Agricultural Water Management 275 (2023) 108000

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Interactive effects of reduced irrigation and nitrogen fertilization on resource use efficiency, forage nutritive quality, yield, and economic benefits of spring wheat in the arid region of Northwest China

Muhammad Kamran[a], Zhengang Yan[a], Shenghua Chang[a], Jiao Ning[a], Shanning Lou[a], Irshad Ahmad[a], Muhammad Usman Ghani[a], Muhammad Arif[b], Ayman El Sabagh[c], Fujiang Hou[a,*]

[a] *State Key Laboratory of Herbage Improvement and Grassland Agro-ecosystems, Key Laboratory of Grassland Livestock Industry Innovation, Ministry of Agriculture and Rural Affairs, Engineering Research Center of Grassland Industry, Ministry of Education, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China*

[b] *Department of Agronomy, The University of Agriculture, Peshawar, Pakistan*

[c] *The Department of Field Crops, Siirt University, Turkey*

ARTICLE INFO

Handling Editor - B.E. Clothier

Keywords:
Grain and forage yield
Forage nutritive quality
Crop water productivity
Nitrogen fertilizer productivity
Economic benefits
Spring wheat

ABSTRACT

In arid regions, supplemental irrigation and fertilization are the major driving factors for sustaining crop production. With the increasing water scarcity, rising fertilizer costs, and growing environmental concerns, identifying appropriate irrigation and nitrogen (N) amounts for simultaneously improving resource use efficiency and yield benefits is essential for sustainable crop production in arid regions. A two-year field study was conducted in the arid region of Northwest China to evaluate the effects of reduced irrigation and N treatments, including $W_{80}F_{75}$ (600 mm irrigation and 225 kg N ha^{-1}), $W_{80}F_{50}$ (600 mm irrigation and 150 kg N ha^{-1}), $W_{60}F_{75}$ (450 mm irrigation and 225 kg N ha^{-1}), and $W_{60}F_{50}$ (450 mm irrigation and 150 kg N ha^{-1}) on resource use efficiency, forage yield (DM), forage nutritive values, grain yield, and economic benefit of spring wheat in comparison with the farmers' management practice ($W_{100}F_{100}$, 750 mm irrigation and 300 kg N ha^{-1}). Results indicated that moderately reduced irrigation and N ($W_{80}F_{75}$) significantly improved the forage nutritive quality, evident by high crude protein yield, relative feed value, digestible dry matter, dry matter intake, total digestible nutrients, and net energy for lactation. No significant difference in DM yield was observed between $W_{100}F_{100}$ and $W_{80}F_{75}$ treatments during both years. However, the grain yield for $W_{80}F_{75}$ treatment was 12.9 % greater than that of $W_{100}F_{100}$ in 2015. In addition, $W_{80}F_{75}$ treatment increased the resource use efficiency, net returns, and cost-befit ratios by reducing the input amounts while maintaining comparable yields to that of $W_{100}F_{100}$. However, the $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments significantly decreased the DM, grain yield, nutritive values, resource efficiency and economic benefits of spring wheat compared to $W_{80}F_{75}$. Therefore, the application of 600 mm irrigation and 225 kg N ha^{-1} to spring wheat is an appropriate management practice for reducing inputs while achieving high resource use efficiency, forage quality and economic benefits without compromising the yield of spring wheat in the arid region of Northwest China.

1. Introduction

Global agricultural production is projected to be increased by more than 70 % by 2050 to meet the increasing food, feed, and fiber demands of the ever-growing world population (Kamran et al., 2018c; Teixeira et al., 2014). With limited arable lands, this production increase needs to be achieved through the intensification of crop productivity, i.e. more produce per unit of cultivated land (Teixeira et al., 2014). Wheat (*Triticum aestivum* L.) is one of the most widely grown staple food crops, providing 20 % of the protein and 21 % of the food calories to over 4.5 billion people globally (Chen et al., 2018). Additionally, wheat dry matter (straw) is a valuable feed resource for the pastoral-based livestock industry (Blümmel et al., 2019). Northern China is an important wheat production region, representing 25 % of China's total farmland

* Corresponding author.
E-mail address: cyhoufj@lzu.edu.cn (F. Hou).

https://doi.org/10.1016/j.agwat.2022.108000
Received 9 September 2022; Received in revised form 22 October 2022; Accepted 26 October 2022

while providing 66 % of the wheat production (Zhang et al., 2020). In recent years, the importance of wheat for its dual purpose (grain + forage) has enormously increased with the development of the regional livestock industry and rising food and feed demands (Hou et al., 2021; Zhang et al., 2018). Due to scarce precipitation and soil degradation in Northwest China, intensive agronomic practices are widely adopted by farmers to boost grain yield (Si et al., 2020; Tang et al., 2018). However, the effects of these practices on the forage yield and nutritive quality are often overlooked. Therefore, appropriate irrigation and fertilization are essential to ensure the competing demands of animal feed with high nutritional quality while maintaining sustainable grain production from limited arable land in the region.

The interaction and complementary effects of water and nitrogen (N) are recognized as the primary factors that influence crop growth and final yields (Jalil Sheshbahreh et al., 2019; Kaplan et al., 2019; Zhang et al., 2020). Water facilitates N availability, which in turn, increases water use efficiency (Wang et al., 2014). In China, agricultural practices with over-reliance on irrigation and fertilization are widely adopted by producers to boost crop production (Kamran et al., 2022; Si et al., 2020). For instance, the average application of irrigation and N by wheat farmers in Northwest China reaches 700 mm and 300 kg ha^{-1}, respectively (Chen et al., 2018; Lu et al., 2014; Wang et al., 2012, 2010). Unfortunately, the N recovery efficiency of cereal crops is very poor (about 20% or less), lower than the world average (33 %), resulting in over 70% N losses to the environment (Cui et al., 2010; Zhang et al., 2021). Few studies have suggested that these intensive agronomic practices are untenable, both from economic and ecological benefit perspectives (Si et al., 2020; Tan et al., 2017; Wang et al., 2012). Furthermore, the increasing water scarcity and soil degradation in the context of global climate change are increasingly threatening agriculture productivity and sustainability, particularly in arid and semi-arid regions (Ding et al., 2021; Gonzalez-Dugo et al., 2010; Kheir et al., 2021), demanding rationalized irrigation and nutrient management. Recent studies have proposed reduced irrigation and fertilizer amounts to a certain level as an effective approach for sustaining crop production in water-deficit regions (Hou et al., 2019; Ma et al., 2022; Si et al., 2020; Zhang et al., 2020). However, water limitation influences plants' response to fertilization and decreases plant nutrient acquisition by constraining mineralization and N transport from bulk soil to the rhizosphere in dry soil (Kunrath et al., 2018). Moreover, the climatic conditions and agriculture systems are highly diverse in time and space, and the concept of reduced irrigation and fertilization for a specific region may not be suitable for other regions. Hence, a site-specific implementation strategy is needed to identify appropriate water and N amounts for maintaining optimal yields, forage nutritive quality, and economic benefits of spring wheat in the arid region of Northwest China, where irrigation meets over 90% of crop water demands.

Greater biomass is the desired goal for forage producers (Lithourgidis et al., 2006; Ronga et al., 2020), but high nutritional qualities are more valuable for the profitability of forage production and the livestock enterprises it supports (Zhang et al., 2018). Crude protein, fiber contents, and relative feed value are the essential quality metrics used for assessing forage nutritive values (Agnew et al., 2022). Among the field management practices, irrigation and fertilization had the strongest impact on nutritional composition (Islam et al., 2012; Kaplan et al., 2019; Tang et al., 2018). Previous studies have reported a trade-off between maximizing forage yield and quality attributes (Kamran et al., 2022; Kaplan et al., 2019; Rostamza et al., 2011), requiring both factors to be considered while adopting irrigation and N management practices for maximizing the economic benefits. In addition, improving crop water and fertilizer productivity is important in areas with deficit water and poor soil nutrients (Kunrath et al., 2018; Teixeira et al., 2014). Several studies have examined the effects of irrigation and/or N on the resource use efficiencies of wheat based on the DM or grain yield (Lai et al., 2022; Sharma et al., 2020; Si et al., 2020; Wang et al., 2016). However, to our knowledge, no study has assessed crop water productivity (CWP) and N fertilizer productivity (NFP) for wheat managed both for grain and forage purposes. Also, a comparable method of calculating the CWP and NFP of forage crops using indices that integrate forage nutritional quality and yield has not been previously used. Thus, we applied a novel approach to calculate resource use efficiencies based on yield and nutritional quality (e.g. crude protein and forage value) to provide more valuable assessments of the treatments used in the study.

Previous studies have mainly focused on irrigation and N fertilizer management for increasing wheat grain yield. However, little is known if grain and forage yield, forage nutritive quality, and resource efficiency of wheat can simultaneously be improved with optimized irrigation and N regimes in arid regions. We hypothesized that the current irrigation and N management for spring wheat in the arid region of Northwest China is excessive and not conducive to higher yield benefits. Instead, optimizing irrigation and N amounts would be valuable in improving resource use efficiency, nutritional quality indices, and economic benefits. Therefore, the objectives of the present study were to investigate the effects of different reduced irrigation and N regimes on grain yield, biomass accumulation, forage nutritive indices, and to determine a suitable management practice for optimum CWP, NFP, and net returns for spring wheat in the arid regions of Northwest China. The results of this study will provide new insights into the sustainable cultivation of dual-purpose spring wheat in arid regions and would help in overcoming the increasing food and feeds demands in the context of climate change.

2. Materials and methods

2.1. Experimental site location and climate data

Field trials were performed over two spring wheat growing seasons (2015–2016) at the Research Station of Lanzhou University (38° 38′N, 103° 05′E) in the Minqin Oasis, Gansu Province, China. The site is an irrigation-dependent oasis located in the Northwest inland area and has a typically arid continental climate with cold winters and hot dry summers. The average annual air temperature in the region is 7.8 ºC, the annual total sunshine duration is 3000 h, and frost-free period is about 170 days. The average annual precipitation is 110.7 mm, and the annual evaporation reaches 2644 mm. The meteorological data for precipitation, temperature, and solar radiation during the experimental periods were obtained from the local meteorological station and presented in Fig. 1.

The soil at the experimental site is sandy loam, classified as "Aridsols". Before the commencement of the experiment, soil (0–20 cm soil profile) at the research site had 8.5 pH, 9.3 g kg^{-1} organic matter, 38.7 mg kg^{-1} available nitrogen, 20.3 mg kg^{-1} available phosphorus, and 54.5 mg kg^{-1} available potassium.

2.2. Crop management and experimental design

Seeds of spring wheat (Yongliang 4, a widely grown cultivar in the region) were planted on 18th March 2015 and 20th March 2016 at a seeding rate of 185 kg ha^{-1} with row spacing of 20 cm. The experiment comprised five different combinations of irrigation and N treatments. In detail, the treatments included the farmers' practice, i.e. $W_{100}F_{100}$ (750 mm irrigation and 300 kg N ha^{-1}), and four other reduced irrigation and N treatments, including $W_{80}F_{75}$ (600 mm irrigation and 225 kg N ha^{-1}), $W_{80}F_{50}$ (600 mm irrigation and 150 kg N ha^{-1}), $W_{60}F_{75}$ (450 mm irrigation and 225 kg N ha^{-1}), and $W_{60}F_{50}$ (450 mm irrigation and 150 kg N ha^{-1}). The W_{80} and W_{60} represent 80% and 60% of the total amount of border irrigation (W_{100}), while F_{75} and F_{50} indicate 75 % and 50 % of the total N fertilizer (F_{100}) applied by local farmers during the spring wheat growing seasons, respectively. For each treatment, irrigation water was applied in equal parts at the sowing (25 %), jointing (25 %), heading (25 %) and grain-filling (25 %) stages. The irrigation schedules were based on soil moisture depletion and water requirements

