

Article

Effects of Water–Nitrogen Interaction on Sandy Soil, Physiology, and Morphology of Tall Fescue (*Festuca arundinacea* Schreb) Turf

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Abstract: The soil water and nitrogen (N) levels are the important factors affecting turfgrass growth. However, the impact of the water–N interaction on tall fescue (*Festuca arundinacea* Schreb) in terms of the N metabolism and plant morphology remains uncertain. Therefore, the objective of this study was to investigate the impacts of different N and water levels on the physiological and morphological responses of tall fescue. The experiment was designed with N (N₀, N₂, and N₄ representing N application rates of 0, 2, and 4 g m^{−2}, respectively) and irrigation [W₁, W₂, W₃, W₄, and W₅ representing field water capacities (FWCs) of 90~100%, 75~85%, 60~70%, 45~55%, and 30~40%, respectively] treatments, and the relevant indexes of the soil water content and soil NH₄⁺–N and NO₃[−]–N levels as well as the physiology and morphology of the tall fescue were determined. The results demonstrated significant changes in the contents of soil water (SWC) and N and the physiological and morphological indexes, except for the enzymes related to N metabolism, including nitrite reductase (NiR), glutamate dehydrogenase (GDH), and glutamate synthetase (GOGAT). The water stress significantly enhanced the water and N use efficiencies (WUE and NUE), except the NUE in the W₅ treatment. The N stress significantly influenced the SWC, soil NO₃[−]–N content, and physiological and morphological indexes, excluding malondialdehyde, NiR, GOGAT, and above- (AGB) and below-ground biomass, resulting in the increased WUE and NUE. The application of a low N rate effectively alleviated the detrimental impacts of water stress on the SWC and glutamine synthetase activity. In conclusion, W₂ and N₂ are deemed more appropriate treatments for the low-maintenance measures of tall fescue turf. Among all the treatments, N₂W₂ is recommended as the optimal water–N interaction treatment due to its ability to conserve resources while still ensuring high turf quality.

Keywords: water stress; nitrogen fertilizer; turf quality; low maintenance



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1. Introduction

The maintenance costs in modern stadiums have always been a hot topic [1]. Sports venues with natural turfs often need to consider optimizing the investment in their turf maintenance processes while ensuring the necessary conditions for hosting events, thereby achieving efficient turf management [2]. Therefore, the turf industry needs scientists and managers to devise strategies that effectively minimize the inputs for turf management while upholding an optimal level of quality [3].

The reduction in irrigation is a pivotal measure in low-conservation management [2]. Turfgrasses possess the ability to adapt to adverse growing conditions by efficiently utilizing limited water during periods of water shortage, and this compensatory effect is considered a self-protective mechanism [4]. Implementing an appropriate water stress regime enhances stress tolerance by upregulating proline (Pro) accumulation [5], and the augmentation of the Pro levels leads to an increase in the water use efficiency (WUE) [6]. However, excessive

water stress in the soil could contribute to the loss of effective nutrient ions, such as NH_4^+ , NO_3^{2-} , phosphorus, and potassium [7–9]. As the soil water content increases, plant roots are less compelled to grow deeper in search of moisture, thereby constraining root development and subsequently diminishing nutrient uptake [10]. Additionally, excessive water also creates an anoxic environment and leads to leaf wilting and a reduction in the above-ground biomass (AGB) [11], thereby compromising the turf quality [7–9,12]. Therefore, optimal irrigation facilitates soil nutrient and water utilization, promoting physiology activity and the dry matter (DM) and turf quality. Clarifying the optimal irrigation can provide a theoretical basis for low-maintenance lawns.

In addition to implementing irrigation measures, the application of fertilizers can also be restricted to limit the maintenance input. Nitrogen (N) is a crucial macronutrient essential for plant growth and development, playing a pivotal role as a primary limiting factor in the context of turfgrass [3]. The element N is also a crucial constituent of chlorophyll (Chl) and numerous metabolites, proteins, and nucleic acids that have been implicated in enhancing plant stress tolerance [13]. An adequate N supply enhances the turf color (TC), growth rate (GR), and stress tolerance of turfgrass [14]. Under high N levels, despite an increase in the root DM, there is a reduction in the turfgrass root length, thereby constraining the uptake of N from the soil by the roots [15]. Nitrogen uptake by tall fescue (*Festuca arundinacea* Schreb) exhibits a significant increase under low- and medium-N treatments, in contrast to high-N treatment [16]. The nitrogen uptake use efficiency (NUE) of turfgrasses can be enhanced in response to the reduced N availability [17]. The primary objective of N application is to sustain a dense and vigorous turf [3]. However, the results of Zere and Bilgili [18] demonstrate that the application of 3 g m^{-2} of fertilizer maintained a superior quality in warm-season turfgrasses compared to the application of 4 g m^{-2} . Therefore, the judicious application of low-N fertilizer presents a viable approach to the low-maintenance management of turfgrass [2].

Nitrate N (NO_3^- -N) and ammonium N (NH_4^+ -N) are the predominant N forms assimilated by plant roots from the soil [15,19]. The conversion of NO_3^- to NH_4^+ is facilitated by the nitrate reductase (NR) and nitrite reductase (NiR) [20]. NH_4^+ is ultimately bound to glutamate via the glutamine synthetase (GS) and glutamate synthetase (GOGAT) pathway [21]. Under N stress conditions, when the GS and GOGAT cycling pathway is inhibited, NH_4^+ is directly assimilated into glutamate through the synergistic mechanism of glutamate dehydrogenase (GDH), which subsequently participates in the biosynthesis of other amino acids and proteins [22]. Under low-N conditions, there could be an observed increase in the activities of GS and GDH in leaves [23]. This augmentation enhances the plant N metabolism and facilitates the assimilation of NH_4^+ into glutamate [21]. Furthermore, Li et al. [3] determined that glutamate plays a crucial role in Chl synthesis, particularly in the pathway where N from protochlorophyllides (Pchlides) originates from glutamate. Pro serves as a versatile amino acid within plant cells, with alterations in its levels affecting protein synthesis [24]. Consequently, the N metabolism pathway contributes to plant growth and development while bolstering resistance mechanisms under unfavorable environmental conditions [25].

The potential synergy between irrigation and fertilization promoting turfgrass growth is worth exploring. Due to the stimulation of turfgrass growth by fertilizers, their irrigation often increases proportionally with the N application rate, which is because adequate fertilizer increases the growth rate of the plant, which, in turn, increases the plant's water requirement [26]. In contrast, the detrimental impact of drought stress on the quality of Kentucky Bluegrass (*Poa pratensis* Linn) in grassland can be mitigated through the judicious application of optimal N levels [27]. The results have already shown this compensatory effect [28], demonstrating that under equal fertilization conditions, the turf quality was superior at an irrigation rate of 1.00 Epan, while both irrigation rates of 0.25 Epan and 0.50 Epan maintained acceptable turf color levels. This suggested a potential substitutability between N and water resources, wherein adjusting the availability of one can alleviate the associated costs of the other [29–32]. In other words, turf grass can mitigate the adverse

effects of water stress or N stress by implementing moderately reduced management strategies for N fertilizer or irrigation, respectively, thereby achieving the objective of reducing the turf maintenance requirements [33].

