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Sustainable grassland management through an intercropping system based on cutting optimization

Longshuai Ma [a,b,c], Guanrong Dai [a,b,c], Fangru Wan [a,b,c], Xiaozheng Wang [a,b,c], Yinjuan Li [d], Baoqing Zhang [e,*]

[a] State Key Laboratory of Herbage Improvement and Grassland Agro-ecosystems, Lanzhou University, Lanzhou 730020, China
[b] College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China
[c] Qingyang National Field Scientific Observation and Research Station of Grassland Agro-Ecosystems, Lanzhou University, 745000, China
[d] College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou 225009, China
[e] Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, Gansu 730000, China

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ABSTRACT

In arid and semi-arid regions, the restoration of degraded grasslands necessitates strategies that balance agricultural production with ecological sustainability. Large-scale alfalfa cultivation has been implemented in the Loess Plateau of China to establish cultivated grassland aimed at vegetation recovery and soil erosion control. However, this approach presents a critical dilemma: although alfalfa effectively stabilizes soil and supports local livelihoods, its high water demand exacerbates the already severe water scarcity that exists in such dryland ecosystems. To address this issue, a two-year field experiment was conducted in Qingyang, Gansu Province to evaluate the effects of monocultures and intercropping of wheat and alfalfa, along with precision cutting management of alfalfa, on yield, water use (WU), and water productivity (WP). Three cropping patterns were implemented: sole wheat, sole alfalfa, and wheat/alfalfa intercropping with seven alfalfa cutting treatments (T-20C1, T-20C2, T-20C3, T-10C1, T-10C2, T-10C3, and T). Results indicated that a significant increase in productivity of the intercropping system by 8.7 %—21.2 % in 2022 and 16.3 %—31.0 % in 2023 compared to that of monocultures. The land equivalent ratio of the intercropping system under the T-10C2 treatment reached 1.15 in 2022 and 1.21 in 2023. Compared with that of sole wheat, the yield of intercropped wheat under the T treatment was significantly reduced, by 25.6 % in 2022 and 12.7 % in 2023. Except for the T-20C1 treatment in 2022, the yield of intercropped wheat under other treatments did not exhibit statistically significant differences when compared with that of sole wheat in both 2022 and 2023. Compared with the yield under the T treatment, the yield of intercropped wheat under the T-10C1, T-20C3, T-10C2, and T-10 treatments increased significantly, by 23.3 %—46.3 % in 2022 and 13.9 %—20.4 % in 2023. Compared with that of sole alfalfa, the yield of intercropped alfalfa increased significantly, by 45.4 %—48.8 % in 2022 and 49.7 %—44.6 % in 2023. Compared with the sole cropping system, the WU of all treatments in the intercropping system decreased by 1.1 %—13.1 % compared to the sole cropping system in 2022, while the WP increased by 0.1 %—24.0 % in 2022 and 7.7 %—23.5 % in 2023. Overall, results indicated that optimized cutting of alfalfa improves WP and reduces total WU in wheat/alfalfa intercropping systems. This provides a water-saving solution for cultivated grasslands in arid areas, achieving a synergy between ecological restoration and agricultural WU.

1. Introduction

Grasslands are vital ecosystems that cover 40 % of global land (Bardgett et al., 2021). Cultivated grasslands, or artificial grassland, refers to the establishment of a herbaceous community through seeding following the complete eradication of the original vegetation, employing integrated agricultural techniques. These ecosystems play a particularly important roles in mitigating ecological degradation through vegetation restoration, soil erosion control, and soil health improvement, particularly in arid and semi-arid regions (Dong et al., 2020).

* Corresponding author.
E-mail address: baoqzhang@lzu.edu.cn (B. Zhang).

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They also enhance economic resilience by producing high-quality forage, which improves livestock yields and supports herder livelihoods. However, against the backdrop of intensifying global climate change (Tollefson, 2021) and water scarcity (Zhang et al., 2017; Liu et al., 2022), the improvement of water productivity (WP) has become increasingly imperative, particularly in arid and semi-arid regions. Additionally, population growth (Godfray et al., 2010; FAO, 2023) poses substantial challenges to global food and forage security (Makkar, 2018; Daduwal et al., 2024; Alseekh et al., 2025). Although monoculture remains the dominant agricultural model, its prolonged practice has been linked to biodiversity loss, environmental pollution, soil degradation (Cherlet et al., 2018), and increased pest/disease outbreaks (Rockström et al., 2017; FAO, 2019), rendering it unsustainable. Cultivated grassland systems face similar limitations, highlighting the urgent need for sustainable alternatives. Intercropping has emerged as an efficient and sustainable agricultural system that enhances the economic returns of farmers (Li et al., 2021; Tao et al., 2024; Thierfelder et al., 2024), and has received growing research attention (Ouma and Jeruto, 2010; Sharma et al., 2017; Reichmann et al., 2025). The integration of forage and grain crops in intercropping systems offers a viable solution to increase biodiversity and system stability. Recognizing these benefits, China, Europe, and the United States are currently actively promoting intercropping technologies to address the pressing issues of food security, forage shortages, and land degradation (Pinto et al., 2024; Liu et al., 2025; Reichmann et al., 2025).

