard errors (SE, $n = 3$). Different lowercase letters show that the mean values are significant based on LSD multiple range tests at $p < 0.05$.

Cumulative emissions of soil CO_2 increased gradually with the increase in days after sowing (Figure 3). During the whole growth period of winter wheat, the total CO_2 emissions ranged from 3824.93 to 4659.05 kg ha^{-1} across the treatments (Figure 3). The total CO_2 emissions in the different treatments decreased in the following order: CK > T3 > T4 > T2 > T1. Thus, the reductions in the total CO_2 emissions were greater when the early growth period was not irrigated than when the late growth period was not irrigated. Over the winter wheat growing season, the cumulative soil CO_2 emissions in CK were 17.90% higher than those in T1, 14.47% higher than those in T2, 9.23% higher than those in T3, and 7.75% higher than those in T4.

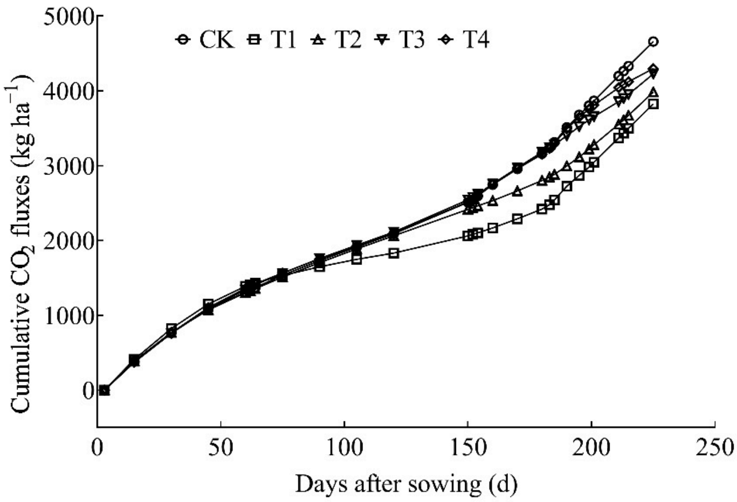

Figure 3. Cumulative soil CO_2 emissions (kg ha^{-1}) under different irrigation treatments during a winter wheat growing season.

3.1.2. Seasonal Emission Fluxes and Cumulative Emissions of Soil N_2O under Different Irrigation Treatments

In all irrigation treatments, the N_2O emissions showed a consistent seasonal pattern of variation during the winter wheat growing season (Figure 4). The emissions remained relatively high in the early growth stages and then decreased. The fluxes were relatively low from 75 d to 150 d after sowing, fluctuating between 20.69 and 46.31 mg m^{-2} h^{-1}, but then slowly increased and gradually stabilized 150 d after sowing.

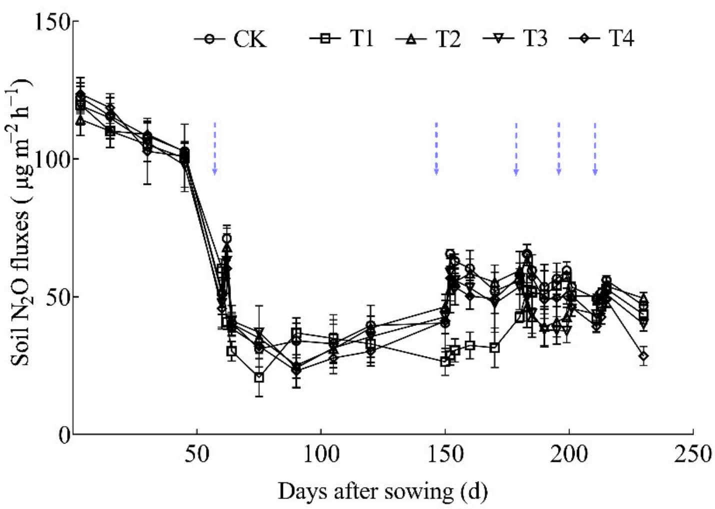

Figure 4. Changes in the soil N_2O fluxes (μg m^{-2} h^{-1}) under different irrigation treatments during a winter wheat growing season. The blue arrows denote irrigation.

In all the treatments, there were gradual increases in the cumulative soil N_2O emissions with the days after sowing (Figure 5). During the whole growth period of winter wheat, across the treatments, the total N_2O emissions ranged from 3.96 to 4.79 kg ha^{-1} (Figure 5).