Thus, soil water deficit indirectly affects the plant N uptake, thereby reducing the N status of the plants [34]. Optional irrigation increases the plant WUE and NUE compared to high irrigation and fertilization and improves the plant metabolic processes [35]. In fact, the “low-input” turfgrasses have shown potential in improving the turf quality. The majority of the existing studies primarily focus on investigating the individual effects of water or N management on turfgrass [18,23,36], or on comparing the growth differences between grass species under varying water and fertilizer treatments [37,38]. And most of the research mainly focuses on qualitative discussions, with a dearth of quantitative analysis. Tall fescue, being one of the most drought-tolerant and widely utilized cool-season turfgrasses in sports field turf, exhibits high resilience to water stress and N stress. However, the underlying mechanism by which low-maintenance practices impact tall fescue in terms of the soil nutrient cycling and plant physiology and morphology needs to be further studied. Additionally, the feasibility of implementing low-maintenance management strategies under conditions of water–N interaction has yet to be determined. Therefore, it is vital to elucidate the ability of tall fescue to ensure a good turf quality despite low-water and low-N interaction conditions, and to quantify the specific low-N and low-water conditions to provide specific measures for sports field turf maintenance.

We hypothesized (1) that the appropriate adjustment of N fertilizer could mitigate the detrimental effects of water stress on tall fescue growth; and (2) that the optimal integration of water and N management can achieve water conservation and fertilizer reduction while maintaining good-quality tall fescue turf. This study will provide a theoretical foundation for low-maintenance turf management.

2. Materials and Methods

2.1. Experimental Site and Design

The pot experiment was conducted from 28 June to 22 September 2023 at the National Garden Experimental Teaching Center of Beijing Forestry University (116°03′ N–116°23′ E) under controlled greenhouse conditions with average temperatures ranging from 15 to 27 °C and humidity within 65–85%. The experimental site is characterized by a temperate monsoon climate, featuring hot and rainy summers as well as cold and dry winters. The average annual temperature ranges from 8 to 21 °C, while the total rainfall was 209.8 mm. It should be noted that the selected experimental site was indoors.

Tall fescue seeds, provided by Beijing Zhengdao Company, Beijing, China, were planted directly in pots with an upper diameter of 24 cm, a bottom diameter of 19.5 cm, and a height of 26.5 cm. The sandy soil used in the experiment was sieved through a 2 mm mesh sieve (sandy particle size and nutrient analysis are shown in Tables 1 and 2). Each pot was filled with 15 kg of sieved sandy soil, which left 1 cm to the top of the pot. An amount of 2 g m^{−2} compound fertilizer (N:P₂O₅:K₂O = 15:5:25) was mixed with a 0.5 cm depth of surface sandy soil. The bottom of the pot was sealed with non-woven fabric to prevent any sand leakage. The seeds were hand-sown and evenly spread on the soil surface at a rate of 60 g m^{−2} (equivalent to 2.71 g pot^{−1}). Then, the tops of the pots were covered with non-woven fabric to minimize water loss.

Table 1. Particle size analysis of sand.

Aperture (mm)	>3.4	2–3.4	1–2	0.5–1	0.25–0.5	0.15–0.25	0.05–0.15	<0.05
Percentage (%)	—	—	0.33	16.4	73.9	8.70	0.33	0.33

Table 2. Nutrient composition in sand.

Soil pH	Electrical Conductivity (ms cm ⁻¹)	Organic Matter (g kg ⁻¹)	Total Nitrogen (g kg ⁻¹)	Available Phosphorus (mg kg ⁻¹)	Available Potassium (mg kg ⁻¹)
6.60	0.14	0.92	0.10	1.34	18.9

Prior to the establishment of tall fescue turfs, the implementation of conventional conservation measures was recommended. Pre-emergence irrigation should adhere to the principle of “seeing dry and seeing wet”, ensuring the timely rehydration of turfgrass when the surface layer of soil becomes dry in order to maintain a sufficient water supply before emergence. A sprinkler nozzle was used for irrigation from the top of the pot to prevent water loss by rapid decline (400–600 mL per irrigation). The frequency of irrigation was 1–2 times per day, with each irrigation session moistening the soil up to a depth of 10 cm. Following emergence, daily irrigation at approximately 8:30 a.m. was advised until mid-June, with additional watering required at 5:00 p.m. due to the high temperatures, which ensured that the soil remained moist until the experimental treatments started. Each irrigation ensured that the wet soil layer reached a minimum depth of 20 cm.

When the tall fescue reached a height of 6–8 cm, it was trimmed to a length of 3 cm. Following the initial mowing on 11 July, all the pots were thoroughly watered and allowed to sit for a duration of 12 h before the experimental treatment. The experimental treatments, including irrigation and N application, were conducted until both the tall fescue and topsoil had dried. The conventional irrigation treatment involved achieving a soil water content equivalent to the field water capacity (FWC; %) level after irrigation, which was determined to be 9.53% using the following calculation:

$$FWC = [(W_1 - W_2)/W_2] \times 100$$

where W_1 is the fresh soil sample weight, g; W_2 is the weight of the soil sample after drying, g.

The conventional N application treatment was 4 g m⁻² per application. Subsequently, five irrigation treatments (W_1 , W_2 , W_3 , W_4 , and W_5 : 100~90% FWC; 85~75% FWC; 70~60% FWC; 55~45% FWC; and 40~30% FWC, respectively) were implemented along with three fertilization treatments (N_0 , N_2 , and N_4 : 0, 2, and 4 g m⁻², respectively). The conventional irrigation (W_1) and N (N_4) applications served as control treatments (CK). A total of three replications were established comprising forty-five potted plants. The amount of each irrigation event was determined using the weighing method by calculating the weight difference between the soil weight at the target water content and that before irrigation. Urea was utilized as the source of N, which was applied on July 12, August 12, and September 12. Manual weeding was conducted throughout the whole process of the experiment. Due to prevailing high-temperature (the maximum temperature was above 30 °C) and -humidity (>80%) conditions, the broad-spectrum, turf-specific fungicides (50% Pyrimethanil fungicide) were sprayed weekly or biweekly from July to September.

2.2. Sampling and Measurements

2.2.1. Collection of Samples

The experimental samples were taken after 68 d of treatment. The leaves were trimmed to a length of 3 cm, placed in a Ziplock bag, and immediately transported back to the laboratory in an ice box. The leaf water content (LWC) and Chl levels were immediately determined, while the remaining samples were stored at −80 °C for the subsequent analysis of the Pro, malondialdehyde (MDA), leaf total N (LTN), and N metabolism-related enzymes. Following completion of the experiment, all the soil in each pot was drawn out, and fresh soil was used for testing the soil moisture content (SWC) and NO₃[−]-N and NH₄⁺-N contents. The AGB and below-ground biomass (BGB) indicators were obtained by separating the above-ground and below-ground parts.