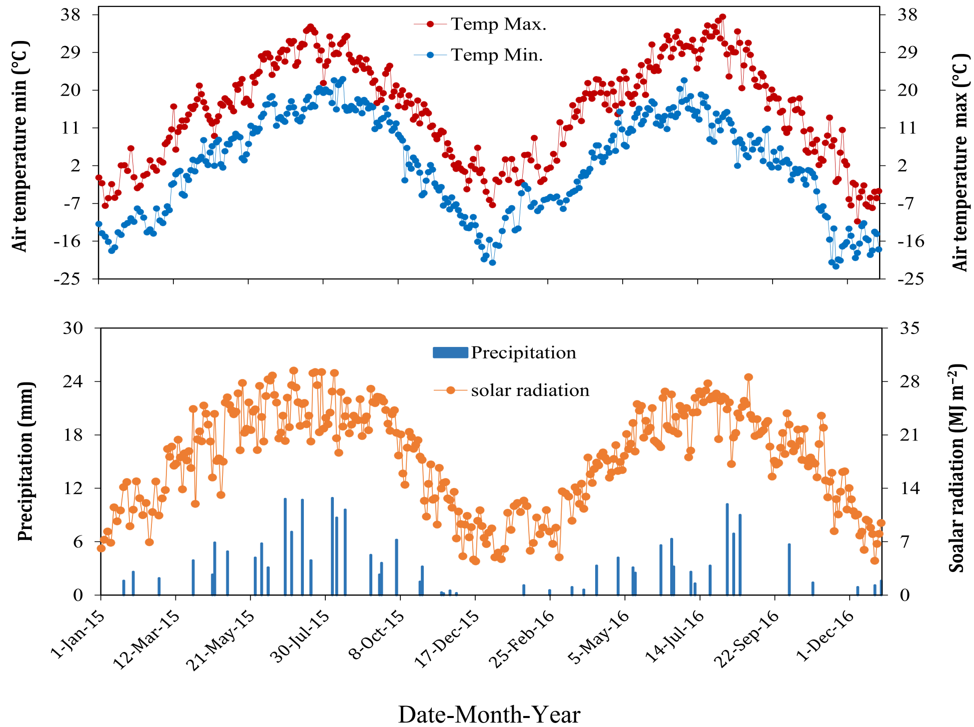

Fig. 1. Daily minimum and maximum air temperature, rainfall, and solar radiation at the experimental site during spring wheat growing years (2015 and 2016).

at the critical crop growth stages. For each irrigation event, the amount of water applied was manually determined and recorded by a water flow meter. Urea (46 % N) as N source was applied in split doses before irrigation events (60 % at first irrigation and 40 % at third irrigation). Treatments were organized in a randomized complete block (RCB) design with four replications. Each treatment plot was 10 m × 10 m (100 m^2) with a 1.5 m buffer between adjacent plots. Field ridges covered with impervious plastic membranes were built between adjacent plots to prevent lateral water and N movement. Recommended phosphorus (120 kg P_2O_5) and potassium (150 kg K_2O ha^{-1}) fertilizers were uniformly applied across all the treatment plots. No herbicides were applied in both crop growing seasons.

2.3. Sampling, measurements, and calculation

2.3.1. Measurement of forage biomass

Wheat plants were harvested from two separate randomly selected areas (each 4 m^2) within each replicated plot at tillering (TL), jointing (JO), booting (BO), and grain-filling (GF) stages. Plants were hand-cut at ground level with manual shears, and fresh forage biomass was determined immediately with an electric scale. Subsequently, the samples were oven-dried at 65 °C until constant weight to estimate the dry matter yield (DM). The final DM yield was determined at harvesting.

2.3.2. Measurement of forage nutritive values

For the determination of forage nutritive values, oven-dried plant samples were crushed into fine powder, passed through a 1-mm mesh screen, and prepared for chemical analysis. The concentration of crude protein (CP %) was estimated by determining N content using the standard Kjeldahl method (Zhang et al., 2018). The concentration of acid detergent fiber (ADF %) and neutral detergent fiber (NDF %) was determined following the methods of Van Soest et al. (1991).

Digestible dry matter (DDM %), total digestible nutrients (TDN %), dry matter intake (DMI %), relative feed value (RFV), and net energy for lactation (NE_L) were estimated following the equations adopted from Lithourgidis et al. (2006). At harvest, these data were converted for the whole plant on DM basis. The equations used for calculation were as follows:

$$\text{DDM} = 88.9 - 0.779 \times \text{ADF (\% DM)} \tag{1}$$

$$\text{DMI} = 120/\text{NDF (\% DM)} \tag{2}$$

$$\text{TDN} = (-\,1.291 \times \text{ADF}) + 101.35 \tag{3}$$

$$\text{RFV} = \text{DMD} \times \text{DMI}/1.29 \tag{4}$$

$$\text{NE}_\text{L} = (1.004 - 0.0119 \times \text{ADF}) \times 2.205 \tag{5}$$

To accurately assess the relative nutrition values of the total dry biomass obtained at the final harvest for different treatments, the CP and RFV yield were calculated (Zhang et al., 2018).

$$\text{CP yield (kg ha}^{-1}) = \text{DM yield (kg ha}^{-1}) \times \text{CP (g g}^{-1}) \tag{6}$$

$$\text{RFV yield (kg ha}^{-1}) = \text{DM yield (kg ha}^{-1}) \times \text{RFV (g g}^{-1}) \tag{7}$$

2.3.3. Determination of grain yield

The wheat crop was harvested manually at physiological maturity from a 16 m^2 area (4 × 4 m) at two random locations in each plot. After threshing the spikes by hand, the grain samples were cleaned and sun-dried, and grain yield was determined at 14% moisture content.

2.3.4. Calculation of crop water productivity

Crop water productivity (CWP) was calculated based on the total wheat yield, CP yield, and RFV (Zhang et al., 2018):

$$CWP_{yield}\ \left(kg\ \ mm^{-1}\right) = \frac{total\ \ wheat\ \ yield}{total\ \ water\ \ applied} \tag{8}$$

$$CWP_{CP}\ \left(kg\ \ mm^{-1}\right) = \frac{CP\ \ yield}{total\ \ water\ \ applied} \tag{9}$$

$$CWP_{RFV}\ \left(kg\ \ mm^{-1}\right) = \frac{RFV\ \ yield}{total\ \ water\ \ applied} \tag{10}$$

2.3.5. Calculation of nitrogen fertilizer productivity

Nitrogen fertilizer productivity (NFP) for total wheat yield, CP yield, and RFV were calculated using the formulas (Li et al., 2017):

$$NFP_{yield} \quad (kg \quad kg^{-1}) = \frac{total \quad wheat \quad yield}{N \quad application \quad rate} \tag{11}$$

$$NFP_{CP} \quad (kg \quad kg^{-1}) = \frac{CP \quad yield}{N \quad application \quad rate} \tag{12}$$

$$NFP_{RFV} \quad (kg \quad kg^{-1}) = \frac{RFV \quad yield}{N \quad application \quad rate} \tag{13}$$

2.3.6. Calculation of economic benefits

The net returns for each treatment were determined by subtracting the total input from the total output, while the benefit-cost ratios were determined by dividing net returns by total input (Zhang et al., 2020).

$$\text{Net returns} = \text{total output} - \text{total input} \tag{14}$$

$$\text{Benefit-cost ratio} = \text{net returns/total input} \tag{15}$$

The total input costs include materials costs (seeds, irrigation water, fertilizers, and pesticide costs), labor costs (field preparation, ridges and furrows construction, sowing, fertilizer application, irrigating, weeding, harvesting), and machinery costs (mainly irrigation system). The total output was calculated using the total wheat yield (straw + grain, kg ha^{-1}) and their per unit yearly average market price (RMB kg^{-1}).

2.4. Statistical analysis

Data presented in tables and figures are the mean of four replicates (n = 4). The ANOVA (analysis of variance) for the two-year data of grain yield, dry matter yield, forage nutritive values, resource use efficiencies, and net benefit returns was performed with the SPSS 20.0 software package (IBM Corp., USA). Years and combined irrigation and nitrogen treatments were treated as fixed effects, while replication was considered a random effect in a factorial design. Multiple comparisons of mean values were performed using Tukey's significant difference test at $P < 0.05$. Pearson's correlation and principal component analysis (PCA) were performed by using Origin 2022 (Origin Lab Corp., USA) to identify the relationship and interactions of measured variables. Figures were generated using Origin 2022 and Microsoft Excel 2010 (Microsoft Corp., USA).

3. Results

3.1. Forage fresh biomass production and dry matter yield

Fresh biomass of spring wheat was significantly ($P < 0.05$) affected by different irrigation and N treatments during 2015 and 2016 (Fig. 2a-b). The forage biomass followed a gradually increasing trend with the progression of the crop growth period and reached peak values (12.58–18.41 t ha^{-1}) at the BO stage (Fig. 2a-b). Thereafter, the forage biomass declined at the GF stage (7.85–13.60 t ha^{-1}), owing to the onset

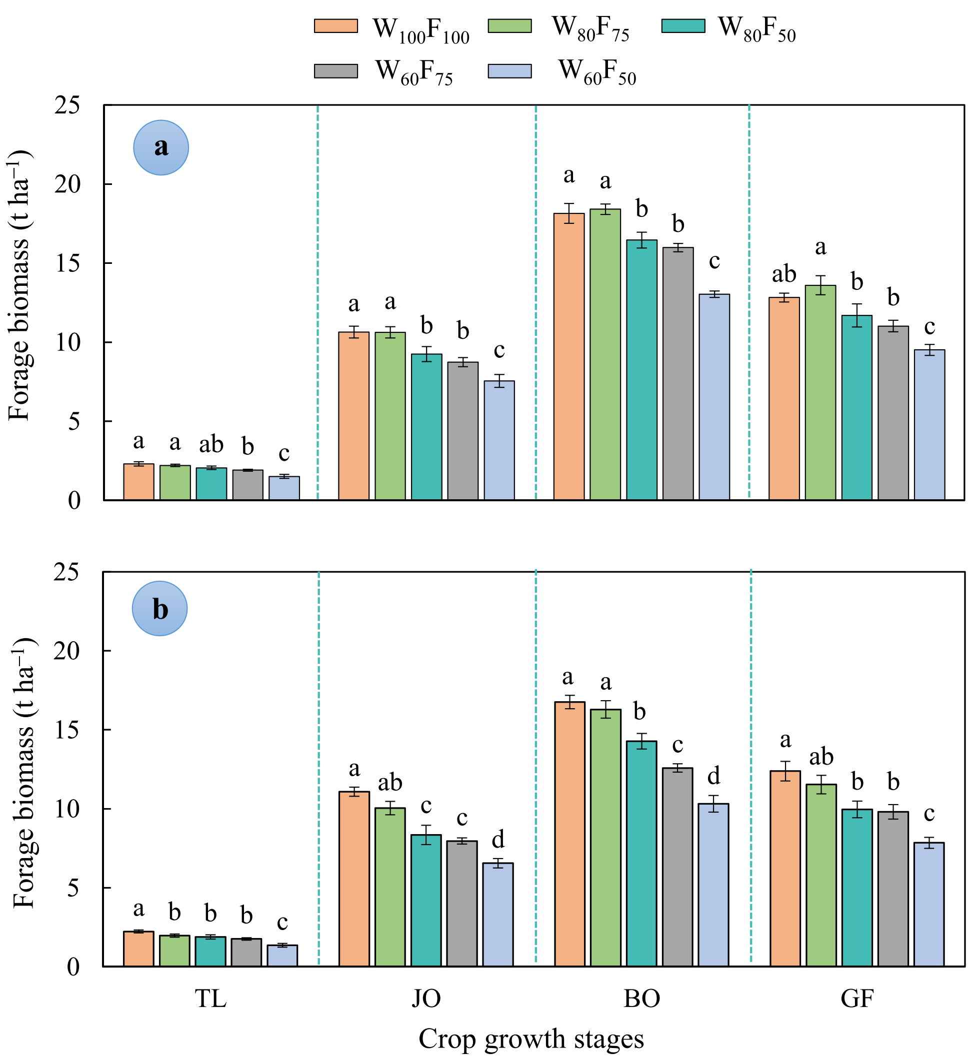

Fig. 2. Effects of irrigation and nitrogen treatments on fresh forage biomass at different growth stages of spring wheat in 2015 (a) and 2016 (b). Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters at each stage indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. $W_{100}F_{100}$ (750 mm irrigation and 300 kg N ha^{-1}), $W_{80}F_{75}$ (600 mm irrigation and 225 kg N ha^{-1}), $W_{80}F_{50}$ (600 mm irrigation and 150 kg N ha^{-1}), $W_{60}F_{75}$ (450 mm irrigation and 225 kg N ha^{-1}), and $W_{60}F_{50}$ (450 mm irrigation and 150 kg N ha^{-1}). TL: tillering stage; JO: jointing stage; BO: booting stage; and GF: grain-filling stage.

of leaf senesces. At each sampling stage, greater biomass was achieved with $W_{100}F_{100}$ and $W_{80}F_{75}$ during both years. The difference between $W_{100}F_{100}$ and $W_{80}F_{75}$ treatments was non-significant at various sampling stages (except for the TL stage in 2016) (Fig. 2a-b). However, too much decrease in irrigation and N amounts resulted in a linear decline in biomass, and the lowest biomass was achieved for $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments.