Throughout the winter wheat reproductive period, the highest total N_2O emissions were in CK with 4.79 kg ha^{-1}. The total N_2O emissions in CK were 17.44% higher than those in T1, 14.23% higher than those in T2, 9.55% higher than those in T3, and 9.24% higher than those in T4 ($p < 0.05$). Thus, the average N_2O emission flux during the whole growth period of winter wheat was lower in the limited irrigation treatments (T1, T2, T3, and T4) than in the fully irrigated CK.

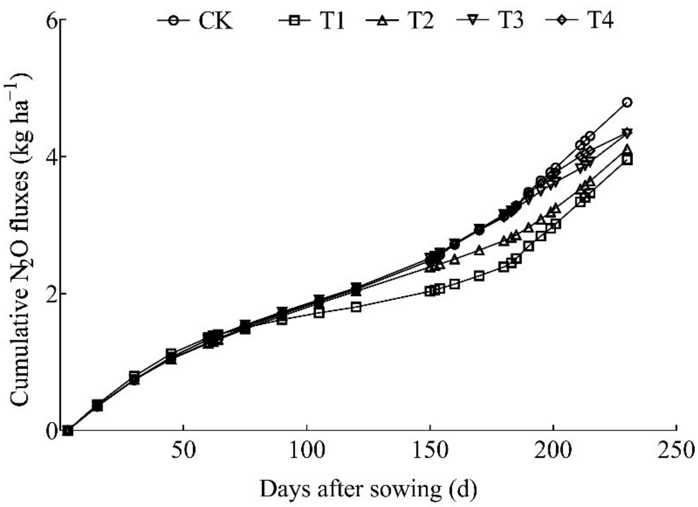

Figure 5. Cumulative soil N_2O emissions (kg ha^{-1}) under different irrigation treatments during a winter wheat growing season.

3.2. Effects of Different Irrigation Treatments on Winter Wheat Yield and Grain Protein Content

As Figure 6 shows, the average winter wheat yield was between 5610 and 6818 kg ha^{-1}, and there were significant differences among the irrigation treatments. The highest yield was in CK, and the lowest was in T4. The wheat yields in CK, T1, T2, and T3 were 1.22, 1.09, 1.12, and 1.03 times, respectively, that in T4. The protein contents in different treatments decreased in the following order: T4 > T3 > T1 > T2 > CK (Figure 7). The protein contents in T3 and T4 were significantly higher than that in CK, T1, and T2. However, there were no significant differences among CK, T1, and T2 ($p < 0.05$). The grain protein contents in CK, T1, T2, and T3 were 16.53%, 14.65%, 15.83%, and 3.16% lower, respectively, than that in T4.

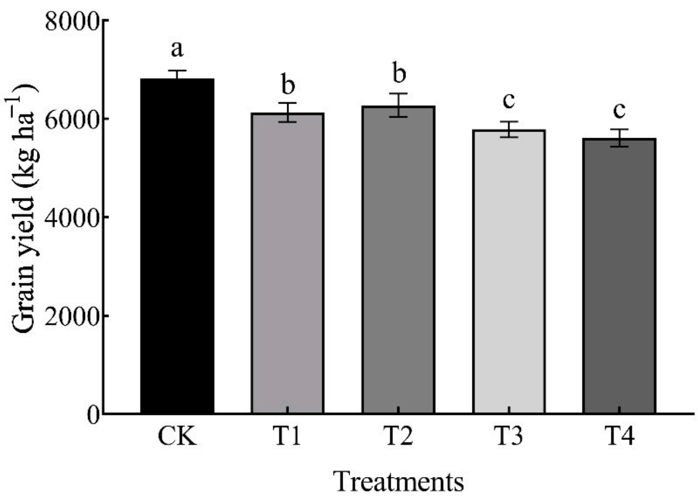

Figure 6. Winter wheat grain yield (kg ha^{-1}) under different irrigation regimes; vertical bars represent standard errors (SE, $n = 3$). Different lowercase letters show that the mean values are significant based on LSD multiple range tests at $p < 0.05$.