In the Loess Plateau of China, severe soil erosion and water scarcity pose significant threats to the sustainability of cultivated grasslands and agricultural systems (Li et al., 2023b; He et al., 2024; Zhao et al., 2025). Hence, large-scale alfalfa-based cultivation has been widely implemented for soil erosion control in the region. However, these alfalfa-dominant cultivated grassland systems have experienced widespread degradation owing to inadequate management practices and limited economic returns (Fan et al., 2010; Ge et al., 2020). The wheat/alfalfa intercropping system, a traditional practice now regaining prominence, demonstrates ecological and productive advantages through spatiotemporal niche complementarity (Mu et al., 2023, Su et al., 2024). Despite the different growth conditions between intercropping and sole cropping systems, management practices continue to be predominantly derived from monoculture approaches. Current research on intercropping regulation primarily focuses on spatial configurations, such as crop combinations and row arrangements (Feng et al., 2020; Chen et al., 2024; Wang et al., 2023), which lack the capacity for dynamic adjustment based on annual climatic variability. Recent studies indicate that adjusting alfalfa cutting timing influence the productivity of intercropping systems (Wan et al., 2024); however, the impacts on total system water use (WU) and WP remain unclear. This highlights the critical need to investigate whether optimized alfalfa cutting management, specifically focusing on timing and spatial arrangement, can effectively reduce WU while simultaneously maintaining the economic benefits and ecological significance of this vulnerable region, thereby ensuring the long-term sustainability of cultivated grassland systems.

In conventional intercropping systems, such as soybean/maize and wheat/maize, the component crops are harvested only once per cycle (Raseduzzaman et al., 2025; Ma et al., 2019). The wheat/alfalfa system offers unique management opportunities, as alfalfa allows multiple harvests each year. This distinctive characteristic enables the implementation of cutting interventions during critical growth stages to optimize spatiotemporal resource allocation and minimize interspecific competition. Although studies have demonstrated the yield advantages arising from temporal resource compensation in wheat/maize relay systems following wheat harvesting (Ma et al., 2020b; Yin et al., 2017), the corresponding compensatory effects in wheat/alfalfa systems remain poorly understood. Current research knowledge have significant gaps regarding: (1) how alfalfa cutting management impact the overall system productivity and WP, and (2) whether strategic adjustments can concurrently enhance yields and reduce WU in water-limited environments. To address these research questions, a two-year comprehensive field investigation was carried out to evaluate the system performance under various cutting regimes, focusing on: (a) treatment effects on component and total system yields, and (b) associated modifications in WU and WP patterns.

This research provides critical insights for the development of optimized management protocols in cultivated grasslands, specifically contributing to: (i) science-based cutting strategies that enhance WU efficiency through improved niche differentiation; (ii) practical methods to achieving intensive sustainable agriculture in arid regions; and (iii) empirical evidence demonstrating ways to achieve balanced productivity and ecological conservation in vulnerable agroecosystems, particularly in critical grain/forage intercropping systems. Our findings will advance both the theoretical understanding of perennial—annual crop interactions and provide practical solutions for water-scarce agricultural systems, ultimately supporting the more sustainable utilization of limited regional water resources through improved intercropping management.

2. Materials and methods

2.1. Site description

The experiment was conducted over the period 2021—2023 at the Qingyang National Field Scientific Observation and Research Station of Grassland Agroecosystems, Gansu Province, China (35°40′ N, 107°51′ E, 1297 m a.s.l.). The long-term average temperature (2001–2022) at this location was 10.1 ℃, while the mean temperature over our experimental period (2021–2023) was 10.6 ℃. The long-term average annual precipitation (2001–2022) was 572.3 mm, with the majority occurring between July and September. The annual precipitation values for 2021, 2022, and 2023 were 480.5, 433.0, and 666.6 mm, respectively. During the experimental growth periods, the annual precipitation was 620.9 mm in year 2021—2022 and 605.7 mm in year 2022—2023 (Fig. 1).

The experimental site is characterized by silty loam soil, with a field capacity of 28.6 % and a soil bulk density of 1.32 g cm^{-3} within the 0—2 m depth. Prior to the experiment, soil samples were collected from the experimental field in September 2021. The basic chemical parameters of the soil were as follows: total nitrogen was 0.76 g kg^{-1}, available nitrogen was 5.25 mg kg^{-1}, and available phosphorus was 9.26 mg kg^{-1}.

2.2. Experimental design and field management

A two-year experiment was conducted using a randomized complete block design, comprising nine treatments with three replicates for each treatment. The experimental design included three cropping systems (sole wheat, sole alfalfa, and wheat/alfalfa intercropping) and seven alfalfa cutting treatments in the wheat/alfalfa intercropping system. The cutting treatments, detailed in Fig. 2, were: (i) cutting the first border rows of intercropped alfalfa 20 days before the onset of the first flowering stage, following by cutting the remaining rows during the first flowering stage (T-20C1); (ii) cutting the first and second border rows of intercropped alfalfa 20 days before the onset of the first flowering stage, following by cutting the remaining rows during the first flowering stage (T-20C2); (iii) cutting all six rows of intercropped alfalfa 20 days before the onset of the first flowering stage (T-20C3); (iv) cutting the first border rows of intercropped alfalfa 10 days before the onset of the first flowering stage, following by cutting the remaining rows during the first flowering stage (T-10C1); (v) cutting the first and second border rows of intercropped alfalfa 10 days before the onset of the first flowering stage, following by cutting the remaining rows during the first flowering stage (T-10C2); (vi) cutting all six rows of intercropped alfalfa 10 days before the onset of the first flowering stage (T-10C3); and (vii) cutting all six