Results showed significant effects of the year, treatments, and their interaction on the dry matter (DM) yield of spring wheat (Fig. 3a). The average DM yield of all treatments was greater by 9.4 % in 2015 compared to that in 2016. The DM yield achieved for different treatments ranged from 4.1 to 7.2 t ha^{-1} in 2015 and from 3.6 to 6.9 t ha^{-1} in 2016 (Fig. 3a). Statistically, no significant difference in DM was evident between $W_{100}F_{100}$ (7.0 and 6.9 t ha^{-1}) and $W_{80}F_{75}$ (7.2 and 6.7 t ha^{-1}) treatments in 2015 and 2016. Except for $W_{80}F_{75}$, the DM of spring wheat was markedly decreased with other reduced irrigation and N treatments in both crop growing seasons (Fig. 3a). Compared to $W_{100}F_{100}$, the DM yield for $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments were decreased by 18.2 %, 22.9 %, and 41.6 % in 2015 and 21.4 %, 38.2 %, and 48.9 % in 2016, respectively.

3.2. Grain yield as affected by reduced irrigation and N treatments

Different irrigation and N treatments significantly influenced the wheat grain yield in both crop growing seasons. No significant difference in grain yield was evident between 2015 and 2016. Interestingly, the highest grain yield was achieved with $W_{80}F_{75}$ (7.3 and 6.8 t ha^{-1}), which was greater by 14.1 % and 7.9 % compared to $W_{100}F_{100}$ (6.4 and 6.3 t ha^{-1}) in 2015 and 2016, respectively (Fig. 3b). However, excessively reduced irrigation and N treatments showed detrimental effects on grain yield. The $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments resulted in grain yields of 5.4, 4.2, and 4.0 t ha^{-1} in 2015 and 5.4, 4.7, and 3.9 t ha^{-1} in 2016 (Fig. 3b). In comparison, the grain yield for $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments was decreased by 15.6 %, 34.4 %, and 37.5 % in 2015 and by 14.3 %, 25.4 %, and 38.1 % in 2016 compared to that of $W_{100}F_{100}$, respectively.

3.3. Crude protein as affected by reduced irrigation and N treatments

The dynamic of crude protein (CP) concentration at various stages during the spring wheat growing period with different treatments are presented in Fig. 4. Initially, the CP followed an increasing trend from TL

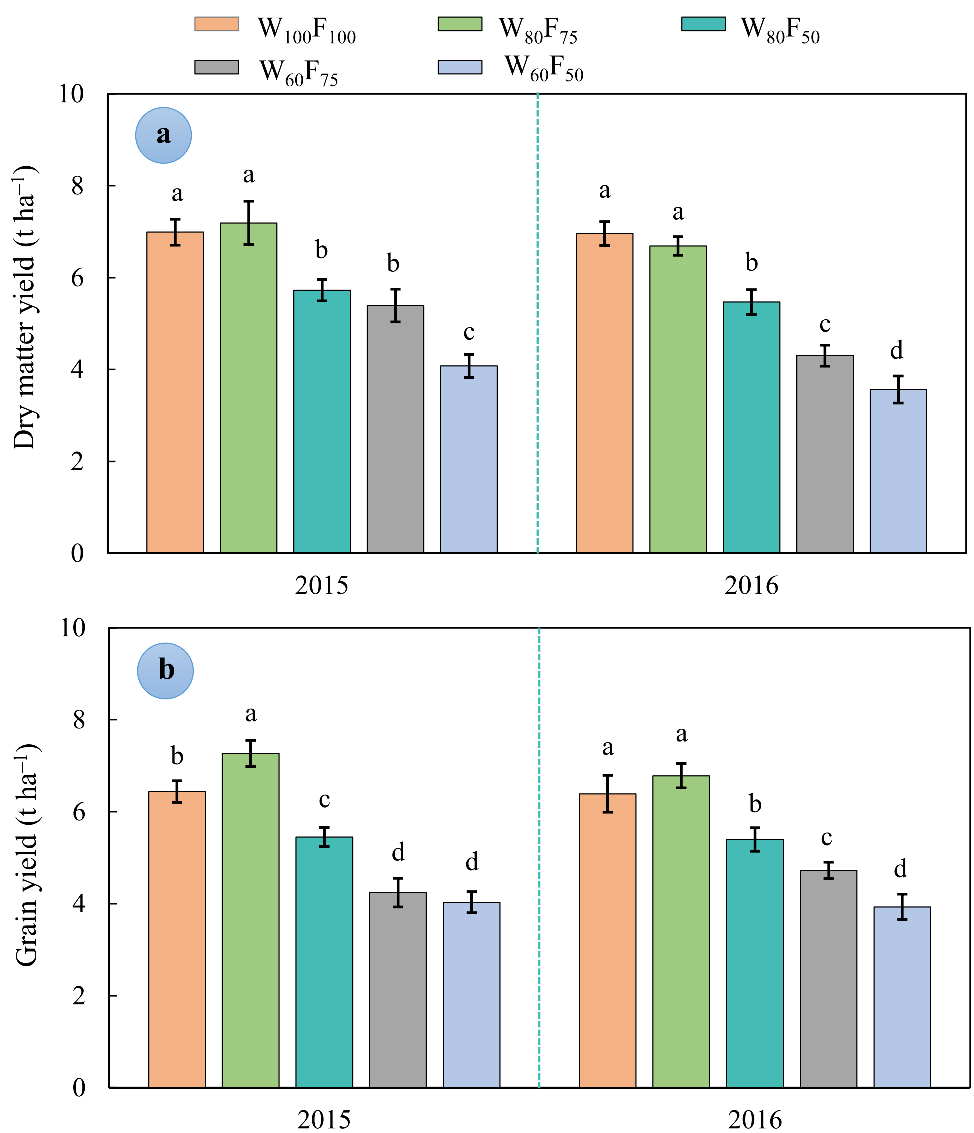

Fig. 3. Effects of different irrigation and nitrogen treatments on dry matter (forage) and grain yield of spring wheat in 2015 and 2016. Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

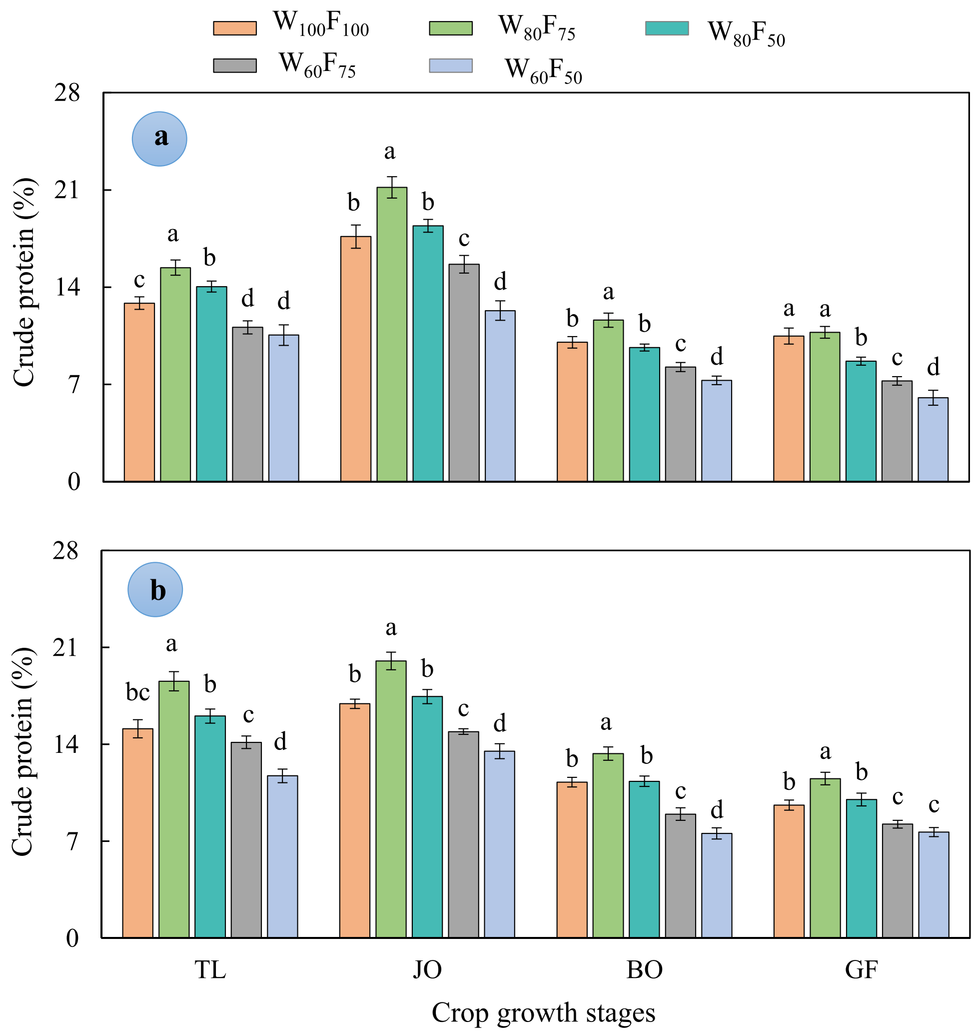

Fig. 4. Effects of different irrigation and nitrogen treatments on crude protein concentration at different growth stages of spring wheat in 2015 (a) and 2016 (b). Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters at each stage indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

to JO stage and then gradually decreased until GF stage. In general, CP concentration exhibited a similar trend in both wheat growing seasons and tended to increase with a moderate decrease in irrigation and N ($W_{80}F_{75}$) but markedly decreased with severely reduced irrigation and N rates as compared to the conventional full application during the whole crop growing period (Fig. 4a-b).

The CP yield for the total DM at harvesting was significantly ($P < 0.01$) affected by irrigation and N treatments, but the effect of the year

Table 1
Analysis of forage nutritional quality indices including crude protein (CP), relative feed value (RFV), acid detergent fiber (ADF), neutral detergent fiber (NDF), digestible dry matter (DDM), dry matter intake (DMI), total digestible nutrients (TDN), and net energy for lactation (NE_L) of the wheat dry matter at harvest with different irrigation and nitrogen treatments in 2015 and 2016.

Year	Treatments	CP yield (kg ha^{-1})	RFV yield (t ha^{-1})	ADF (g kg^{-1})	NDF (g kg^{-1})	DDM (g kg^{-1})	DMI (g kg^{-1})	TDN (g kg^{-1})	NE_L (%)
2015	$W_{100}F_{100}$	749.3a	10.16b	330.2a	465.5a	631.8d	25.8e	587.2d	1.44d
	$W_{80}F_{75}$	746.2a	14.10a	210.6d	326.6e	724.9a	36.8a	741.6a	1.75a
	$W_{80}F_{50}$	493.1b	10.71b	225.6d	346.1d	713.3a	34.7b	722.3a	1.71a
	$W_{60}F_{75}$	388.1c	8.52c	256.6c	398.9c	689.1b	30.1c	682.2b	1.63b
	$W_{60}F_{50}$	243.1d	5.34d	274.8b	442.6b	675.0c	27.1d	658.8c	1.58c
2016	$W_{100}F_{100}$	687.0b	10.27b	294.4a	500.5a	659.6c	24.0e	633.4c	1.53c
	$W_{80}F_{75}$	755.6a	12.94a	211.5c	373.1e	724.2a	32.2a	740.4a	1.75a
	$W_{80}F_{50}$	547.5c	9.35c	204.7c	407.7d	729.5a	29.4b	749.2a	1.76a
	$W_{60}F_{75}$	354.3d	7.36d	263.5b	429.1c	683.7b	28.0c	673.3b	1.61b
	$W_{60}F_{50}$	272.4e	5.27e	290.6a	475.5b	662.6c	25.2d	638.3c	1.54c
Treatments (T)		* *	* *	* *	* *	* *	* *	* *	* *
Year (Y)		NS	* *	*	* *	*	* *	*	*
T × Y		NS	*	* *	*	* *	* *	* *	* *

Data are presented as the mean of four replicates (n = 4). Means followed by different small letters within a column indicate significant differences based on Tukey's significant difference test ($P < 0.05$). * and * * indicates significant difference at $P < 0.05$ and $P < 0.01$, while NS indicate non-significant differences ($P > 0.05$). Abbreviations for treatment names are similar to those described in Fig. 2

and its interaction with treatment (T × Y) was non-significant ($P > 0.05$) (Table 1). The CP yield ranged from 243.1 to 749.3 kg ha^{-1} in 2015 and from 272.4 to 755.6 kg ha^{-1} in 2016 for different treatments (Table 1). Among all the treatments, the highest CP yield was achieved for the $W_{80}F_{75}$ (746.2 and 755.6 kg ha^{-1}), followed by $W_{100}F_{100}$ (749.3 and 687.0 kg ha^{-1}). Whereas the lowest CP yield was obtained for $W_{60}F_{50}$ (243.1 and 272.4 kg ha^{-1}) and $W_{60}F_{75}$ (388.1 and 354.3 kg ha^{-1}) treatments in 2015 and 2016, respectively (Table 1). The CP yield for the $W_{80}F_{75}$ treatment was similar to that of $W_{100}F_{100}$ in 2015 but was greater by 10.0% in 2016. On the other hand, the CP yield of $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments was decreased by 34.2 %, 48.2 %, and 67.6 % in 2015 and by 20.3 %, 48.4 %, and 60.3 % in 2016 when compared to $W_{100}F_{100}$ treatment, respectively.