2.2.2. Measurement Methods

The SWC and LWC were determined through the drying method at 105 °C and 80 °C, respectively. The soil NO_3^- -N or NH_4^+ -N contents were first sieved over 3 mm mesh, extracted with 2 mol L^{-1} KCl, and measured with a continuous-flow analyzer (AutoAnalyzer3, SEAL, Frankfurt, Germany) [39].

The microplate method (UV-2600, Shimadzu corporation, Kyoto, Japan) was employed to determine the levels of Chl, Pro, and MDA. The absorbance values were measured at 665 and 649 nm for Chl, at 520 nm for Pro, and at 600 and 532 nm for MDA [40].

The LTN was determined using the Kjeldahl N determination (K1100, Hanon Instrument, Jinan, China) on a dry sample weighing 0.1000–0.2000 g. The root total N (RTN) was determined using the flow analyzer (Vario MACRO cube, Hanau, Germany) on 25 mg of DM [41].

The activities of NR, NiR, GS, GOGAT, and GDH were determined following the instructions provided by the Suzhou Grace Biotechnology Co. kit instructions. The leaf tissue (0.1 g) was homogenized with liquid N (NR quartz sand for grinding) in 2 mL of enzyme extract. Subsequently, the absorbance at 530, 540, 540, 450, and 450 nm was measured using an enzyme meter (UV-2600, Shimadzu corporation, Japan) for the activities of NR, NiR, GS, GOGAT, and GDH, respectively [42].

The TC was assessed using the 9-point evaluation method of the National Turfgrass Evaluation Program (NTEP) [43]. The measurements of the normalized differential vegetation index (NDVI) were conducted on the turf using a TCM 500 (Spectrum TM, Beijing, China). To determine the plant height (PH), five plants per treatment were randomly selected and their heights were measured. Three replicates per treatment were averaged.

The water use efficiency (WUE , %) and N use efficiency (NUE , %) were determined using the following methodology [44]:

$$NUE = (m_1 - m_2) / M \times 100\%$$

where m_1 represents the accumulation of N in grass clippings resulting from N application treatments, g; m_2 denotes the N accumulation in grass clippings under the nitrogen-free treatment, g; M signifies the amount of N application, g;

$$WUE = B_1 / B_2 \times 100\%$$

where B_1 is the total biomass, g; B_2 is the total water consumption, mL.

2.3. Data Analysis

The data were subjected to an analysis of variance (ANOVA) using SPSS 27.0.1 software (SPSS Inc., Chicago, IL, USA). ANOVA was performed separately for the soil, physiological, and morphological variables to determine significant differences among the treatments. Statistical significance was considered at $p < 0.05$. The interactions among the soil, physiology, and morphology were established using Origin 2022 (EA, MicroCal, Northampton, MA, USA). The direct and indirect effects of the water and nitrogen treatments on the soil water content, NO_3^- -N or NH_4^+ -N, enzymes, physiological indices, and lawn quality were elucidated through linear regression path analysis. Notably, the enzymatic activity, physiological indices, and turf quality were integrated into a single dataset via principal component analysis.

3. Results

3.1. SWC, NO_3^- -N, and NH_4^+ -N Levels

The irrigation treatment had a significant impact ($p < 0.001$) on the SWC, NO_3^- -N, and NH_4^+ -N levels (Figure 1a–c). The SWC exhibited a significant decrease, and the NH_4^+ -N level initially increased but sharply decreased at W_3 with the increasing water stress (Figure 1a,b). Under the N_0 treatment, the NO_3^- -N content was highest in W_1 , while it was greater in the W_4 treatment than that in the W_2 treatment, and no significant changes were observed

in the other treatments (Figure 1c). The NO_3^- -N content exhibited a decrease in the W_1 and W_2 treatments, an increase in the W_3 treatment, and a decrease in the W_4 treatment compared to the W_3 treatment under both the N_2 and N_4 conditions (Figure 1c).

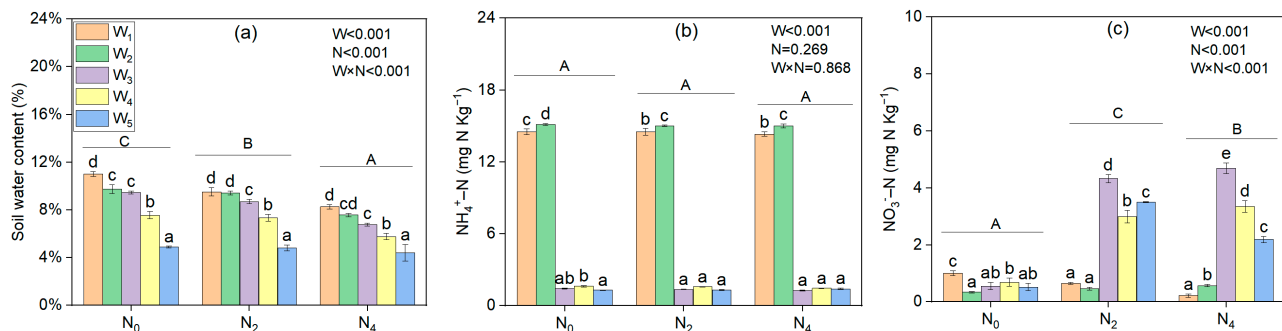


Figure 1. Effects of irrigation and N treatments on (a) the contents of soil water, (b) the contents of NH_4^+ -N, and (c) the contents of NO_3^- -N. Lowercase letters (a, b, c, d, e) indicate significant differences among the irrigation gradients at the same N level; uppercase letters (A, B, C) indicate significant ($p < 0.05$) differences among the N treatments. The statistical significance level was below the threshold $p < 0.05$. Error bars indicate $\pm$ SD of three replicates.

The application of N had significant effects ($p < 0.001$) on the SWC and NO_3^- -N levels (Figure 1a,c). Specifically, there was a notable decrease in the SWC, while the NO_3^- -N levels initially increased and subsequently decreased with the increasing rates of N application (Figure 1a,c).

3.2. Physiological Indexes

The irrigation treatment exerted a significant influence on the levels of LTN ($p < 0.001$), RTN ($p < 0.05$), Chl ($p < 0.001$), LWC ($p < 0.001$), Pro ($p < 0.01$), and MDA ($p < 0.001$) (Figure 2a–f). The LTN, RTN, LWC, and Pro exhibited a biphasic pattern of initial increase followed by subsequent decrease (Figure 2a,b,e), whereas the Chl and MDA exhibited a decline under increasing water stress (except for the Chl in the N_0W_1 treatment) (Figure 2c,d).

The application of N had significant effects on the LTN ($p < 0.001$), RTN ($p < 0.001$), Chl ($p < 0.01$), LWC ($p < 0.05$), and Pro ($p < 0.01$) levels (Figure 2a–e). The LTN, RTN, and Chl contents were significantly increased (Figure 2a–c), while the LWC initially increased but subsequently decreased with the increasing N application rates (Figure 2d). Additionally, there was a significant reduction in the Pro content with the N application rate (Figure 2e).