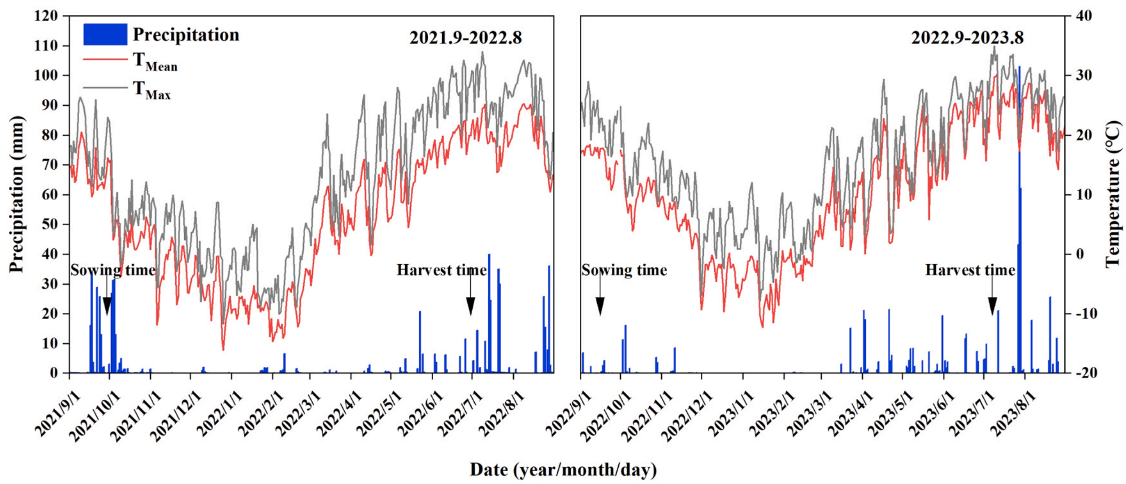

Fig. 1. Daily precipitation, daily mean temperature and daily maximum temperature during the 2021—2022 and 2022—2023 growing seasons at the experimental site.

rows of alfalfa during the first flowering stage (T). The alfalfa cutting date is determined according to the growth stages of wheat. Rows 1 and 6 were defined as the primary border rows, rows 2 and 5 as the secondary border rows, and rows 3 and 4 as the central rows in the intercropped alfalfa (Fig. 2). Alfalfa was harvested three times in 2022 and four times in 2023. Because wheat and alfalfa were only in the co-growth phase during the first alfalfa harvest, the different cutting treatments described above were applied to the intercropped alfalfa only at the first harvest of each year.

Each experimental plot measured 100 m^2 (10 m × 10 m), with a designated 1 m buffer zone between adjacent plots to minimize the influence of neighboring plots. In both the intercropping and sole-cropping systems, the rows of wheat and alfalfa were spaced equally: specifically, 20 cm for wheat rows and 30 cm for alfalfa rows. The distance between wheat and alfalfa in intercropping system was 25 cm (Fig. 2). Each wheat/alfalfa plot contained three replicate intercropping strips, each planted with six rows of wheat (120 cm wide) and six rows of alfalfa (180 cm wide). This arrangement ensured that wheat and alfalfa occupied 40 % and 60 % of the intercropped plots, respectively.

The wheat variety was '*Triticum aestivum* L. cv. Zhongmai 36', and the alfalfa variety was '*Medicago sativa* L. cv. Longdong'. Both wheat and alfalfa were grown under rainfed conditions without artificial irrigation. The seeding rates for intercropped wheat and alfalfa were consistent with those employed in the sole cropping system, specifically, 150 kg ha^{-1} for wheat and 15 kg ha^{-1} for alfalfa. Alfalfa seeds were sown in April 2021 and exhibited regreening in mid-to-late March each year. Wheat seeds were sown on 21 September 2021 and 15 September 2022, and harvested on 30 June 2022 and 10 July 2023, respectively. At the time of sowing, nitrogen fertilizer was applied at rates of 54 kg N ha^{-1} for wheat and 150 kg N ha^{-1} for alfalfa, Phosphate fertilizer application rates were 138 kg P_2O_5 ha^{-1} for wheat and 75 kg P_2O_5 ha^{-1} for alfalfa. The fertilizer used for wheat included diammonium phosphate (18 % N, 46 % P_2O_5), whereas alfalfa was fertilized with urea (46 % N) and calcium superphosphate (16 % P_2O_5). During the jointing stage of wheat, Urea (46 % N) was applied as a topdressing fertilizer at a rate of 100 kg N ha^{-1}. No irrigation was applied during the experimental period. Weeding, fertilization, and other field management practices adhered to local agricultural norms.

2.3. Measurements

2.3.1. Yield measurement

The aboveground biomass accumulated from all cutting times was taken as the total yield of alfalfa. Samples of intercropped alfalfa and sole alfalfa were sampled withinw an area of 3.6 m^2 (six rows of alfalfa, each ro 2 m long). The samples were dried at 105 ℃ for 30 min to inhibit enzymatic activity, subsequently temperature was adjusted to 75 ℃ and dried to a constant weight for the measurement of aboveground biomass. During wheat harvest, all plants within a 3.6 m^2 area (six rows of wheat, each row 3 m long) were collected from both sole-cropped and intercropped wheat plots. The wheat samples were threshed and dried to measure the grain yield of wheat. Sampling areas were positioned over 50 cm from the edge of the plots to ensure representativeness.