3.4. Relative feed value as affected by irrigation and N treatments

During both spring wheat growing seasons, the relative feed value (RFV) gradually decreased with the advancement of the crop growth period. The RFV values ranged from 327.8 % to 383.9 % at TL stage, 206.5–314.3 % at JO stage, 146.8–213.11 at BO stage, and 122.6–206.5 at GF stage in 2015 and 2016 (Fig. 5a-b). At each stage, there were significant differences in RFV values among treatments. Remarkably, the RFV values were increased by reducing the irrigation and N rates when compared to conventional full application management. At most of the sampling stages, the RFV was greater for $W_{80}F_{75}$, $W_{80}F_{50}$, and $W_{60}F_{75}$ treatments, while the values were lower for the $W_{100}F_{100}$ treatment (Fig. 5a-b).

The treatments, year and their interaction significantly affected the total RFV yield at harvesting (Table 1). Among the various treatments, the highest RFV yield was achieved for $W_{80}F_{75}$ (14.10 and 12.94 t ha^{-1}). The RFV yield for the $W_{80}F_{75}$ treatment was greater by 38.8 % and 26.0 % compared to the conventional $W_{100}F_{100}$ treatment in 2015 and 2016, respectively. Except for $W_{80}F_{75}$, other reduced irrigation and N treatments significantly decreased the RFV yield compared to $W_{100}F_{100}$ in both years (Table 1). In comparison, the RFV yield for the $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments decreased by 16.1 % and 47.4 % in 2015, while it decreased by 28.3 % and 48.7 % in 2016 compared to that of $W_{100}F_{100}$, respectively.

3.5. Fiber contents as affected by reduced irrigation and N treatments

Based on the different effects of treatments on the shoot fiber, the accumulation of acid detergent fiber (ADF) and neutral detergent fiber (NDF) of spring wheat was assessed at various growth stages (Figs. 6–7). The concentration of ADF and NDF progressively increased following the crop growth period, and the maximum values were observed at GF stage. During the wheat growing seasons, the concentration of ADF and NDF ranged from 10.0 % to 14.8 % and 19.6–25.3 % at TL stage,

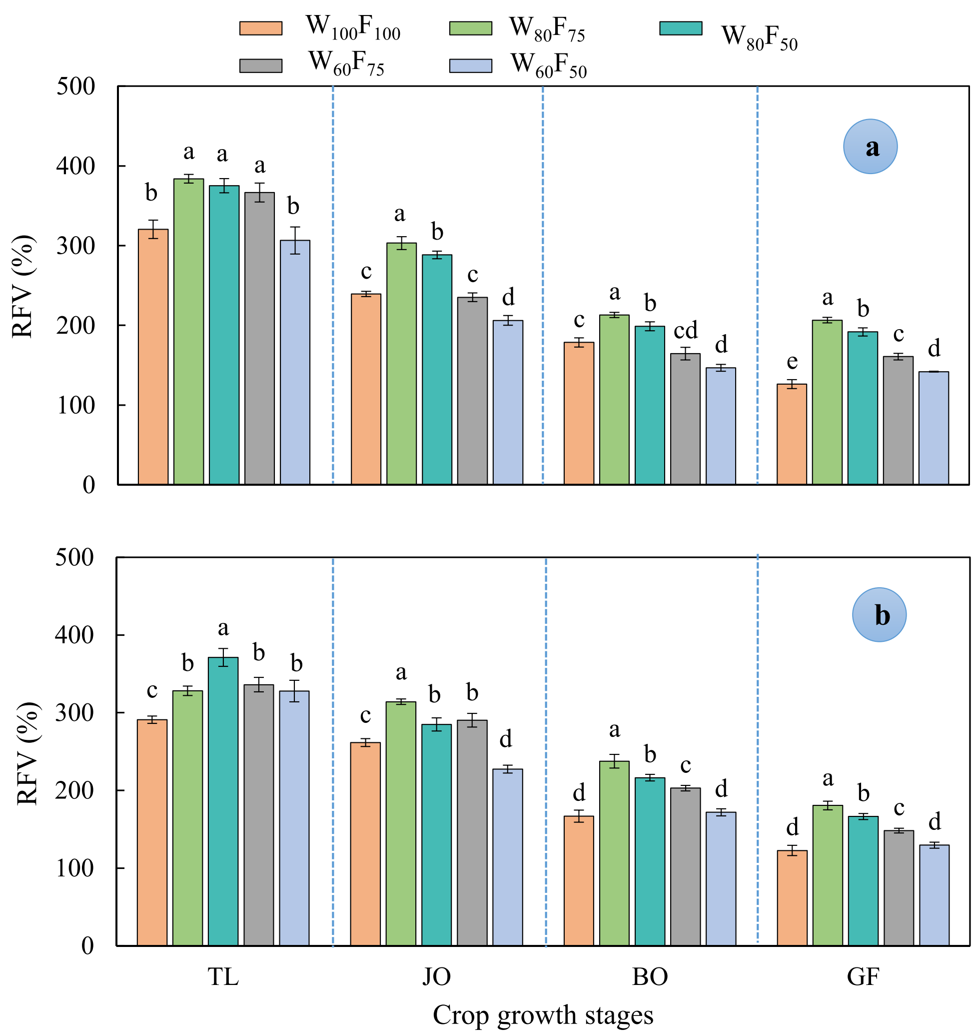

Fig. 5. Effects of different irrigation and nitrogen treatments on relative feed value (RFV) at different growth stages of spring wheat in 2015 (a) and 2016 (b). Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters at each stage indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

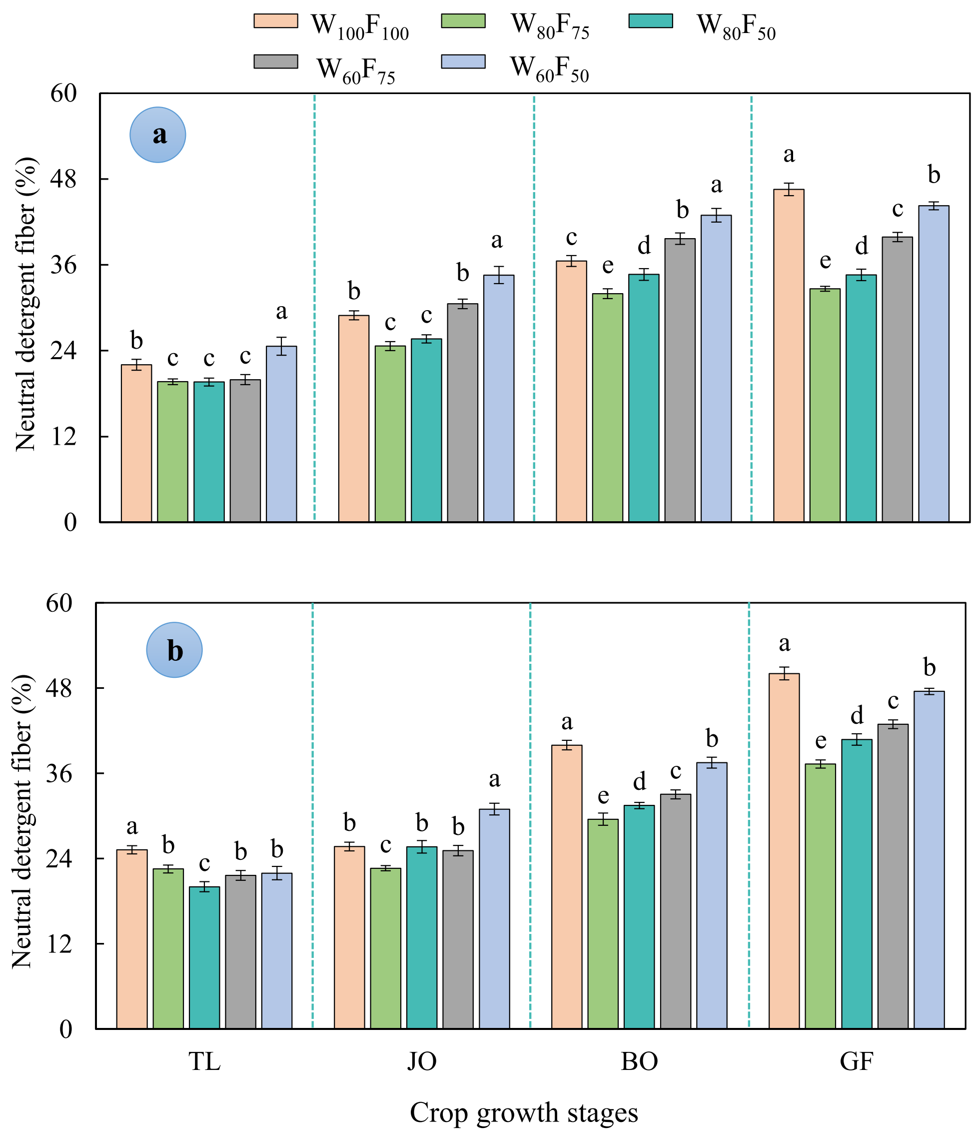

Fig. 6. Effects of different irrigation and nitrogen treatments on neutral detergent fiber concentration at different growth stages of spring wheat in 2015 (a) and 2016 (b). Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters at each stage indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

11.1–21.4 % and 22.6–31.0 % at JO stage, 17.2–27.2 % and 29.5–42.9 % at BO stage, and 21.1–33.0 % and 32.6–50.1 % at GF stage (Figs. 6–7). At each sampling stage, the ADF and NDF concentrations were greater for $W_{100}F_{100}$ treatment.

At harvesting, the ADF and NDF content per unit DM of wheat was significantly affected by year, treatments, and their interaction (Table 1). The $W_{100}F_{100}$ resulted in the highest ADF (330.2 and 294.4 g kg^{-1}) and NDF (465.5 and 500.5 g kg^{-1}) contents in 2015 and 2016, respectively (Table 1). Initially, the ADF and NDF contents followed a decreasing trend with moderately reduced irrigation and N but increased again with the excessive reduction of irrigation and N. The lowest ADF and NDF contents were achieved for the $W_{80}F_{75}$ and $W_{80}F_{50}$ treatments (Table 1). Compared to $W_{100}F_{100}$, the ADF content of $W_{80}F_{75}$ treatment was lowered by 36.2 % and 28.2 % and NDF content by 29.8 % and 25.5 %, while the ADF contents of the $W_{80}F_{50}$ treatments was decreased by 31.7 % and 30.5 % and NDF by 25.6 % and 18.5 % in 2015 and 2016, respectively. The ADF and NDF contents for $W_{60}F_{50}$ were comparable to that of $W_{100}F_{100}$ in both years (Table 1).

3.6. *Digestible dry matter, dry matter intake, total digestible nutrients, and net energy for lactation*

When analyzed at harvest, the digestible dry matter (DDM), dry matter intake (DMI), total digestible nutrients (TDN), and net energy for lactation (NE_L) were significantly affected by year, treatments, and their interaction (Table 1). Initially, the DDM, DMI, TDN, and NE_L increased with reducing irrigation and N amounts, and the highest values were observed for $W_{80}F_{75}$ and $W_{80}F_{50}$ treatments in both years (Table 1). In comparisons, the DDM, DMI, TDN and NE_L of $W_{80}F_{75}$ treatment were greater by 14.7 % and 9.8 %, 42.6 % and 34.2 %, 26.3 % and 16.9 %, 21.5 % and 14.4 %, while that of $W_{80}F_{50}$ was greater by 12.9 % and 10.6 %, 34.5 % and 22.5 %, 23.0 % and 18.3 %, 18.8 % and 15.0 % compared to that of $W_{100}F_{100}$ in 2015 and 2016, respectively. In addition, the $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments markedly reduced the DDM, DMI, TDN, and NE_L compared to the $W_{80}F_{75}$ treatment; however, the values were still higher than that for the $W_{100}F_{100}$ treatment (Table 1).