The irrigation treatment exerted highly significant ($p < 0.001$) effects on the activities of NR and GS (Figure 3a,d). The NR activity exhibited a gradual decrease, while the GS activity initially increased and then decreased with the increasing water stress. The N application significantly ($p < 0.001$) influenced the activities of NR, GDH, and GS (Figure 3a,c,d). The low-N treatment led to enhanced GDH and GS activities but reduced NR activity. The interactions between irrigation and N application were observed in relation to the activities of GDH and GS (Figure 3c,d).

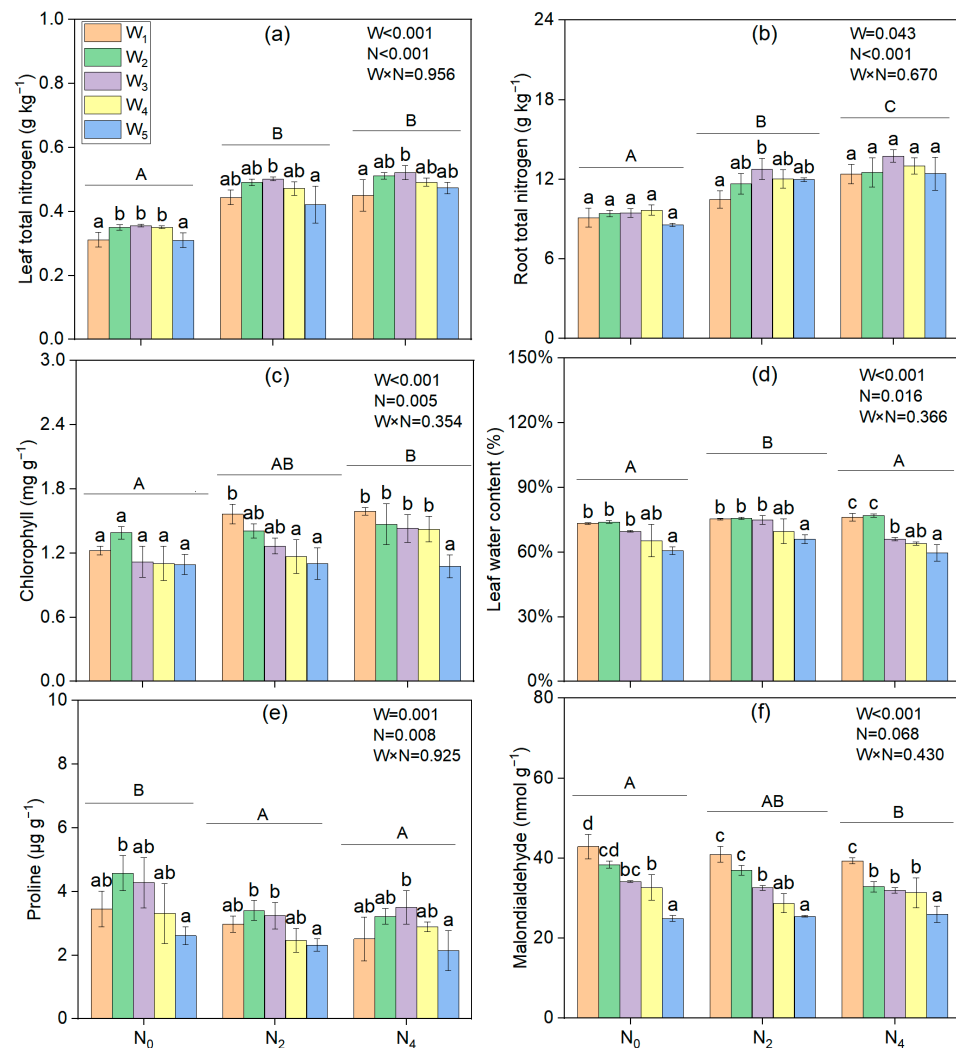


Figure 2. Effects of irrigation and N treatments on the (a) total N contents of leaf; (b) total N contents of root; (c) chlorophyll contents; (d) leaf water content; (e) proline contents; (f) malondialdehyde contents. Lowercase letters (a, b, c, d) indicate significant ($p < 0.05$) differences among the irrigation gradients at the same N level; capital letters (A, B, C) indicate significant ($p < 0.05$) differences among the N treatments. The statistical significance level was below the threshold $p < 0.05$. Error bars indicate $\pm$ SD of three replicates.

3.3. Morphological Parameters

The irrigation treatment exerted a highly significant ($p < 0.001$) influence on all the morphological parameters (Table 3). Both the AGB and BGB exhibited a significant decline in response to the increasing water stress (Table 3). The PH, GR, and NDVI were increased and then decreased with the increasing water stress, showing the highest values in the W₂ treatments, except the NDVI in the N₄ treatment (Table 3).

The morphological parameters, with the exception of the AGB and BGB, exhibited significant ($p < 0.05$) changes in response to the increasing N application rates. The PH and GR demonstrated a substantial increase with higher N application rates. The NDVI was lower under the N₂ treatment (Table 3). The TC was lower in the N₀ treatment and did not show any significant differences between the N₂ and N₄ treatments.

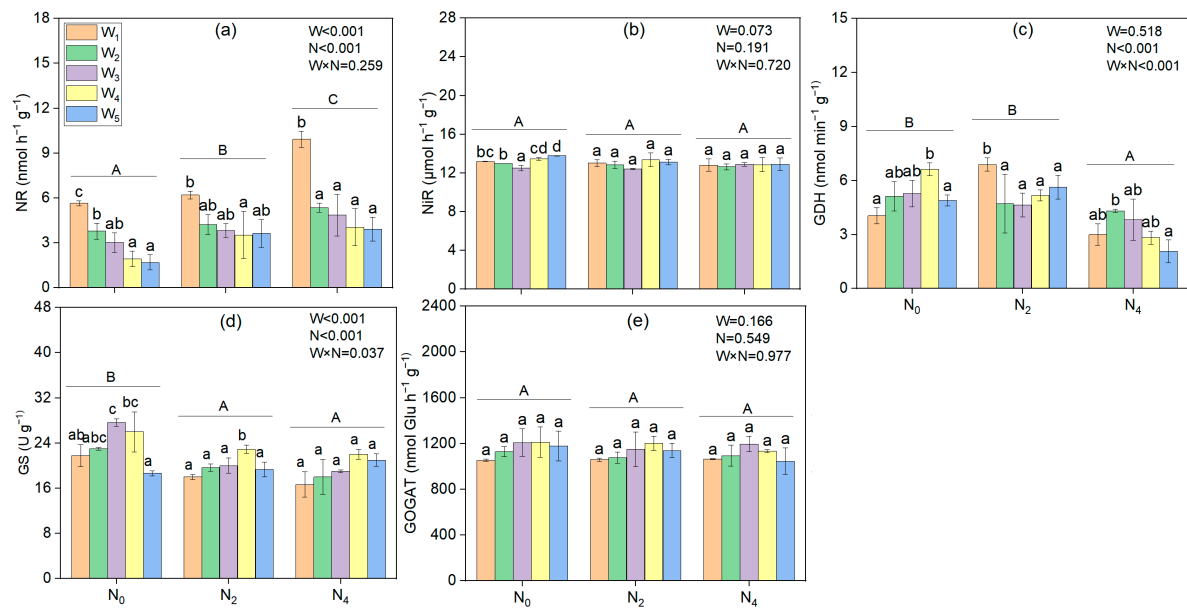


Figure 3. Effects of irrigation and N treatments on the activities of (a) nitrate reductase (NR), (b) nitrite reductase (NiR), (c) glutamate dehydrogenase (GDH), (d) glutamine synthetase (GS), and (e) glutamate synthetase (GOGAT) in leaf. Lowercase letters (a, b, c, d) indicate significant ($p < 0.05$) differences among the irrigation gradients under the same N level; capital letters (A, B, C) indicate significant ($p < 0.05$) differences among the N treatments. The statistical significance level was below the threshold $p < 0.05$. Error bars indicate $\pm$ SD of three replicates.