2.3.2. Soil water measurement

Soil water content was measured using a portable soil moisture meter based on time domain reflectometry (TDR) (TRIME, IMKO Micromodultechnik, Germany) and validated using the oven-drying method. Soil water content was measured using TDR during the entire growth period of wheat and alfalfa. For the sole wheat and alfalfa strips, TDR tubes were set in the center of the strips, with four replicates per plot. For the intercropping treatments, three TDR tubes were arranged as follows: (1) at the center of a wheat strip, (2) between wheat and alfalfa strips, and (3) at the center of an alfalfa strip. Soil moisture was measured every 20 cm in the vertical direction up to a maximum depth of 3 m. During the co-growth period of wheat and alfalfa, soil moisture was measured using TDR every 2 days. During the non-growth periods of wheat and alfalfa, measurements were taken every 5—7 days. Additional measurements were conducted immediately after precipitation events, alfalfa cutting, and wheat harvest.

2.4. Data calculation

2.4.1. Water use

The WU of a crop equates to the crop evapotranspiration (ET_c), which can be calculated using the water balance method, resulting in the following WU calculation formula:

$$WU = ET_c = P - \Delta SWS + U - D - R, \tag{1}$$

where, ET_c is the evapotranspiration measured using the water balance method, P (mm) is the amount of rainfall occurring between two water measurement dates, ΔSWS (mm) is the difference in soil water storage between two water measurement dates, U is the upward capillary rise from the soil profile below 300 cm, D is drainage, and R is runoff. The terrain of the experimental site is flat, with few heavy rainfall events in the area, and each plot has ridges. Therefore, we did not consider R and D in this study. The groundwater in this area is deeper than 40 m, so U was also be ignored.