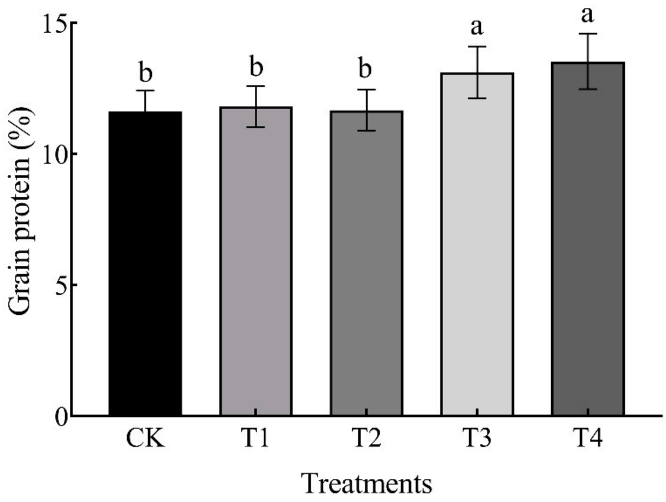

Figure 7. Winter wheat grain protein content (%) under different irrigation regimes; vertical bars represent standard errors (SE, $n = 3$). Different lowercase letters show that the mean values are significant based on LSD multiple range tests at $p < 0.05$.

3.3. Selection of Optimal Irrigation Level

In the comprehensive evaluation of the irrigation treatments (Figure 8), T1 ranked first, with a total mutation membership function value of 0.78, followed by T2 with the second-highest value. The CK treatment (irrigation in all growth stages) had the lowest value of total mutation membership function at 0.25, ranking fifth. Therefore, T1 was the treatment most-suited to maintain the yields and grain quality while reducing GHG emissions.

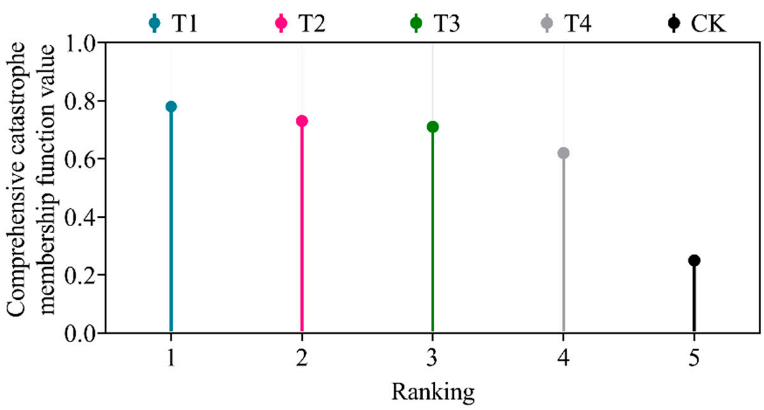

Figure 8. Comprehensive evaluation results of each irrigation treatment.

4. Discussion

Water management is an important factor affecting GHG emissions from wheat fields [8]. Soil moisture can promote or inhibit root growth and affect root respiration, change soil permeability, and affect CO_2 diffusion and microbial respiration and, therefore, affect the total production and emissions of soil CO_2. The emissions of CO_2 in T1, T2, T3, and T4 were lower than those in CK, indicating that water stress significantly affected the CO_2 emissions ($p < 0.05$). The highest emissions in CK, which was irrigated throughout the growth period, were consistent with the results of Liu [26]. A sufficient supply of water favored crop growth and high root respiration and increased soil microbial activity, which led to increases in the total soil respiration and, thus, increase in CO_2 emissions [7,8,18]. In this study, the CO_2 emission fluxes decreased significantly within 120 d after sowing ($p < 0.05$), which was likely caused by the rapid decrease in soil temperature and, therefore, microbial activity [7]. The flux of CO_2 reached a maximum at the filling stage (approximately 185 d after sowing). This result was likely because of warmer weather and increasing soil temperatures and, with the growth of winter wheat root systems, increases in root metabolism and root exudates that stimulated microbial activity [27,28]. In addition, these conditions could accelerate the mineralization of soil organic matter [7,28], which would also contribute to the higher soil CO_2 flux.

Microbial nitrification and denitrification are the primary sources of soil N_2O emissions [28,29]. The soil moisture content affects the activity of nitrifying and denitrifying microorganisms and the movement of N_2O in soil and diffusion into the atmosphere [18,30]. In this study, N_2O emissions were higher in the irrigation treatment (CK) than in the non-irrigation treatments (T1, T2, T3, and T4). Amha [31] reported similar results. Irrigation increases the water content of soil, which decreases the soil permeability, and as a result of oxygen-limited conditions, the N_2O production from nitrification and denitrification increases [28]. In the early stage after sowing, the emissions peaked because the relatively high soil moisture and high substrate concentration due to the base fertilizer created favorable conditions for N_2O emissions [28,32]. At 150 d after sowing, the soil N_2O emission flux increased slowly and then stabilized. The increase might be because increasing the soil temperatures at that time promoted N_2O emissions [28,33]. Winter wheat then entered the rapid growth stage, which accelerated the soil fertility decline, and as a result, the N_2O emissions remained low, and no further emission peaks were observed.