Table 3. Above-ground biomass, below-ground biomass, plant height, growth rate, NDVI, and turf color of tall fescue (*Festuca arundinacea* Schreb) under different levels of N application (N, g m⁻²) and irrigation (water, %).

Treatment		Above-Ground Biomass (g)	Below-Ground Biomass (g)	Plant Height (cm)	Growth Rate (cm d ⁻¹)	NDVI	Turf Color
Nitrogen	Water						
N ₀	W ₁	0.15 ± 0.03 b	0.10 ± 0.01 c	5.24 ± 0.21 a	0.32 ± 0.03 a	0.65 ± 0.05 a	6.40 ± 0.07 ab
	W ₂	0.13 ± 0.01 b	0.09 ± 0.00 bc	6.51 ± 0.12 c	0.50 ± 0.02 c	0.74 ± 0.03 b	6.53 ± 0.04 b
	W ₃	0.11 ± 0.02 ab	0.07 ± 0.01 ab	5.83 ± 0.21 b	0.40 ± 0.03 b	0.71 ± 0.03 ab	6.47 ± 0.04 ab
	W ₄	0.08 ± 0.02 a	0.07 ± 0.01 a	5.79 ± 0.15 b	0.40 ± 0.02 b	0.66 ± 0.01 a	6.43 ± 0.04 ab
	W ₅	0.07 ± 0.03 a	0.06 ± 0.01 a	5.31 ± 0.23 a	0.33 ± 0.03 a	0.70 ± 0.01 ab	6.33 ± 0.09 a
N ₂	W ₁	0.16 ± 0.02 b	0.06 ± 0.01 b	6.17 ± 0.15 ab	0.45 ± 0.02 ab	0.67 ± 0.06 ab	6.67 ± 0.04 b
	W ₂	0.15 ± 0.02 b	0.06 ± 0.01 b	7.13 ± 0.40 c	0.59 ± 0.06 c	0.74 ± 0.042 b	6.70 ± 0.07 b
	W ₃	0.13 ± 0.02 b	0.06 ± 0.00 ab	6.41 ± 0.23 bc	0.49 ± 0.03 bc	0.65 ± 0.03 ab	6.33 ± 0.09 a
	W ₄	0.08 ± 0.02 a	0.04 ± 0.01 a	6.31 ± 0.11 ab	0.47 ± 0.02 ab	0.61 ± 0.06 a	6.20 ± 0.07 a
	W ₅	0.07 ± 0.02 a	0.04 ± 0.00 a	5.65 ± 0.40 a	0.38 ± 0.06 a	0.59 ± 0.01 a	6.17 ± 0.04 a
N ₄	W ₁	0.18 ± 0.03 c	0.07 ± 0.01 b	7.07 ± 0.07 bc	0.58 ± 0.01 bc	0.75 ± 0.01 b	6.47 ± 0.09 c
	W ₂	0.14 ± 0.01 bc	0.05 ± 0.00 ab	7.40 ± 0.40 c	0.63 ± 0.06 c	0.73 ± 0.01 b	6.63 ± 0.04 c
	W ₃	0.10 ± 0.01 b	0.05 ± 0.02 ab	6.77 ± 0.10 ab	0.54 ± 0.01 ab	0.68 ± 0.00 ab	6.27 ± 0.09 b
	W ₄	0.06 ± 0.02 a	0.04 ± 0.01 a	6.44 ± 0.04 a	0.49 ± 0.01 a	0.65 ± 0.06 a	6.17 ± 0.09 b
	W ₅	0.06 ± 0.01 a	0.04 ± 0.01 a	6.32 ± 0.16 a	0.47 ± 0.02 a	0.64 ± 0.01 a	5.90 ± 0.07 a
p-value							
Water		<0.001	0.006	<0.001	<0.001	<0.001	<0.001
Nitrogen		0.683	0.183	<0.001	<0.001	0.037	<0.001
Water × Nitrogen		0.186	0.247	0.112	0.112	0.166	<0.001

N₀, N₂, and N₄: These represent nitrogen fertilizer treatments, and the footnotes 0, 2, and 4 indicate that 0, 2, and 4 g m⁻² of nitrogen fertilizer was applied. W₁, W₂, W₃, W₄, and W₅: W denotes the soil water content, and footnotes 1–5 indicate the amount of irrigation at 100–90% FWC; 85–75% FWC; 70–60% FWC; 55–45% FWC; and 40–30% FWC. Lowercase letters (a, b, c) indicate significant differences among irrigation gradients at $p < 0.05$ under the same N level. Boldface numbers indicate significance at $p < 0.05$.

3.4. WUE and NUE

The WUE exhibited a significant increase and the NUE increased until W₄ and then decreased in response to the intensified water stress (Table 4). Both the WUE and NUE experienced notable decreases as the N application rate increased (Table 4).

Table 4. Water use efficiency (WUE) and N use efficiency (NUE) of tall fescue (*Festuca arundinacea* Schreb) under the different N application (N, g m^{−2}) and irrigation (water, %) levels.

Treatment		WUE (%)	NUE (%)
Nitrogen	Water		
N ₀	W ₁	0.036 ± 0.006 a	—
	W ₂	0.039 ± 0.002 ab	—
	W ₃	0.051 ± 0.002 bc	—
	W ₄	0.058 ± 0.004 c	—
	W ₅	0.063 ± 0.013 c	—
N ₂	W ₁	0.034 ± 0.001 a	31.30 ± 0.41 a
	W ₂	0.037 ± 0.004 a	35.31 ± 5.22 a
	W ₃	0.050 ± 0.003 b	36.62 ± 3.09 a
	W ₄	0.049 ± 0.009 b	75.13 ± 5.94 b
	W ₅	0.054 ± 0.006 b	50.61 ± 2.31 ab
N ₄	W ₁	0.032 ± 0.003 a	29.55 ± 1.97 a
	W ₂	0.033 ± 0.002 a	32.78 ± 2.25 a
	W ₃	0.042 ± 0.001 a	35.21 ± 0.95 a
	W ₄	0.045 ± 0.010 a	55.59 ± 4.84 b
	W ₅	0.045 ± 0.007 a	25.87 ± 3.89 a
<i>p</i> -value			
Water		<0.001	<0.001
Nitrogen		0.716	0.017
Water × N		<0.001	0.187

N₀, N₂, and N₄: These represent N fertilizer treatments, and the footnotes 0, 2, and 4 indicate that 0, 2, and 4 g m^{−2} of N fertilizer was applied; W₁, W₂, W₃, W₄, and W₅: W denotes the soil water content, and footnotes 1–5 indicate the amount of irrigation at 100–90% FWC; 85–75% FWC; 70–60% FWC; 55–45% FWC; and 40–30% FWC. Lowercase letters (a, b, c) indicate significant differences among irrigation gradients at *p* < 0.05 under the same N level. Boldface numbers indicate significance at *p* < 0.05.