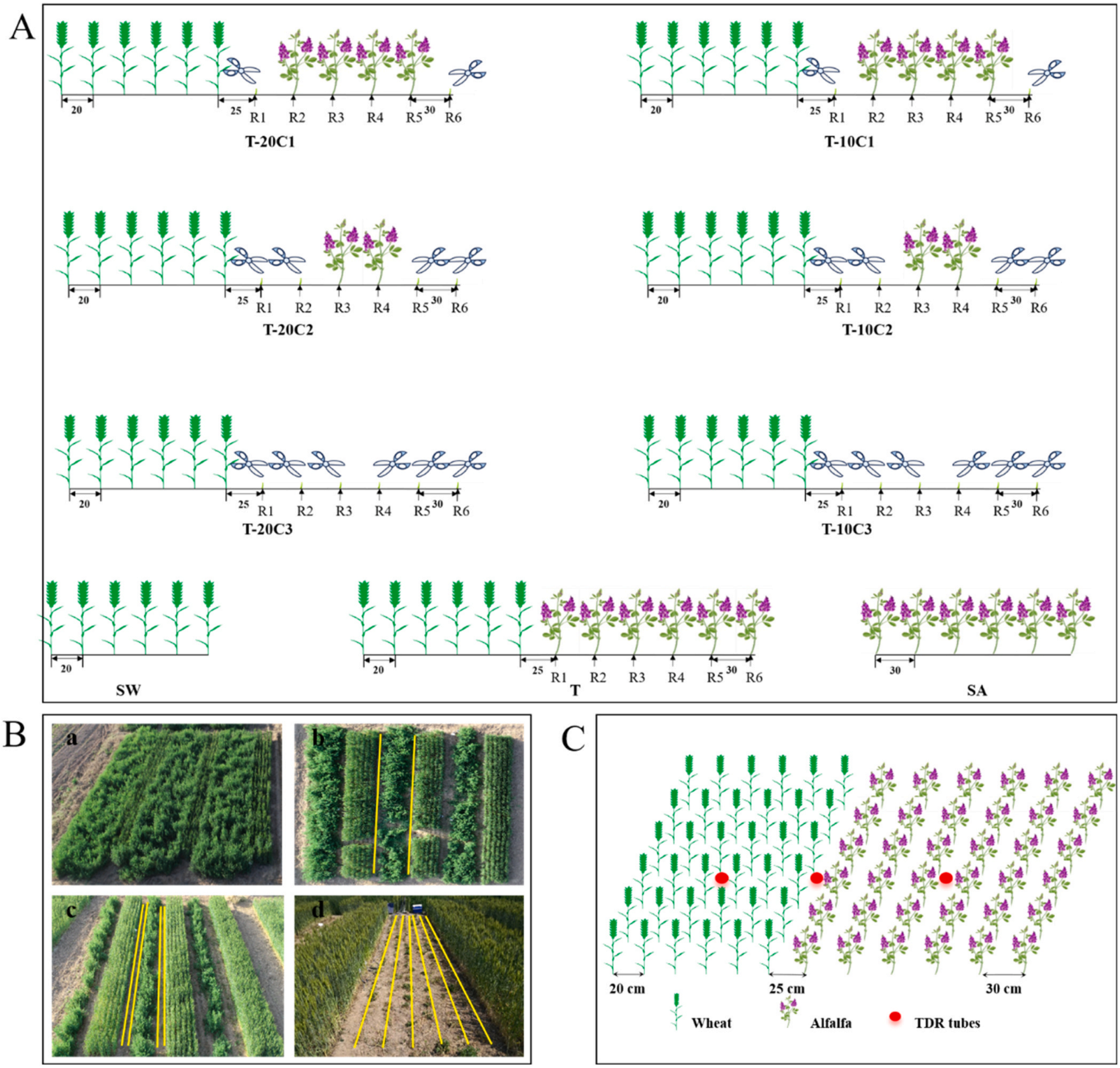

Fig. 2. Experimental setup. (A) Schematic diagram of cutting treatment for intercropped alfalfa (unit: cm). (B) Field photos. (C) Schematic diagram of the installation locations of time domain reflectometry (TDR) tubes. T-20C1, cutting the first border rows (R1 and R6) of intercropped alfalfa 20 days prior to the onset of the first flowering stage, and conducting the cutting for the remaining rows (R2, R3, R4, R5) during the first flowering stage; T-20C2, cutting the first border rows and second border rows (R1, R2, R5, R6) of intercropped alfalfa 20 days prior to the onset of the first flowering stage, and conducting the cutting for the remaining rows (R3 and R4) during the first flowering stage; T-20C3, cutting the all six rows (R1, R2, R3, R4 R5, R6) of intercropped alfalfa 20 days prior to the onset of the first flowering stage; T-10C1, cutting the first border rows (R1 and R6) of intercropped alfalfa 10 days prior to the onset of the first flowering stage, and conducting the cutting for the remaining rows (R2, R3, R4, R5) during the first flowering stage; T-10C2, cutting the first border rows and second border rows (R1, R2, R5, R6) of intercropped alfalfa 10 days prior to the onset of the first flowering stage, and conducting the cutting for the remaining rows (R3 and R4) during the first flowering stage; T-10C3, cutting the all six rows (R1, R2, R3, R4 R5, R6) of intercropped alfalfa 10 days prior to the onset of the first flowering stage; T, treating it the same as with a single alfalfa, all six rows of alfalfa at the first flowering stage. The remaining stages of intercropped alfalfa, as well as all cutting dates for sole alfalfa, occur during the flowering stage. B) shows: a, wheat/alfalfa intercropping during co-growth stage; b, cutting the first border rows (R1 and R6) of intercropped alfalfa; c, cutting the first border rows and second border rows (R1, R2, R5, R6) of intercropped alfalfa; d, the all six rows (R1, R2, R3, R4 R5, R6) of intercropped alfalfa.

2.4.2. Land equivalent ratio (LER)

The advantage of intercropping was evaluated using the LER, calculated as follows:

$$LER = \frac{Y_{IW}P_W}{Y_W} + \frac{Y_{IA}P_A}{Y_A}, \tag{2}$$

where, Y_{IW} and Y_{IA} are the yields of wheat and alfalfa, respectively, in the intercropping system; Y_W and Y_A are the yields of wheat and alfalfa, respectively, in the sole cropping system; and P_W and P_A represent the planting proportions of wheat and alfalfa, respectively, in the intercropping system. An LER $>$ 1.0 indicates that the efficiency of land use in the intercropping system is better than that in the sole cropping system, whereas a values $<$ 1.0 indicates that intercropping negatively effects the efficiency of land use.

2.4.3. Water productivity

The WP values of wheat and alfalfa were calculated on the basis of grain yield and aboveground biomass yield, respectively, according to the following formula:

$$WP = \frac{Y}{ET_c}, \tag{3}$$

where, WP (kg m^{-3}) is the water productivity, Y (kg ha^{-1}) is the yield of crop, and ET (m^3 ha^{-1}) is the WU of the crop systems.

Using the above formula (3), the WP values of the intercropping and sole cropping systems were calculated as follows:

$$WP_I = \frac{P_W Y_{IW} + P_A Y_{IA}}{P_W WU_{IW} + P_A WU_{IA}}, \tag{4}$$

$$WP_S = \frac{P_W Y_{SW} + P_A Y_{SA}}{P_W WU_{SW} + P_A WU_{SA}}, \tag{5}$$

where, WP_I and WP_S (kg m^{-3}) represent the total WP of the intercropping and sole cropping systems, Y_{IW} and Y_{IA} (kg ha^{-}) represent intercropped wheat and alfalfa yields, Y_{SW} and Y_{SA} (kg ha^{-1}) represent the yields of sole wheat and sole alfalfa. WU_{IW}, WU_{IA}, WU_{SW}, and WU_{SA} (m^3 ha^{-1}) represent the total WU of intercropped wheat, intercropped alfalfa, sole wheat, and sole alfalfa. P_W and P_A represent the planting proportions of wheat and alfalfa in the intercropping system.

2.4.4. Changes in WU (ΔWU)

The WU advantage of intercropping systems relative to sole cropping systems was assessed through the calculation of ΔWU calculated as follows (Mao et al., 2012):

$$\Delta WU = \frac{WU_I}{PLER_W WU_{SW} + PLER_A WU_{SA}} - 1, \tag{6}$$

where, ΔWU is the changes in water capture by intercrops relative to that by sole crops; WU_I (m^3 ha^{-1}) is the total WU of the intercropping system; and $PLER_W$ and $PLER_A$ are partial LERs for intercropped wheat and alfalfa, respectively.