As the irrigation increased, an increase in the grain yield, with a concomitant decrease in the protein content, was observed [14,34]. Therefore, how to ensure the wheat quality is an important consideration when attempting to increase the wheat yield. The wheat grain yield is related to the biomass at maturity, with a high biomass leading to a high yield [13]. When plants suffer from a water deficit, the leaf extensibility decreases and the initial turgor threshold increases, which limit the leaf growth [35]. Water stress is also not conducive to CO_2 diffusion into leaf chloroplasts from the surrounding environment [36], which leads to decreases in the crop photosynthetic rate and accumulation of crop biomass [37] and, ultimately, to a decline in production. The results were similar in this study, and the winter wheat yield in CK without water stress during the growth period was higher than that in the drought treatments. Among the drought treatments, the yields of T1 and T2 were higher than those of T3 and T4. This result might be explained, because under sufficient soil moisture conditions before sowing, irrigation is more critical in key stages, such as heading and filling, than in the early stages. In the late stages, irrigation can achieve higher yields by increasing the number of panicles and grain weight [38–40]. Thus, although water stress reduces the crop yield, optimizing the irrigation period can reduce losses. In the arid areas of Northwest China, these results will be important in developing water-saving strategies. The grain quality of wheat is based on the nutritional, milling, and processing quality, with the protein content of grain an important factor [41]. Wang et al. [42] reported that differences in the irrigation management affect soil–plant water transport and the regulation of crop physiology and, as a result, grain quality. Noorka and Silva [43] evaluated the effects of water stress on the wheat grain protein content and showed that, under normal irrigation and water stress, the wheat protein content ranged from 11.20% to 13.92%. In this study, the grain protein content of winter wheat under different irrigation schemes ranged from 11.61% to 13.53%, which was similar to the results of Noorka and Silva [43]. The grain protein contents of winter wheat in T3 and T4 were significantly higher than that in the other treatments ($p < 0.05$). Compared with water regulation before the heading stage, the grain protein content can also increase significantly with drought stress after the heading stage [14]. In addition, Rezaei et al. [44] found that the grain protein content increased with the decreasing water availability. This study had similar results; that is, the protein content of CK was the lowest. In the absence of water stress, increases in carbohydrate accumulation diluted proteins and led to a decrease in the protein content [42]. However, with water stress during grain filling, the carbon fixation was limited, and because there was less synthesis and accumulation of carbohydrates in the seeds, the proteins were not diluted and the contents increased [45,46].

The catastrophe progression method is used to comprehensively evaluate selected indicators. It reduces the weight of indicators and human subjectivity and can also determine the importance of the indicators themselves, which is more scientific and practical. This method has been widely used in the comprehensive evaluation of agricultural practices [47,48]. In this study with winter wheat, the crop yield and quality and GHG emissions were the indices of the comprehensive evaluation of the effects of the different irrigation treatments. The T1 treatment was ranked first in the comprehensive evaluation, with a total mutation membership function value of 0.78. Therefore, the T1 treatment is recommended as the best irrigation scheme to maintain yields and reduce GHG emissions in winter wheat. The results of this study were obtained under automated rolling rainout shelter conditions, which have some limitations and need to be verified in the field in the future.

5. Conclusions

Different irrigation schemes had significantly different effects on the soil GHG emissions during the whole growth period of winter wheat. With water stress applied at different growth stages of winter wheat in different irrigation treatments, the soil CO_2 and N_2O emissions decreased in the order CK > T4 > T3 > T2 > T1. Although water stress significantly reduced the crop yield, ensuring irrigation from the jointing to filling stages reduced the yield loss. Thus, the T1 treatment was ranked first in the comprehensive evaluation, with a total mutation membership function value of 0.78. Therefore, we recommend the T1 treatment as the best irrigation management strategy to maintain high yields and grain quality and reduce GHG emissions in winter wheat in the arid and semiarid areas of Northwest China.

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