3.7. *Crop water productivity and nitrogen fertilizer productivity*

The crop water productivity of wheat based on the total yield

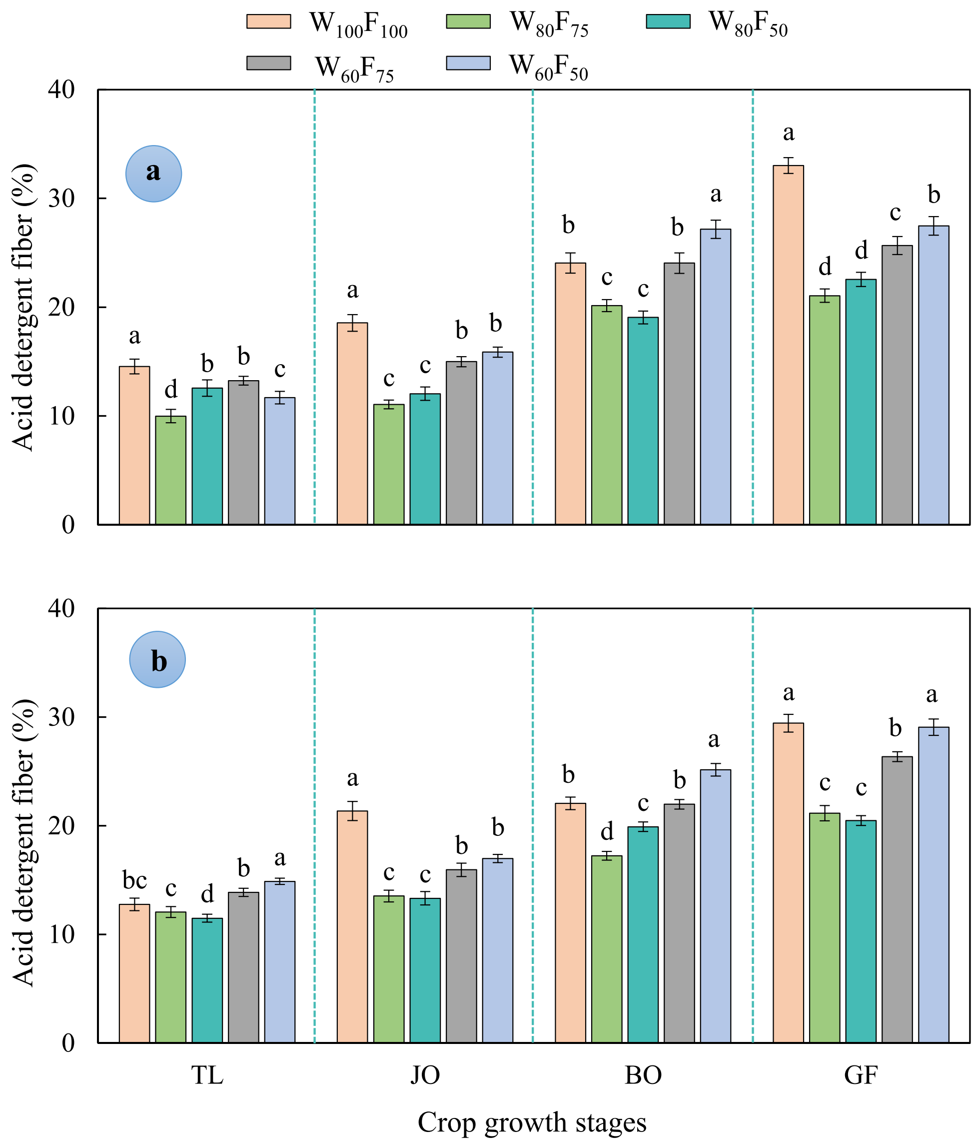

Fig. 7. Effects of different irrigation and nitrogen treatments on acid detergent fiber concentration at different growth stages of spring wheat in 2015 (a) and 2016 (b). Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters at each stage indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

production (CWP_{yield}), CP yield (CWP_{CP}), and RFV yield (CWP_{RFV}) was strongly influenced by treatments. The highest values were obtained for the $W_{80}F_{75}$ treatment in both years (Fig. 8). Compared to $W_{100}F_{100}$, the CWP_{yield} for $W_{80}F_{75}$ treatment was increased by 28.3 % and 23.33 %, CWP_{CP} by 22.8 % and 36.8 %, and CWP_{RFV} by 70.3 % and 55.7 % in 2015 and 2016, respectively. However, the $W_{80}F_{50}$ and $W_{60}F_{75}$ treatments markedly declined the CWP_{yield} and CWP_{RFV} compared to $W_{80}F_{75}$, but the values were still higher than that for the $W_{100}F_{100}$ treatment in both years (Fig. 8). No significant difference in CWP_{yield} was observed between the $W_{100}F_{100}$ and $W_{60}F_{50}$ treatments. However, the CWP_{CP} and CWP_{RFV} for $W_{60}F_{50}$ treatment were significantly lower than that for $W_{100}F_{100}$ (Fig. 8).

The fertilizer productivity for total yield (NFP_{yield}), CP content (NFP_{CP}), and RFV (NFP_{RFV}) was also significantly affected by irrigation and N treatments and year (except for NFP_{CP}). The interaction of year and treatments was significant only for NFP_{RFV} (Fig. 9). Initially, reducing the irrigation and N application amounts increased the NFP, and the highest values were achieved for $W_{80}F_{50}$, followed by $W_{80}F_{75}$ treatment during both years (Fig. 9). Compared to $W_{100}F_{100}$, the NFP_{yield}, NFP_{CP}, and NFP_{RFV} for $W_{80}F_{50}$ treatment was increased by 64.0 % and 62.7 %, 31.6 % and 59.4 %, 110.8 % and 82.2 %, while that for $W_{80}F_{75}$ treatment was increased by 39.5 % and 33.1 %, 32.8 % and 46.7 %, 85.1 % and 68.0 % in 2015 and 2016, respectively. However, the $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments decreased the NFP_{yield}, NFP_{CP}, and NFP_{RFV} compared to $W_{80}F_{75}$ and $W_{80}F_{50}$ treatments, and the values were comparable to that of $W_{100}F_{100}$ during both years (Fig. 9).

3.8. Economic benefits with reduced irrigation and N treatments

The net returns ranged from 7148 – 16417 RMB ha^{-1} in 2015 and 6324 – 15019 RMB ha^{-1} in 2016 (Table 2). Among the various treatments, the highest net returns were achieved for $W_{80}F_{75}$ (16417 RMB ha^{-1}) in 2015, which was greater by 11.1% compared to $W_{100}F_{100}$ (14776 RMB ha^{-1}). However, no significant difference in net returns was manifested between $W_{80}F_{75}$ (15019 RMB ha^{-1}) and $W_{100}F_{100}$ (14726 RMB ha^{-1}) in 2016. On the other hand, $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments markedly reduced the net returns of spring wheat in both years (Table 2). Compared to $W_{100}F_{100}$, the net returns for $W_{80}F_{50}$, $W_{60}F_{75}$, $W_{60}F_{50}$ treatments were decreased by 20.6 %, 38.5 %, and 51.6 % in 2015, and 22.9 %, 42.4 %, and 57.1 % in 2016, respectively.

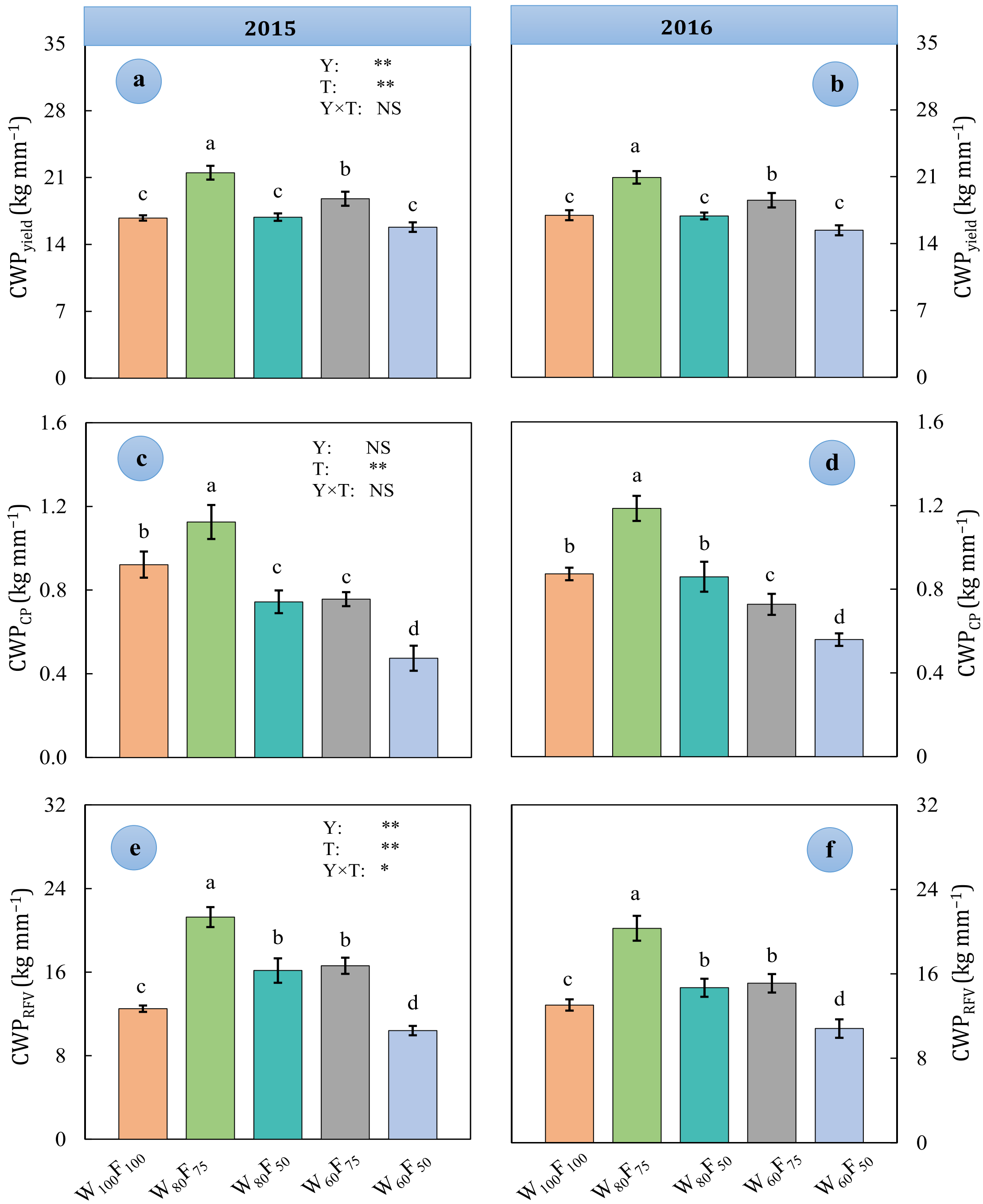

Fig. 8. Effects of different irrigation and nitrogen treatments on crop water productivity (CWP) of spring wheat in 2015 and 2016. Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

The benefit-cost ratio among different treatments ranged from 1.29 – 2.73 in 2015 and 1.14 – 2.50 in 2016, respectively (Table 2). The highest benefit-cost ratio of 2.73 and 2.50 was achieved for $W_{80}F_{75}$, which was greater by 19.7 % and 10.1 % than $W_{100}F_{100}$ treatment in 2015 and 2016, respectively. Too much reduction in irrigation and N application steadily declined the benefit-cost ratio of spring wheat, and the lowest ratios were achieved for $W_{60}F_{75}$ (1.56 and 1.46) and $W_{60}F_{50}$ (1.29 and 1.14) treatments (Table 2). Compared to $W_{100}F_{100}$, the cost-benefit ratios for $W_{80}F_{50}$, $W_{60}F_{75}$, and $W_{60}F_{50}$ treatments was lowered by 10.5 %, 31.6 %, and 43.4 % in 2015 and by 12.8 %, 35.7 %, and 49.8 % in 2016, respectively.

3.9. Correlation and principal component analysis

The Pearson correlation analysis revealed significant positive correlations of resource use efficiency indices (CWP_{yield}, CWP_{CP}, CWP_{RFV}, NFP_{CP}, and NFP_{RFV}) with yield, crude protein content, and RFV of spring wheat but negative relations with ADF and NDF content (Fig. 10a). The net returns followed a strong positive relationship with crude protein, RFV, resource use efficiency, grain and forage yields while presenting a negative relationship with ADF and NDF contents. In addition, the correlation analysis indicated a significant positive relationship between crude protein and RFV with forage yield, while negative correlations of ADF and NDF with forage yield (Fig. 10a).