4. Discussion

4.1. Effects of Irrigation Treatment

The application of irrigation altered the SWC and influenced both the composition and concentration of N in the soil, consequently impacting the physiological processes of the tall fescue (Figure 1a). As a result, these changes ultimately affected the visual aesthetics and overall quality of the turf (Table 3). The SWC exhibited a significant (*p* < 0.001) decrease with the increasing water stress (Figure 1a). It is worth noting that the root system is particularly susceptible to this adverse condition caused by water stress [45]. Excessive irrigation, in contrast, can lead to root atrophy due to oxygen deprivation [46], thereby impairing the plant's ability to uptake water and nutrients from the soil. As the soil water content increases, plant roots are less compelled to grow deeper in search of moisture, and the root system is the main organ of the plant for absorbing water and nutrients. Therefore, the increase in the soil water content limits the uptake of water from the soil by the root system as well as the soil NO₃[−]-N and soil NH₄⁺-N [10]. In addition, excessive water also increased the NO₃^{2−} loss and limited the uptake of soil NO₃^{2−} by the root system [7]. It affected the synthesis of NO₃[−]-N and NH₄⁺-N. NO₃[−]-N was significantly and positively correlated with the LTN and RTN (*p* < 0.05) (Figure 4), so the loss of NO₃^{2−} blocked the LTN and RTN synthesis and negatively affected the GR and PH by restricting the synthesis of NO₃[−]-N (Figure 4), affecting the appearance quality of the lawn. The loss of NH₄⁺ diminished the NH₄⁺-N synthesis and thus weakened the enzymatic activity of the NR, negatively affecting the N metabolism cycle (Figure 4). It also weakened the Chl synthesis, which affects plant photosynthesis and had a significant impact on the appearance quality of the lawn in terms of the AGB, NDVI, and TC (Figure 4). The main forms of N absorption from soil by plants are NO₃[−]-N and NH₄⁺-N [15,19]. The soil NH₄⁺-N and NO₃[−]-N contents exhibited significant (*p* < 0.001) changes under the enhanced water stress (Figure 1b,c). A sharp decrease in the soil NH₄⁺-N content was

observed under the W_3 treatment (Figure 1b), possibly due to the promotion of NH_4^+-N uptake by the tall fescue that led to a reduction in the soil NH_4^+-N content under the appropriate water stress conditions (W_3). Additionally, the lowest soil NO_3^--N content in the W_2 treatment indicated (excluding N_4 processing) that the W_2 treatment was optimal for the tall fescue's uptake of NO_3^--N [47,48]. Under water stress, the LTN and RTN initially increased and then decreased, with the RTN surpassing the LTN by a considerable margin [12,49] (Figure 2a,b). This disparity can be attributed to the upward transport of N absorbed by roots through transpiration, followed by its assimilation into various cellular pathways within the above-ground plant tissues [50]. The Pro and Chl contents exhibited significant variations under the increasing water stress conditions (Figure 2c,e). They are both associated with glutamate in the N metabolism pathway [51]. Specifically, the Pro content initially increased and then decreased in response to water stress [52], and so did the GS activity, as a crucial enzyme in the N metabolism pathway, binding NH_4^+ into glutamate [20,25]. Interestingly, similar patterns were observed for both the GS activity as well as the Pro content changes during water stress, indicating a positive correlation between them (Figure 4) [53,54]. Except for the N_0W_1 treatment, there was a significant decrease in the Chl content with the increasing water stress levels (Figure 2c). This decline can be attributed to protochlorophyllide's dependence on glutamate from the N metabolism pathway, since protochlorophyllide plays a crucial role in Chl synthesis [5]. Moreover, the intensified water stress led to a notable reduction in the NR activity, which weakened the conversion of NO_3^- to NH_4^+ [25,55]. Consequently, this inhibition hindered glutamate synthesis, thereby reducing the availability of N derived from protochlorophyllide for Chl synthesis, ultimately affecting the turf coloration [25,55]. Notably, there was also a strong positive correlation observed between the NR activity and Chl content (Figure 4).

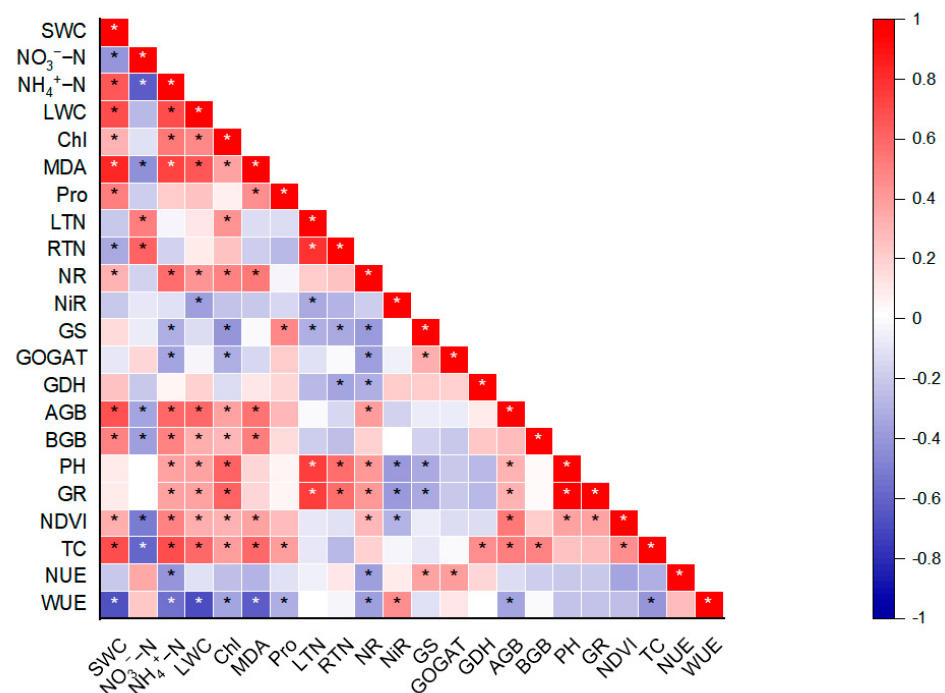


Figure 4. Correlation analysis between parameters under different water and N application levels. Soil water content (SWC); soil nitrate N (NO_3^--N); soil ammonium N (NH_4^+-N); leaf water content (LWC); chlorophyll (Chl); malondialdehyde (MDA); proline (Pro); leaf total N (LTN); root total N (RTN); nitrate reductase (NR); nitrite reductase (NiR); glutamine synthetase (GS); glutamate synthetase (GOGAT); glutamate dehydrogenase (GDH); above-ground biomass (AGB); below-ground biomass (BGB); plant height (PH); growth rate (GR); normalized differential vegetation index (NDVI); turf color (TC); N use efficiency (NUE); water use efficiency (WUE). *, $p < 0.05$ level.