2.4.5. Changes in WP (ΔWP)

Based on the concept of "the change in water-use efficiency by intercropping relative to that by sole crops (ΔWUE)" (Morris and Garrity, 1993), we here propose the change in WP by intercropping relative to that by sole crops (ΔWP), calculated as follows:

$$\Delta WP = \frac{Y_I/WU_I}{PLER_W Y_{SW}/WU_{SW} + PLER_{WA} Y_{SA}/WU_{SA}} - 1, \tag{7}$$

where, ΔWP is the changes in WP; WU_I (mm) is the total WU of the intercropping system; $PLER_W$ and $PLER_A$ are partial LERs for intercropped wheat and alfalfa, respectively; Y_I (kg ha^{-1}) is the intercropping yield; Y_{SW} (kg ha^{-1}) is the yield of sole wheat; and Y_{SA} (kg ha^{-1}) is the yield of sole alfalfa.

2.5. Statistical analysis

Statistical analyses were performed using SPSS software (SPSS Statistics 26.0, SPSS Institute Ltd., USA). All data were analyzed using one-way ANOVA. Means were compared using Duncan's multiple range test at $p < 0.05$. All graphs were constructed using Origin 2021 software (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Yield and LER

The yield of the intercropping system yield was significantly higher by 8.7 %−21.2 % and 16.3 %−31.0 % compared to the average yield of sole cropping system in 2022 and 2023, respectively (Table 1). The yield of intercropped wheat under T treatment showed a significant decrease of 25.6 % (2022) and 12.7 % (2023) compared with that of sole wheat (Fig. 3). In 2022, the T-20C1 treatment resulted in significantly ($p < 0.05$) lower wheat yields than those of sole cropping. However, no other treatments showed significant effect on yield compared to sole wheat across both years. Compared with treatment T, the modified cutting regimes (T-10C1, T-20C3, T-10C2, and T-10C3) enhanced intercropped wheat yields by 23.3 %—46.3 % (2022) and 13.9 %—20.4 % (2023). For alfalfa, all intercropping treatments (T-20C1, T-20C2, T-10C1, T-10C2, T-10C3, and T) significantly increased yields relative to sole alfalfa stands, by 45.4 %—48.8 % in 2022 and 44.6 %—49.7 % in 2023. Except for the intercropping T treatment in 2022, the LERs of all other intercropping systems over the two study years were > 1 (Table 1). In particular, the highest LER of 1.15 and 1.21 was achieved under the T-10C2 treatment in 2022 and in 2023, respectively.

3.2. Proportional yield contribution by different alfalfa cuts

Across treatments T-20C1, T-10C1, T-10C2, and sole alfalfa, the yield contribution of alfalfa exhibited a consistent descending pattern of first cut > second cut > third cut > fourth cut (Fig. 4). In contrast, the remaining treatments demonstrated peak productivity during the second cut. Comparative analysis revealed that in 2022, the first-cut yield contribution ratio of intercropped alfalfa was reduced by 0.3 %—11.5 % relative to sole alfalfa across all treatments except T-10C1. This reduction more pronounced in 2023, as all intercropping treatments exhibited lower contribution of first-cut compared to monoculture. The T-20C3 treatment exhibited the most substantial decrease in first-cut yield over both experimental years. Conversely, the second and third cuts of intercropped alfalfa consistently resulted in higher yield contributions compared to sole cropping.

Table 1
Total yields and land equivalent ratios (LERs) for wheat/alfalfa intercropping in 2022 and 2023 in Qingyang, China.

Year	2022		2023	
Treatment	Total yield (t ha^{-1})	LER	Total yield (t ha^{-1})	LER
T−20C1	14.52 ± 0.26[a]	1.11 ± 0.02[a]	14.8 ± 0.35[ab]	1.15 ± 0.03[b]
T−20C2	14.44 ± 0.14[a]	1.14 ± 0.01[a]	13.64 ± 0.19[c]	1.10 ± 0.01[bc]
T−20C3	12.18 ± 0.33 [cd]	1.03 ± 0.02[bc]	12.15 ± 0.07[d]	1.03 ± 0.004[d]
T−10C1	13.69 ± 0.30[ab]	1.08 ± 0.03[ab]	13.89 ± 0.32[c]	1.12 ± 0.03[b]
T−10C2	14.16 ± 0.18[a]	1.15 ± 0.02[a]	15.30 ± 0.24[a]	1.21 ± 0.01[a]
T−10C3	13.90 ± 0.44[ab]	1.14 ± 0.03[a]	14.29 ± 0.12[bc]	1.16 ± 0.007[ab]
T	13.01 ± 0.28[bc]	0.99 ± 0.02[c]	13.59 ± 0.15[c]	1.07 ± 0.002 [cd]
Sole cropping	11.98 ± 0.46[d]	-	11.69 ± 0.27[d]	-

Note: Specific details of alfalfa cutting treatments (T-20C1, T-20C2, T-20C3, T-10C1, T-10C2, T-10C3, and T) are shown in Fig. 2. Values for the intercropped wheat and alfalfa are based on a comparable land area equivalent to that of the sole crops. Land equivalent ratios are calculated from the averaged grain yields. Values followed by the same superscript letters in the same column are not significantly different between different treatments for the same crop in the same year based on the LSD test at $p< 0.05$.