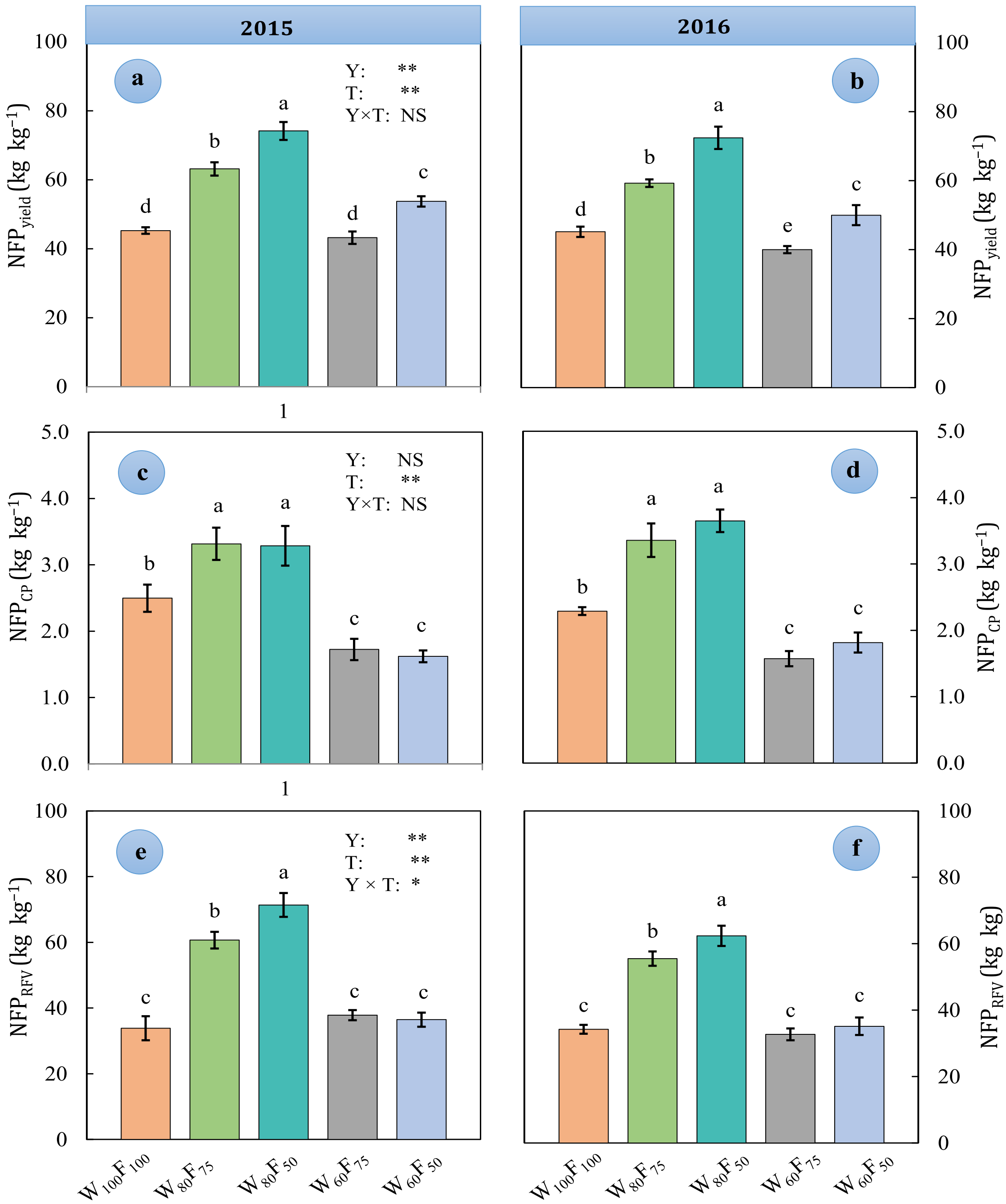

Fig. 9. Effect of different irrigation and nitrogen treatments on nitrogen fertilizer productivity (NFP) of spring wheat in 2015 and 2016. Data are presented as the mean of four replicates ± SD (n = 4). Vertical bars with different letters indicate significant differences among treatment means based on Tukey's significant difference test at $P < 0.05$. Abbreviations for treatment names are similar to those described in Fig. 2.

In addition, the PCA ordination plot was prepared to present the concerted information on the resource use efficiency, forage yield and quality traits, and net returns in relation to irrigation and nitrogen treatments (Fig. 10b). The first two principal components (PCs) explained 85.9 % of the total variance (being 63.9 % in PC1 and 22.0 % in PC2). The plot showed clear segregation of the variables and treatments into different groups (quadrants). The upper left quadrant of the negative side of PC1 (Q1) included the conventional $W_{100}F_{100}$ treatment that delivered high ADF and NDF contents (Fig. 10b). A second group clustered on the positive side of PC1 (Q2) included $W_{80}F_{75}$ treatment representing higher grain yield, crop water productivity (CWP_{yield}, CWP_{CP}, and CWP_{RFV}) along with premium forage quality (high CP and RFV) of spring wheat. The lower left quadrant (Q3) depicted the treatments ($W_{60}F_{75}$ and $W_{60}F_{50}$) of the lowest yield, forage quality traits, and resource use efficiency (Fig. 10b). Finally, $W_{80}F_{50}$ treatments in Q4 had the highest DMI, NE_L, and nitrogen fertilizer productivity (NFP_{yield}, NFP_{CP}, and NFP_{RFV}).

4. Discussion

4.1. Response of wheat yield to reduced irrigation and N treatments

The agroecosystems in arid regions are highly vulnerable due to limited available water and soil nutrient resources (Kheir et al., 2022; Li et al., 2022; Wang et al., 2018). Supplemental irrigation and N fertilization are key solutions to sustaining plant growth and improving the

Table 2
Analysis of economic benefit for the spring wheat with different irrigation and nitrogen treatments in 2015 and 2016.

Year	Treatments	Input costs (RMB ha^{-1})					Output (RMB ha^{-1})	Net returns (RMB ha^{-1})	Benefit-cost ratio
		Seed	Fertilizer	Irrigation	Other costs*	Total cost			
2015	$W_{100}F_{100}$	1036	1998	1000	2450	6484	21260b	14776b	2.28b
	$W_{80}F_{75}$	1036	1728	800	2450	6014	22431a	16417a	2.73a
	$W_{80}F_{50}$	1036	1458	800	2450	5744	17480c	11736c	2.04c
	$W_{60}F_{75}$	1036	1728	600	2450	5814	14904d	9090d	1.56d
	$W_{60}F_{50}$	1036	1458	600	2450	5544	12692e	7148e	1.29e
2016	$W_{100}F_{100}$	1036	1998	1000	2450	6484	21210a	14726a	2.27b
	$W_{80}F_{75}$	1036	1728	800	2450	6014	21033a	15019a	2.50a
	$W_{80}F_{50}$	1036	1458	800	2450	5744	17095b	11351b	1.98c
	$W_{60}F_{75}$	1036	1728	600	2450	5814	14291c	8477c	1.46d
	$W_{60}F_{50}$	1036	1458	600	2450	5544	11868d	6324d	1.14e

*Other costs included the cost associated with field plots, sowing, fertilizer application, irrigation application, pesticides, herbicide, and harvest at maturity. Abbreviations for treatment names are similar to those described in Fig. 2.

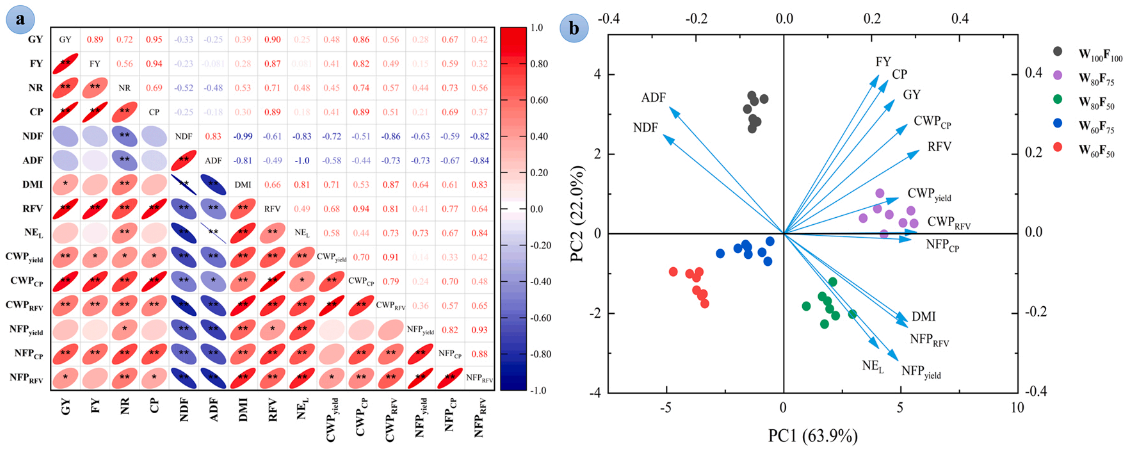

Fig. 10. Correlation analysis for yield, net returns, forage nutritive value, and resource use efficiency indices of spring wheat (a). * and * *represent the significant differences at $P < 0.05$ and $P < 0.01$, respectively. The biplot graph from the principal component analysis (PCA) shows the relationship between measured variables and represents the separation of all treatments among the first two principal components, i.e., PC1 and PC2 (b). The variables included GY, grain yield; FY, forage yield; NR, net returns; CP, crude protein; NDF, neutral detergent fiber; ADF, acid detergent fiber; DMI, dry matter intake; RFV, relative feed value; NE_L, net energy for lactation; CWP, crop water productivity; and NFP, nitrogen fertilizer productivity. Abbreviations for treatment names are similar to those described in Fig. 2.

yield stability of crops (Chen et al., 2018; Gonzalez-Dugo et al., 2010; Ma et al., 2022). An adequate N supply is essential for utilizing the benefits of additional water, and reciprocally, an adequate water supply is required to utilize the benefits of N fertilizers (Kunrath et al., 2018; Wang et al., 2015). In general, reducing irrigation and/or N levels are believed to decrease crop yield (Jiang et al., 2013; Zhong et al., 2021). However, a moderate decrease in irrigation and N ($W_{80}F_{75}$) in the present study did not show any detrimental effects on DM and grain yield of spring wheat. These results partly support our hypothesis that the farmers' practiced irrigation and N application in the arid region of northwest China are excessive, and a rational decrease would not limit the crop water and nutrient demands required for optimal growth and productivity of spring wheat. Consistent with these results, previous studies have shown that appropriate irrigation and N amounts in water-deficit arid regions were more beneficial than their excessive applications (Li et al., 2022; Si et al., 2020; Yang et al., 2017; Zhang et al., 2006). A higher grain yield with $W_{80}F_{75}$ treatment is endorsed to the synergistic effects of optimum water and N on carbon assimilation and grain-filling efficiency (Guo et al., 2014; Si et al., 2020; Wang et al., 2014). Previously, Teixeira et al. (2014) and Wang et al. (2015) reported that rational irrigation and fertilizer ensure optimal resource acquisition and improve photosynthetic and carboxylation efficiency, resulting in greater crop yields. In addition, both DM and grain yield were markedly decreased with severe deficit irrigation and N treatments ($W_{60}F_{75}$ and $W_{60}F_{50}$). This is because of an increase in the osmotic pressure of the rhizosphere, which causes plants to acquire more energy for maintaining cell water contents, decreasing the plant's ability to transpire and absorb nutrients (Gonzalez-Dugo et al., 2010; Jalil Sheshbahreh et al., 2019). Moreover, dry soil limits the mineralization and transport of N from bulk soil to the rhizosphere, which reduces N availability to plants (Kunrath et al., 2018). Nitrogen limitation, on the other hand, reduces leaf and stem expansion (Islam et al., 2012; Si et al., 2020; Teixeira et al., 2014) and resource capture (radiation interception and N uptake), accelerates the onset of senescence and chlorophyll degradation (Kamran et al., 2020; Kaplan et al., 2019; Wang et al., 2013), which causes a reduction in assimilates and the grain sink capacity (Çakir, 2004; Srivastava et al., 2018; Wang et al., 2014). Also, the irrigation and N limitations exacerbate premature kernel abortion (Çakir, 2004; Gao et al., 2017), which could be another possible reason for lower grain yield with $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments.