The root system serves as an inherent indicator of the turf quality [56]. Enhanced water stress significantly ($p < 0.01$) decreased the AGB, which exhibited a significant positive correlation with the TC (Figure 4). These findings suggested that water stress diminished the AGB, subsequently impacting the color and overall quality of the turf (Figure 4).

The decline in the turf quality is primarily attributed to the impaired turfgrass physiology [33]. Significant positive correlations were observed between the physiological indicators (the LWC and MDA) and turf quality indicators (the TC, NDVI, AGB, and BGB) (Figure 4). Furthermore, water stress had significant effects on the LWC and MDA levels (Figure 2d,f). The increasing water stress led to a significant ($p < 0.001$) decrease in the LWC values (except for the W_2 treatment) [57] and influenced the TC (Figure 4). The W_2 treatment had comparatively higher LWC values than the W_1 treatment, indicating that the W_2 treatment better retained the internal leaf water for an extended period of time. The MDA content decreased significantly ($p < 0.001$) with increasing water stress (Figure 2f), as the excessive accumulation of MDA can damage cellular organelles and disrupt normal physiological activities [58]. Therefore, the decreasing content of MDA under the enhanced water stress ensured the maintenance of physiological activities.

Extrinsic indicators of the turf quality encompass the visual aspects of the turf, including the TC, NDVI, etc. The impacts of water stress on the PH, GR, NDVI, TC, WUE, and NUE were found to be significant (Tables 3 and 4). The TC and NDVI exhibited a tendency to initially increase and then decrease or significantly ($p < 0.001$) decrease with increasing water stress [59]. Adequate irrigation promotes the growth in both cool-season and warm-season turfgrasses [12,60]. In the N_4 treatment group, the PH was higher in the W_2 treatment compared to W_1 by approximately 4.6%, while the GR increased by around 8.6% (Table 3). For sports field turf management purposes, lower GRs along with reduced PHs can lead to decreased mowing frequencies, resulting in cost savings for maintenance activities [61]. Although better results were observed in the W_1 treatment, the overall findings suggested that the W_2 treatment was more suitable for application on low-maintenance turfs due to its potential for achieving water savings of up to 15% (Figure 2 and Table 3).

4.2. Effects of N Fertilizer

The N stress showed significant ($p < 0.05$) associations with the SWC, soil NO_3^- -N, LTN, RTN, Chl, LWC, Pro, and activities of enzymes, such as NR, GDH, and GS (Figures 1–3). The SWC significantly increased under N stress conditions (Figure 1a) due to the reduced water uptake capacity of the plant roots during N deficiency [62,63]. The soil NO_3^- -N levels were significantly ($p < 0.001$) correlated with the N stress, showing an increasing trend followed by a decrease (Figure 1c). This may be due to the fact that plants with normal N fertilizer application (N_4) take up NO_3^- -N from the soil more readily than plants with less N fertilizer treatments (N_2). Plants respond to abiotic stresses through alterations in their N metabolism pathways [14]. In this experiment, the NR activity increased significantly under the elevated N conditions, which is involved in the process of N metabolism, facilitating the conversion of NO_3^- to NH_4^+ [64] (Figure 3a). To prevent excessive NH_4^+ accumulation, plants utilize either the GS, GOGAT, or GDH pathways for the binding of NH_4^+ to glutamate [65]. The enzyme activities of GS and GDH increased significantly ($p < 0.001$) under the intensified N stress conditions (Figure 3c,d) [66]. When stressful conditions inhibit the GS and GOGAT cycling pathway, NH_4^+ directly binds to glutamate through the synergistic action of GDH, which later participates in amino acid and protein synthesis processes [22]. Pro synthesis is closely associated with glutamate in the N metabolism pathway [67]. The Pro content significantly increased under the enhanced N stress conditions (Figure 2e), potentially due to the promotion of N metabolic pathways and the subsequent Pro synthesis. Furthermore, our experimental results demonstrated significant correlations between the Pro level and GS activity (Figure 4).

The total N accumulation in both the roots and leaves of the tall fescue significantly ($p < 0.05$) increased with the increasing N levels, with a greater accumulation observed in the roots compared to the leaves, reflecting the pattern of N transfer within the plant [68].

The LWC ($p < 0.001$) and Chl ($p < 0.01$) exhibited significant changes under the enhanced N stress conditions [69], initially increasing followed by a decrease, while the Chl showed a significant ($p < 0.01$) decrease (Figure 2c,d). The increased LWC promoted Chl accumulation in the leaves [70], where both the LWC and Chl were higher under the N_2 treatment compared to N_0 (Figure 2c,d). And the experimental results demonstrated a significant correlation between the LWC and Chl (Figure 4). The Chl content was also significantly ($p < 0.05$) and positively correlated with the AGB (Figure 4). Therefore, the increase in Chl contributed to the increase in the AGB, which subsequently affected the visual quality of the tall fescue. Plants exhibit green-holding characteristics through higher Chl contents, which resulted in a better TC with a good appearance quality (Figure 4) [71]. Additionally, both the NUE and WUE significantly ($p < 0.05$) increased under the enhanced N stress conditions (Table 4).

Nitrogen application is an essential management practice for improving the turf quality, and increasing the N application rate significantly ($p < 0.01$) enhanced the PH and GR activity (Table 3). However, this also leads to higher mowing frequencies and maintenance costs for sports field turfs, which is not a recommended turf management practice [2]. The N stress exerted a significant ($p < 0.05$) influence on both the NDVI and TC, with significantly ($p < 0.01$) higher TC values observed under the N_2 treatment compared to the N_4 treatment (Table 3). Consequently, the application of the N_2 treatment is deemed more suitable for low-maintenance turfs, in accordance with its superior performance compared to the N_4 treatment [72,73].

4.3. Synergistic Effects of Irrigation and N Fertilizer Application

The interaction between the irrigation and N application practices significantly influenced the SWC, soil NO_3^- -N, GDH, GS activity, and TC (Figures 1 and 3 and Table 3). Under the N_2 treatment, the W_1 treatment exhibited a higher SMC (Figure 1a,c) and higher physiological indicators (Chl and AGB) compared to the W_2 treatment (Figure 2c). However, the W_2 treatment outperformed the W_1 treatment in terms of the physiological indicators (LTN, RTN, LWC, and Pro), morphological indicators (PH, GR, NDVI, and TC), and NUE (Tables 3 and 4). Notably, under the N_2 treatment condition, when a superior turf morphology was desired for ensuring a good turf quality performance, the W_2 treatment resulted in an approximately 15% reduction in the irrigation volume compared to the W_1 treatment.