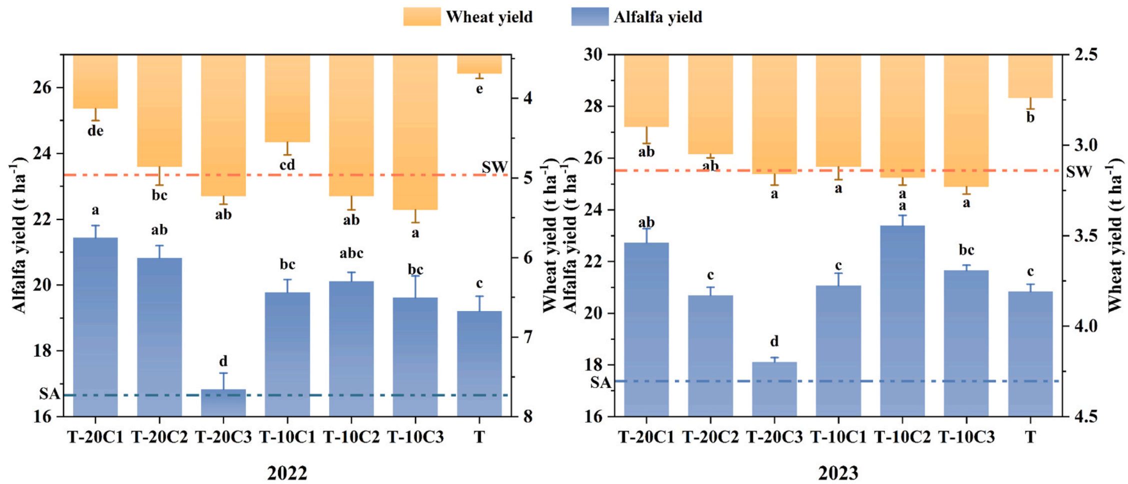

Fig. 3. Comparison of wheat and alfalfa yields (t ha⁻¹) in monoculture and wheat/alfalfa intercropping systems over two growing seasons. Specific details about treatments are shown in Fig. 2; SW, sole wheat; SA, sole alfalfa. Different lowercase letters above bars indicates significant differences ($p < 0.05$) among different treatments.

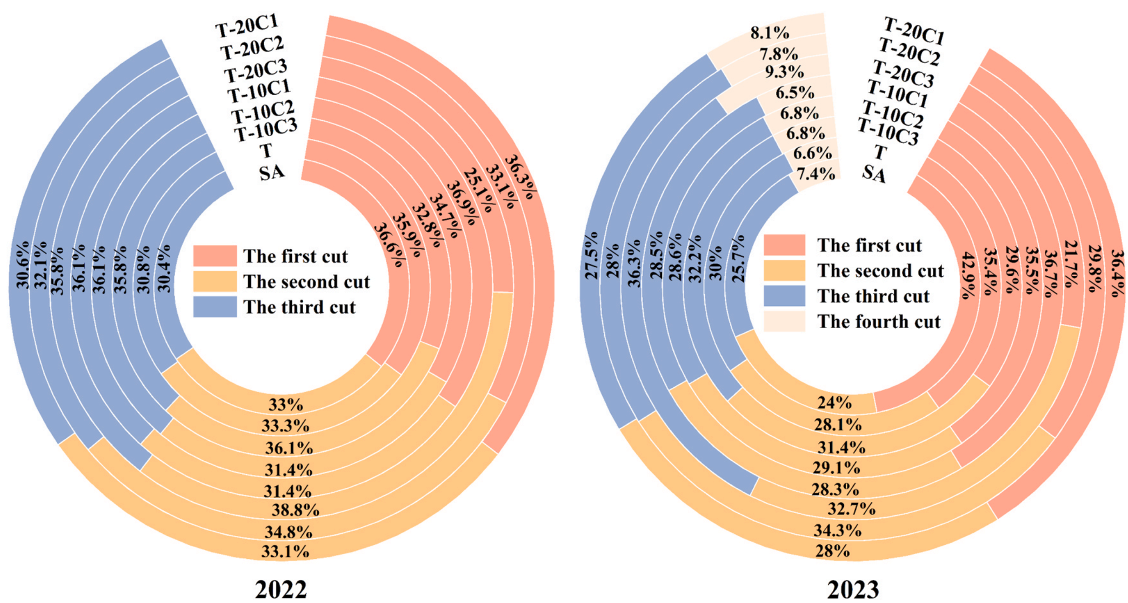

Fig. 4. Contribution ratio of alfalfa yields for different cuts of alfalfa in 2022 and 2023. Specific details about treatments are shown in Fig. 2; SA, sole alfalfa.

3.3. Water use, ΔWU, WP, and ΔWP of the intercropping and sole cropping system

Compared with the sole cropping system, the WU of all treatments in the intercropping system decreased by 1.1 %—13.1 % in 2022 (Fig. 5). In 2023, the WU of the T-10C2 and T treatments in the intercropping system increased by 8.7 % and 7.0 %, respectively, while that of the remaining treatments decreased by 4.4 %—14.3 % relative to the sole cropping system. The WP of the intercropping system was higher than that of the sole cropping system in both years, with increases of 0.1 %–24.0 % in 2022 and 7.7 %—23.5 % in 2023. Additionally, the WP of the intercropping system significantly exceeded that of sole wheat by 147.1 %—205.7 % in 2022 and by 300 %—358 % in 2023. However, the WP of the intercropping system was 17.3 %—27.8 % lower than that of sole alfalfa in 2023. In 2022, all treatments exhibited negative values for ΔWU (Table 2), while in 2023, the T-10C2 and T treatments exhibited positive values. Conversely, all treatments recorded positive values for ΔWP in both 2022 and 2023.