4.2. Impacts of reduced irrigation and N treatments on the nutritive quality

In this study, crude protein contents and RFV decreased while NDF and ADF contents increased with the advancement of the spring wheat growing period. Such trends are distinctive in crops, ascribed to a decrease in leaf area with the onset of leaf senescence (Kamran et al., 2020; Liu et al., 2021; Ronga et al., 2020) and an increase in stem rigidity owing to greater accumulation of fiber contents (Kamran et al., 2018a, 2018b; Zhang et al., 2018), leading to a reduction of nutritive quality. Among treatments, $W_{80}F_{75}$ markedly improved the nutritive quality, evidenced by greater crude protein and RFV yield and lower ADF and NDF content compared to that of $W_{100}F_{100}$ treatment. Consistently, previous studies have also reported high forage quality of different crops with optimized irrigation and fertilization than in well-irrigated and high-fertilized conditions (Kaplan et al., 2019; Ma et al., 2022; Rostamza et al., 2011). Previously, Kamran et al. (2022) and Marsalis et al. (2010) showed a negative correlation between forage quality with irrigation and N fertilizer rates. Excessive irrigation and fertilization often result in lower forage quality because of their interactive effects strengthening the cell wall component and fiber contents (Kaplan et al., 2019), which was also confirmed by greater NDF and ADF contents in our present study. Islam et al. (2012) reported high NDF and ADF ratios and low protein in stalks compared to leaves. Since high irrigation and fertilization levels increase the stem ratios, thereby regulating the fiber concentration (Kaplan et al., 2019; Rostamza et al., 2011). On the other hand, appropriate irrigation and N maintain a high leaf-to-stem ratio and delay maturity, contributing to high crude protein yield and forage quality (Liu et al., 2021; Rostamza et al., 2011). Furthermore, N being an essential element is crucial for the synthesis of chlorophyll, enzymes, and proteins, which regulate almost all metabolic activities of plants (Islam et al., 2012). Therefore, adequate water and N with $W_{80}F_{75}$ treatment will increase plant N uptake, thereby enhancing the synthesis of amino acid and protein contents, which is in close agreement with findings from previous studies (Kaplan et al., 2019; Tang et al., 2018). In addition, quality traits such as DDM, DMI, TDN, and NE_L are highly desirable because of their advantages in boosting animals' ability to absorb the forage nutrients (Lithourgidis et al., 2006; Tang et al., 2018). Compared to both conventional and severe deficit irrigation and N treatments, the $W_{80}F_{75}$ treatment noticeably improved all of the above-mentioned quality components, attributed to the positive effects of $W_{80}F_{75}$ on lowering the undesirable NDF and ADF contents. The crude protein, TDN, and NE_L for wheat in the present study were comparable to previously reported values for corn (Marsalis et al., 2010), pearl millet (Rostamza et al., 2011), and sorghum (Jahanzad et al., 2013; Tang et al., 2018), supporting the importance of DM (straw) yield of spring wheat as a potential feed source for livestock development.

4.3. Impacts of reduced irrigation and N treatments on resource use efficiency

In recent years, studies are increasingly focusing on maintaining the best resource use efficiency and economic productivity with lower inputs to ensure sustainable productivity in arid regions (Fang and Su, 2019; Kheir et al., 2022; Li et al., 2022; Zhang et al., 2006). In the present study, the CWP_{yield} and NFP_{yield} were greater for the $W_{80}F_{75}$ treatment compared to other treatments. This implies that appropriate irrigation and fertilization simultaneously improve the effectiveness of water and nutrition, and such complementary effects could be referred to as synergistic functions (Wang et al., 2016). Because matching fertilizer with irrigation amount improves the crop nutrients absorption and utilization, effectively improving productivity and resource use efficiency (Dai et al., 2019; Jalil Sheshbahreh et al., 2019). Similar results were achieved by Rostamza et al. (2011), Zhang et al., 2020, and Li et al. (2022), who observed that instead of excessive applications, irrigation and N based on crop demand contributed to enhanced resource use efficiencies. In justification, adequate irrigation and N levels increase leaf area index, which enhances light and CO_2 capture and regulates photoassimilates distribution in the plant's above ground parts, translating into higher resource use efficiency (Fang and Su, 2019; Kaplan et al., 2019; Kunrath et al., 2018; Ma et al., 2022; Wang et al., 2016). Since the DM and grain yields in our study were comparable for both $W_{100}F_{100}$ and $W_{80}F_{75}$ treatments, a greater CWP_{yield} and NFP_{yield} obtained for the $W_{80}F_{75}$ treatment is attributed to the lower degree of water and N rates applied. On the other hand, the irrigation and N amounts for $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments were further reduced, but the CWP_{yield} and NFP_{yield} were significantly lower than that for $W_{80}F_{75}$ treatment. This is because the $W_{60}F_{75}$ and $W_{60}F_{50}$ treatments failed to maintain yield benefit, and the DM and grain yield significantly declined compared to the $W_{80}F_{75}$ treatment. Extremely deficit irrigation and N application are linked to poor biomass accumulation and yields by limiting resource capture (Teixeira et al., 2014), adversely affecting photosynthetic capacity (Wang et al., 2010, 2015), reducing carbon assimilation and grain-filling characteristics (Wang et al., 2014, 2013), which consequently decrease the resource use efficiencies. Besides, the previously reported values for crop water productivity (Chen et al., 2018; Lai et al., 2022; Wang et al., 2016; Zhang et al., 2006) and N fertilizer productivity (Chen et al., 2018; Si et al., 2020; Tan et al., 2017) for wheat in north China were lower than those observed in our present study. In explanation, previous studies used wheat solely for grain purpose, while we used wheat for dual purpose and have considered both grain and DM yield for calculating the crop water and fertilizer productivity factor.

Additionally, water and fertilizer productivity based on the nutritive attributes can be used as an important criterion for assessing the efficacy of different agronomic managements in forage crops (Zhang et al., 2018). Our results showed that moderately reduced irrigation and N treatments enhanced the CWP_{CP}, CWP_{RFV}, NFP_{CP}, and NFP_{RFV} of wheat DM yield over that of conventional management. The highest CWP_{CP} and CWP_{RFV} values were achieved for the $W_{80}F_{75}$ treatment, while the greatest NFP_{CP} and NFP_{RFV} values were achieved for $W_{80}F_{50}$ and $W_{80}F_{75}$ treatments in both years. The higher values with $W_{80}F_{50}$ and $W_{80}F_{75}$ treatments are attributed to a greater leaf-to-stem ratio and delayed crop maturity with appropriate irrigation and N application (Islam et al., 2012; Rostamza et al., 2011; Tang et al., 2018), which improved the forage nutritive quality and hence, the CWP and NFP for crude protein and RFV. The CWP and NFP for crude protein ranged from 0.47 to 1.19 kg mm^{-1} and 1.57–3.65 kg kg^{-1}, while that for RFV ranged from 10.40 to 21.27 kg mm^{-1} and 32.70–71.37 kg kg^{-1} in 2015 and 2016, respectively. Unfortunately, no previous studies have calculated similar indices or reported data to compare these values with results from elsewhere. Future studies should therefore focus on integrating forage quality attributes along with biomass and grain yield while calculating CWP and NFP for dual-purpose crops under different agronomic management, which would provide a better understanding of their use as forage crop.

4.4. Impacts of reduced irrigation and N treatments on the economic benefit

Intensive agronomic practices are often believed to boost crop yields and hence, economic benefits (Wang et al., 2018). In the present study, $W_{80}F_{75}$ presented the greatest net returns of spring wheat compared to $W_{1000}F_{100}$, signifying that intensive practices do not necessarily improve the economic benefits, which is in agreement with the findings of a previous study (Li et al., 2022). A higher net return and benefit-cost ratio with $W_{80}F_{75}$ treatment are attributed to (i) reduced input by decreasing irrigation and N application rates and (ii) higher output due to relatively stable yields. Similar results of higher yield and economic benefits with appropriate fertilization and/or irrigation were reported for maize (Wang et al., 2018; Yan et al., 2021), wheat (Li et al., 2019), and alfalfa (Zhang et al., 2020). In this study, the total output (grain + DM yield) with $W_{100}F_{100}$ treatment failed to compensate for the high input costs, lowering the net returns and benefits cost ratio. On the other hand, very low irrigation and N treatments ($W_{60}F_{75}$ and $W_{60}F_{50}$) significantly reduced the input costs but were still not economically beneficial because of resulting in significant yield losses. The $W_{80}F_{75}$ treatment increased the net returns by 2107 RMB ha^{-1} and 776 RMB ha^{-1} (15.2% and 5.4%), and the benefit-cost ratio by 0.54 and 0.30 (24.0 % and 13.5 %) compared with the $W_{100}F_{100}$ treatment. In 2016, the economic benefit and benefit-cost ratio for $W_{80}F_{75}$ treatment were lower than that in 2015 because precipitation was relatively lower, which increased the crop water demand and reduced the effectiveness of $W_{80}F_{75}$ on increasing yield benefit compared to $W_{100}F_{100}$. These findings suggest that the effects of reduced irrigation and fertilization are associated with precipitation, whereas light precipitation could reduce the effectiveness of deficit irrigation and fertilization. Overall, $W_{80}F_{75}$ maintained significantly higher net returns, even in the year of low precipitation, suggesting that the application of 600 mm irrigation and 225 kg N ha^{-1} can be used for wheat production in the arid region of northwest China without yield losses.

5. Conclusions

Present findings illustrated significant prospects for optimizing the irrigation and N fertilizer amounts for spring wheat in the arid region of northwest China. A moderate decrease in irrigation and N ($W_{80}F_{75}$) improved the resource use efficiencies and forage nutritive quality without compromising the grain yield of spring wheat, compared to conventional management ($W_{100}F_{100}$). In addition, the $W_{80}F_{75}$ treatment improved the net returns and the benefit-cost ratio over that of $W_{100}F_{100}$ in both wheat growing seasons. Except for $W_{80}F_{75}$, other deficit irrigation and N treatments presented detrimental effects by reducing grain yield, DM yield, forage nutritive values, resource use efficiency, and economic benefits compared to $W_{100}F_{100}$. Thus, the application of 600 mm irrigation and 225 kg N ha^{-1} can be used as an effective treatment for obtaining optimum yields and is more valuable when considering the forage nutritive values and net income benefit for spring wheat production in the arid region of Northwest China and areas with similar climatic conditions. Nevertheless, the climatic conditions, particularly precipitation amounts and soil properties, may vary between different arid regions, and the optimized irrigation and N treatment in this study may not be favorable to optimal yields and economic benefits in other arid regions. Therefore, future multi-locational studies are suggested to clarify how climatic variations in different arid regions would influence the potential effects of deficit water and fertilization on spring wheat production, forage nutritive quality, and economic benefit. More specific guidelines will help farmers to reduce irrigation and fertilizer inputs while maximizing economic profitability in arid agricultural production systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA2010010203), the Program of National Science and Technology Assistance (KY202002011), the Program for Innovative Research Team of Ministry of Education (IRT_17R50), the Lanzhou City's Scientific Research Funding Subsidy to Lanzhou University, and the Research Fund for International Young Scientists, National Natural Science Foundation of China (RFIS-32150410361).

References

Agnew, J., Sprenger, C., Kendel, Z., Jefferson, P.G., Hnatowich, G., Weber-Enns, J., Shaw, L., Slowski, J., Hall, M., Larson, K., 2022. The effect of nitrogen fertility rate and seeding rate on yield, nutritive value and economics of forage corn in a low corn heat unit region of Western Canada. Field Crops Res. 283, 108520.

Blümmel, M., Updahyay, S.R., Gautam, N., Barma, N.C.D., Abdul Hakim, M., Hussain, M., Yaqub Mujahid, M., Chatrath, R., Sohu, V.S., Mavi, G., Mishra, V.K., Kalappanavar, I.K., Naik, R., Biradar, S., Prasad, S.V.S., Singh, R.P., Joshi, A.K., 2019. Comparative assessment of food-fodder traits in a wide range of wheat germplasm for diverse biophysical target domains in South Asia. Field Crops Res. 236, 68–74.

Çakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89, 1–16.

Chen, J., Wang, P., Ma, Z., Lyu, X., Liu, T.T., Siddique, K.H.M., 2018. Optimum water and nitrogen supply regulates root distribution and produces high grain yields in spring wheat (*Triticum aestivum* L.) under permanent raised bed tillage in arid northwest China. Soil Tillage Res. 181, 117–126.

Cui, Z., Zhang, F., Chen, X., Dou, Z., Li, J., 2010. In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context. Field Crops Res. 116, 140–146.

Dai, Z., Fei, L., Huang, D., Zeng, J., Chen, L., Cai, Y., 2019. Coupling effects of irrigation and nitrogen levels on yield, water and nitrogen use efficiency of surge-root irrigated jujube in a semiarid region. Agric. Water Manag. 213, 146–154.

Ding, Z., Ali, E.F., Elmahdy, A.M., Ragab, K.E., Seleiman, M.F., Kheir, A.M.S., 2021. Modeling the combined impacts of deficit irrigation, rising temperature and compost application on wheat yield and water productivity. Agric. Water Manag. 244, 106626.

Fang, J., Su, Y., 2019. Effects of soils and irrigation volume on maize yield, irrigation water productivity, and nitrogen uptake. Sci. Rep. 9, 7740.

Gao, Z., Liang, X.G., Lin, S., Zhao, X., Zhang, L., Zhou, L.L., Shen, S., Zhou, S.L., 2017. Supplemental irrigation at tasseling optimizes water and nitrogen distribution for high-yield production in spring maize. Field Crops Res. 209, 120–128.

Gonzalez-Dugo, V., Durand, J.L., Gastal, F., 2010. Water deficit and nitrogen nutrition of crops. A review. Agron. Sustain. Dev. 30, 529–544.

Guo, Z., Yu, Z., Wang, D., Shi, Y., Zhang, Y., 2014. Photosynthesis and winter wheat yield responses to supplemental irrigation based on measurement of water content in various soil layers. Field Crops Res. 166, 102–111.