At low N levels, the enhanced water stress significantly increased both the WUE and NUE of the tall fescue while reducing the BGB (Table 4). Additionally, under water stress conditions, the low N levels also increased the WUE and NUE in the tall fescue (Table 4). For the SWC and GS, the N_2 and N_0 treatments had significantly higher values than the N_4 treatment under the same water stress, and the low N significantly mitigated the adverse effects produced by the water stress [54] (Figures 1a and 3d). This finding can be explained based on the least-cost economic theory of photosynthesis, which suggests that N and water are mutually substitutable resources. The SWC was significantly positively ($p < 0.05$) correlated with the CHL and LWC (Figure 4); therefore, low N increased the physiological activities of the tall fescue by increasing the SWC [46]. In the W_4 and W_5 treatments, due to the low SWC, the elevated N application lengthened the root system and promoted water uptake [15], and it led to decreases in the SWC and GS activity (Figures 1a and 3d). Conversely, the low-N application ensured higher values of SWC and GS activity, provided a favorable soil environment for turfgrass growth, and enhanced the N metabolism pathways, thereby enhancing the turf quality [29,30]. Under certain levels of both the water stress and low-N treatments, there was an enhancement in the N metabolism pathways in the tall fescue (Figure 3d). Notably, in terms of the GDH activity, the N_2 treatment exhibited a distinct pattern compared to the other N treatments (N_0 , N_4), with the GDH levels initially decreasing and then increasing under enhanced water stress conditions (Figure 3c). It is possible that under certain N stress and water stress conditions, the opening of the GDH pathway was promoted to ensure the binding of NH_4^+

to glutamate [74]. Therefore, moderate N levels or appropriate water stress (N_2W_2 , N_2W_3) could enhance the N metabolic pathways in tall fescue.

Summarily, the interaction of water and N had direct effects on the SWC, soil NO_3^- -N, and soil NH_4^+ -N, as well as indirect effects on the enzyme activity and other physiological and turf quality indicators [13]. Specifically, under the water–N interaction, the SWC increased the soil NH_4^+ -N by decreasing the soil NO_3^- -N, while the soil NH_4^+ -N enhanced the physiological processes and ultimately improved the turf quality [74]. The water–N interaction also increased the physiological processes by increasing the enzyme activities, which, in turn, increased the turf quality. In addition, the SWC and soil NH_4^+ -N had indirect effects on the turf quality under the water–N interaction. They ultimately improved the turf quality by regulating the enzyme activities as well as other physiological processes (Figure 5).

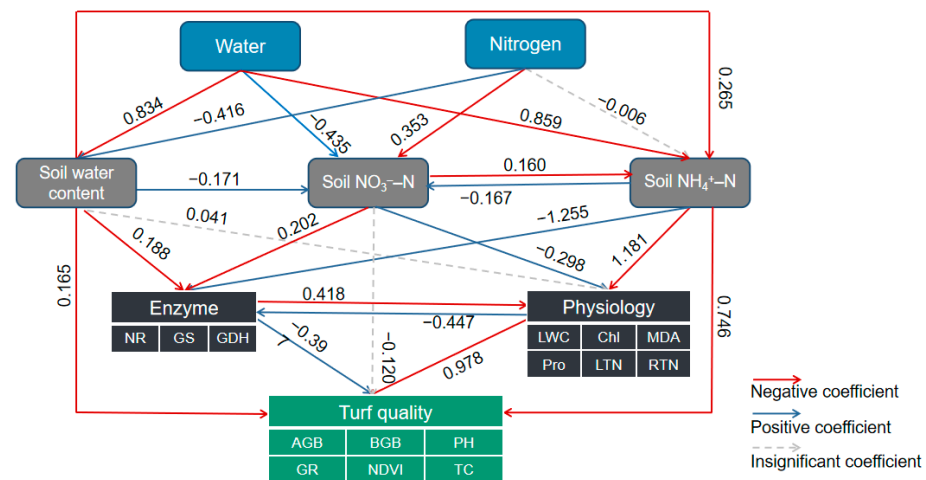


Figure 5. Direct and indirect effects of water and nitrogen treatments on the soil water content, soil NO_3^- -N and NH_4^+ -N contents, enzymes, physiology, and turf quality. NR, GS, GDH, LWC, Chl, MDA, Pro, LTN, RTN, AGB, BGB, PH, GR, NDVI, and TC denote the nitrate reductase, glutamine synthetase, glutamate dehydrogenase, leaf water content, chlorophyll, malondialdehyde, proline, leaf total N, root total N, above-ground biomass, below-ground biomass, plant height, growth rate, normalized differential vegetation index, and turf color, respectively. The red and blue lines indicate significant positive and negative effects, respectively, and the significance level was $p < 0.05$. The numbers around the lines indicate the standardized path coefficient.

In terms of the tall fescue morphology, the N_2W_2 treatment exhibited the highest performance in the TC (Table 3), while N_4W_1 demonstrated superior results in the AGB and NDVI (Table 3). Consequently, both N_4W_1 (CK) and N_2W_2 emerged as the most favorable treatments for the tall fescue appearance and morphology. Considering the low maintenance [2], the N_2W_2 treatment, characterized by maintaining the SWC at an 85–75% FWC and applying 2 g m^{-2} of N fertilizer, proved to be optimal for achieving substantial savings in water usage and N fertilization without compromising the turf quality.

5. Conclusions

The appropriate water and N stresses facilitated the physiological metabolism and morphological development of the tall fescue. Although normal irrigation (W_1) increased the soil water content, malondialdehyde content, nitrate reductase, and above- and below-ground biomass compared to W_2 , the W_2 treatment outperformed W_1 in terms of the soil NH_4^+ -N, total N of the leaves and roots, leaf water content, NDVI, plant height, growth rate, and turf color. The N_2 treatment had higher soil NO_3^- -N, leaf water content, glutamate dehydrogenase, and turf color values than the normal N application (N_4). The water and N use efficiencies were enhanced under both water stress and N stress conditions. Considering the maintenance costs, the combination of W_2 and N_2 is the most suitable for

low-maintenance turfs. Moreover, the low-N application could mitigate the adverse effects of water stress on the soil water content and glutamine synthetase activity. Compared to the control group (N_4W_1), the N_2W_2 treatment exhibited marginal decreases (< 5%) in the above- and below-ground biomass and NDVI, respectively, but showed a 3.6% improvement in the turf color while maintaining an exceptional turf quality in terms of the plant morphology. The recommended management practices in this research included maintaining a field water-holding capacity of 85–75% and applying N at a rate of 2 g m^{-2} while ensuring a good turf quality with minimal maintenance for the tall fescue. These results provide insights into the impact of the water–N interaction on tall fescue in terms of the soil, physiology, and morphology, thereby establishing a theoretical foundation for low-maintenance turfs.

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