Hou, F., Jia, Q., Lou, S., Yang, C., Ning, J., Li, L., Fan, Q., 2021. Grassland Agriculture In China-A Review. Frontiers of Agricultural Science and Engineering 8, 35–44.

Hou, H., Yang, Y., Han, Z., Cai, H., Li, Z., 2019. Deficit irrigation effectively reduces soil carbon dioxide emissions from wheat fields in Northwest China. J. Sci. Food Agric. 99, 5401–5408.

Islam, M.R., Garcia, S.C., Horadagoda, A., 2012. Effects of irrigation and rates and timing of nitrogen fertilizer on dry matter yield, proportions of plant fractions of maize and nutritive value and in vitro gas production characteristics of whole crop maize silage. Anim. Feed Sci. Technol. 172, 125–135.

Jahanzad, E., Jorat, M., Moghadam, H., Sadeghpour, A., Chaichi, M.R., Dashtaki, M., 2013. Response of a new and a commonly grown forage sorghum cultivar to limited irrigation and planting density. Agric. Water Manag. 117, 62–69.

Jalil Sheshbahreh, M., Movahhedi Dehnavi, M., Salehi, A., Bahreininejad, B., 2019. Effect of irrigation regimes and nitrogen sources on biomass production, water and nitrogen use efficiency and nutrients uptake in coneflower (*Echinacea purpurea* L.). Agric. Water Manag. 213, 358–367.

Jiang, J., Huo, Z.L., Feng, S.Y., Kang, S.Z., Wang, F.X., Zhang, C.B., 2013. Effects of deficit irrigation with saline water on spring wheat growth and yield in arid Northwest China. J. Arid Land 5, 143–154.

Kamran, M., Ahmad, I., Wang, H., Wu, X., Xu, J., Liu, T., Ding, R., Han, Q., 2018a. Mepiquat chloride application increases lodging resistance of maize by enhancing stem physical strength and lignin biosynthesis. Field Crops Res. 224, 148–159.

Kamran, M., Ahmad, I., Wu, X., Liu, T., Ding, R., Han, Q., 2018b. Application of paclobutrazol: a strategy for inducing lodging resistance of wheat through mediation of plant height, stem physical strength, and lignin biosynthesis. Environ. Sci. Pollut. Res. 25, 29366–29378.

Kamran, M., Wennan, S., Ahmad, I., Xiangping, M., Wenwen, C., Xudong, Z., Siwei, M., Khan, A., Qingfang, H., Tiening, L., 2018c. Application of paclobutrazol affect maize grain yield by regulating root morphological and physiological characteristics under a semi-arid region. Sci. Rep. 8, 1–15.

Kamran, M., Ahmad, S., Ahmad, I., Hussain, I., Meng, X., Zhang, X., Javed, T., Ullah, M., Ding, R., Xu, P., Gu, W., Han, Q., 2020. Paclobutrazol application favors yield improvement of maize under semiarid regions by delaying leaf senescence and regulating photosynthetic capacity and antioxidant system during grain-filling stage. Agronomy 10, 187.

Kamran, M., Yan, Z., Jia, Q., Chang, S., Ahmad, I., Ghani, M.U., Hou, F., 2022. Irrigation and nitrogen fertilization influence on alfalfa yield, nutritive value, and resource use efficiency in an arid environment. Field Crops Res. 284, 108587.

Kaplan, M., Kara, K., Unlukara, A., Kale, H., Buyukkilic Beyzi, S., Varol, I.S., Kizilsimsek, M., Kamalak, A., 2019. Water deficit and nitrogen affects yield and feed value of sorghum sudangrass silage. Agric. Water Manag 218, 30–36.

Kheir, A.M.S., Alrajhi, A.A., Ghoneim, A.M., Ali, E.F., Magrashi, A., Zoghdan, M.G., Abdelkhalik, S.A.M., Fahmy, A.E., Elnashar, A., 2021. Modeling deficit irrigation-based evapotranspiration optimizes wheat yield and water productivity in arid regions. Agric. Water Manag. 256, 107122.

Kheir, A.M.S., Hoogenboom, G., Ammar, K.A., Ahmed, M., Feike, T., Elnashar, A., Liu, B., Ding, Z., Asseng, S., 2022. Minimizing trade-offs between wheat yield and resource-use efficiency in the Nile Delta – a multi-model analysis. Field Crops Res. 287, 108638.

Kunrath, T.R., Lemaire, G., Sadras, V.O., Gastal, F., 2018. Water use efficiency in perennial forage species: interactions between nitrogen nutrition and water deficit. Field Crops Res. 222, 1–11.

Lai, X., Yang, X., Wang, Z., Shen, Y., Ma, L., 2022. Productivity and water use in forage-winter wheat cropping systems across variable precipitation gradients on the Loess Plateau of China. Agric. Water Manag. 259, 107250.

Li, C., Wang, C., Wen, X., Qin, X., Liu, Y., Han, J., Li, Y., Liao, Y., Wu, W., 2017. Ridge–furrow with plastic film mulching practice improves maize productivity and resource use efficiency under the wheat–maize double–cropping system in dry semi–humid areas. Field Crops Res. 203, 201–211.

Li, C., Feng, H., Luo, X., Li, Y., Wang, N., Wu, W., Zhang, T., Dong, Q., Siddique, K.H.M., 2022. Limited irrigation and fertilization in sand-layered soil increases nitrogen use efficiency and economic benefits under film mulched ridge-furrow irrigation in arid areas. Agric. Water Manag. 262, 107406.

Li, W., Xiong, L., Wang, C., Liao, Y., Wu, W., 2019. Optimized ridge–furrow with plastic film mulching system to use precipitation efficiently for winter wheat production in dry semi–humid areas. Agric. Water Manag. 218, 211–221.

Lithourgidis, A.S., Vasilakoglou, I.B., Dhima, K.V., Dordas, C.A., Yiakoulaki, M.D., 2006. Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. Field Crop Res. 99, 106–113.

Liu, M., Wang, Z., Mu, L., Xu, R., Yang, H., 2021. Effect of regulated deficit irrigation on alfalfa performance under two irrigation systems in the inland arid area of midwestern China. Agric. Water Manag. 248, 106764.

Lu, D., Lu, F., Yan, P., Cui, Z., Chen, X., 2014. Elucidating population establishment associated with N management and cultivars for wheat production in China. Field Crops Res 163, 81–89.

Ma, Q., Zhang, X., Wu, Y., Yang, H., Wang, Z., 2022. Optimizing water and nitrogen strategies to improve forage oat yield and quality on the Tibetan Plateau using APSIM. Agronomy 12, 933.

Marsalis, M.A., Angadi, S.V., Contreras-Govea, F.E., 2010. Dry matter yield and nutritive value of corn, forage sorghum, and BMR forage sorghum at different plant populations and nitrogen rates. Field Crops Res. 116, 52–57.

Ronga, D., Dal Prà, A., Immovilli, A., Ruozzi, F., Davolio, R., Pacchioli, M.T., 2020. Effects of harvest time on the yield and quality of winter wheat hay produced in Northern Italy. Agronomy 10, 917.

Rostamza, M., Chaichi, M.-R., Jahansouz, M.-R., Alimadadi, A., 2011. Forage quality, water use and nitrogen utilization efficiencies of pearl millet (*Pennisetum americanum* L.) grown under different soil moisture and nitrogen levels. Agric. Water Manag. 98, 1607–1614.

Sharma, N., Schneider-Canny, R., Chekhovskiy, K., Kwon, S., Saha, M.C., 2020. Opportunities for Increased nitrogen use efficiency in wheat for forage use. Plants 9, 1738.

Si, Z., Zain, M., Mehmood, F., Wang, G., Gao, Y., Duan, A., 2020. Effects of nitrogen application rate and irrigation regime on growth, yield, and water-nitrogen use efficiency of drip-irrigated winter wheat in the North China Plain. Agric. Water Manag 231, 106002.

Srivastava, R.K., Panda, R.K., Chakraborty, A., Halder, D., 2018. Enhancing grain yield, biomass and nitrogen use efficiency of maize by varying sowing dates and nitrogen rate under rainfed and irrigated conditions. Field Crops Res. 221, 339–349.

Tan, Y., Xu, C., Liu, D., Wu, W., Lal, R., Meng, F., 2017. Effects of optimized N fertilization on greenhouse gas emission and crop production in the North China Plain. Field Crops Res. 205, 135–146.

Tang, C., Yang, X., Chen, X., Ameen, A., Xie, G., 2018. Sorghum biomass and quality and soil nitrogen balance response to nitrogen rate on semiarid marginal land. Field Crops Res. 215, 12–22.

Teixeira, E.I., George, M., Herreman, T., Brown, H., Fletcher, A., Chakwizira, E., de Ruiter, J., Maley, S., Noble, A., 2014. The impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation, water and nitrogen. Field Crops Res. 168, 109–118.

Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583–3597.

Wang, B., Zhang, Y., Hao, B., Xu, X., Zhao, Z., Wang, Z., Xue, Q., 2016. Grain yield and water use efficiency in extremely-late sown winter wheat cultivars under two irrigation regimes in the North China plain. PLoS One 11, e0153695.

Wang, C., Liu, W., Li, Q., Ma, D., Lu, H., Feng, W., Xie, Y., Zhu, Y., Guo, T., 2014. Effects of different irrigation and nitrogen regimes on root growth and its correlation with above-ground plant parts in high-yielding wheat under field conditions. Field Crops Res. 165, 138–149.

Wang, D., Yu, Z., White, P.J., 2013. The effect of supplemental irrigation after jointing on leaf senescence and grain filling in wheat. Field Crops Res. 151, 35–44.

Wang, D., Li, G., Mo, Y., Cai, M., Bian, X., 2018. Evaluation of optimal nitrogen rate for corn production under mulched drip fertigation and economic benefits. Field Crops Res. 216, 225–233.

Wang, Q., Li, F., Zhao, L., Zhang, E., Shi, S., Zhao, W., Song, W., Vance, M.M., 2010. Effects of irrigation and nitrogen application rates on nitrate nitrogen distribution and fertilizer nitrogen loss, wheat yield and nitrogen uptake on a recently reclaimed sandy farmland. Plant Soil 337, 325–339.

Wang, Q., Li, F., Zhang, E., Li, G., Vance, M., 2012. The effects of irrigation and nitrogen application rates on yield of spring wheat (longfu-920), and water use efficiency and nitrate nitrogen accumulation in soil. Aust. J. Crop Sci. 6, 662–672.

Wang, X., Shi, Y., Guo, Z., Zhang, Y., Yu, Z., 2015. Water use and soil nitrate nitrogen changes under supplemental irrigation with nitrogen application rate in wheat field. Field Crops Res. 183, 117–125.

Wang, Z., Zhang, W., Beebout, S.S., Zhang, H., Liu, L., Yang, J., Zhang, J., 2016. Grain yield, water and nitrogen use efficiencies of rice as influenced by irrigation regimes and their interaction with nitrogen rates. Field Crops Res. 193, 54–69.

Yan, F., Zhang, F., Fan, X., Fan, J., Wang, Y., Zou, H., Wang, H., Li, G., 2021. Determining irrigation amount and fertilization rate to simultaneously optimize grain yield, grain nitrogen accumulation and economic benefit of drip-fertigated spring maize in northwest China. Agric. Water Manag. 243, 106440.

Yang, X., Lu, Y., Ding, Y., Yin, X., Raza, S., Tong, Y., 2017. Optimising nitrogen fertilisation: a key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). Field Crops Res. 206, 1–10.

Zhang, B., Li, F.-M., Huang, G., Cheng, Z.-Y., Zhang, Y., 2006. Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. Agric. Water Manag. 79, 28–42.

Zhang, J., Pang, X.P., Wang, Q., Yang, D., Qiao, F.Y., Zhi, D.G., Guo, Z.G., 2020. PRDI can maintain aboveground biomass and increase economic benefits in alfalfa through regulating N:P ratios in roots and leaves. Field Crops Res 253, 107821.

Zhang, Q., Bell, L.W., Shen, Y., Whish, J.P.M., 2018. Indices of forage nutritional yield and water use efficiency amongst spring-sown annual forage crops in north-west China. Eur. J. Agron. 93, 1–10.

Zhang, X., Xiao, G., Li, H., Wang, L., Wu, S., Wu, W., Meng, F., 2020. Mitigation of greenhouse gas emissions through optimized irrigation and nitrogen fertilization in intensively managed wheat–maize production. Sci. Rep. 10, 5907.

Zhang, X., Xiao, G., Bol, R., Wang, L., Zhuge, Y., Wu, W., Li, H., Meng, F., 2021. Influences of irrigation and fertilization on soil N cycle and losses from wheat–maize cropping system in northern China. Environ. Pollut. 278, 116852.

Zhong, Y., Li, J., Xiong, H., 2021. Effect of deficit irrigation on soil CO_2 and N_2O emissions and winter wheat yield. J. Clean. Prod. 279, 123718.