3.4. Water use and WP of wheat

In 2022, the WU of intercropped wheat under the T-10C3 treatment was 8.6 % higher than that under the T treatment (Fig. 6). In 2023, intercropped wheat under the T-10C1 and T-10C3 treatments showed WU increases of 6.7 % and 8.0 %, respectively, compared with that of sole wheat, and the T-10C3 treatment exhibited 8.9 % higher WU compared with the T treatment. The WP of intercropped wheat under the T treatment was 20.4 % lower in 2022 and 15.6 % lower in 2023 compared with that of sole cropping. However, relative to the T treatment, WP under the T-20C2, T-20C3, T-10C1, T-10C2, and T-10C3 treatments increased by 17.7 %—35.3 % in 2022, while the T-20C3, T-10C2, and T-10C3 treatments resulted in 10.1 %—20.2 % higher WP in 2023.

3.5. Water use and WP of alfalfa

In 2022, the WU of the first alfalfa cut in intercropping treatment T-20C3 showed a significant 17.7 % reduction compared with that of sole

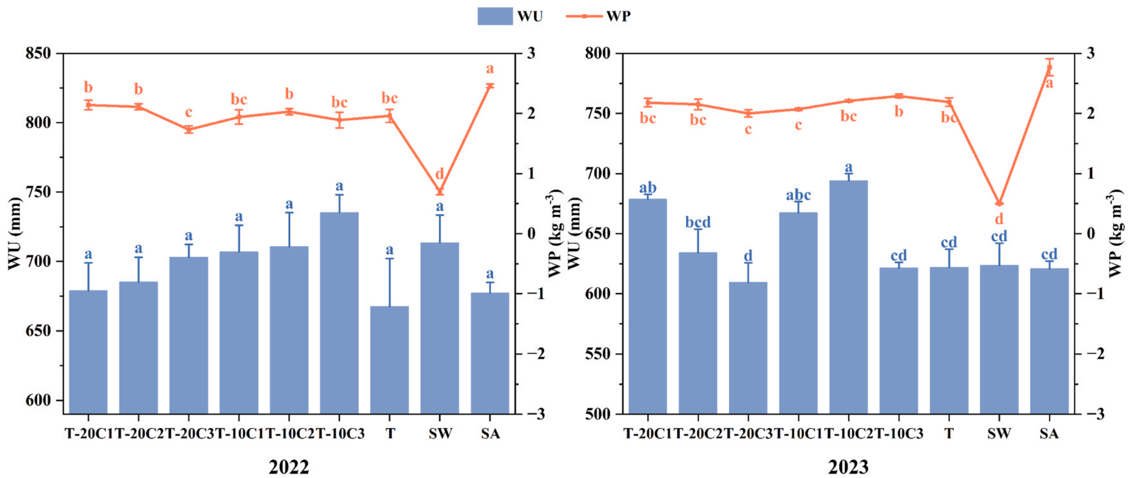

Fig. 5. Water use (WU) and water productivity (WP) of intercropping and sole cropping systems in 2022 and 2023. Specific details about treatments are shown in Fig. 2; SW, sole wheat; SA, sole alfalfa. Different lowercase letters above bars indicates significant differences ($p < 0.05$) among different treatments.

Table 2
Differences in water use (ΔWU) and water productivity(ΔWP) of wheat/alfalfa intercropping in 2022 and 2023 in Qingyang, China.

Year	2022		2023	
Treatment	ΔWU (%)	ΔWP (%)	ΔWU (%)	ΔWP (%)
T−20C1	-11.0 ± 4^{a}	24.0 ± 4^{a}	-5.5 ± 4^{a}	17.3 ± 4^{abc}
T−20C2	-13.1 ± 2^{a}	21.8 ± 3^{a}	-7.9 ± 4^{ab}	15.5 ± 5^{abc}
T−20C3	-1.1 ± 2^{a}	0.1 ± 3^{b}	-5.5 ± 2^{a}	7.7 ± 3^{c}
T−10C1	-4.8 ± 6^{a}	12.0 ± 7^{ab}	-4.4 ± 1^{a}	11.2 ± 1^{bc}
T−10C2	-11.6 ± 1^{a}	17.4 ± 3^{ab}	8.7 ± 0.3^{ab}	18.7 ± 1^{ab}
T−10C3	-6.1 ± 6^{a}	9.0 ± 6^{ab}	-14.3 ± 9^{b}	23.5 ± 2^{a}
T	-2.2 ± 5^{a}	13.0 ± 7^{ab}	7.0 ± 2^{ab}	18.3 ± 3^{abc}

Note: ΔWU indicates the water use difference between intercropping and sole cropping, and ΔWP indicates the water productivity difference between intercropping and sole cropping. Specific details of alfalfa cutting treatments are shown in Fig. 2. Values followed by the same superscript letters in the same column are not significantly different between different treatments in the same year based on the LSD test at $p < 0.05$.

alfalfa. This reduction became more pronounced in 2023, with the intercropping treatments T-20C3, T-10C3, and T recording 21.4 %—35.5 % lower WU values than that of sole alfalfa (Fig. 7). For the second cutting in 2022, intercropped alfalfa under the T-20C2 and T treatments displayed significant WU increases of 29.4 % and 29.5 %, respectively, relative to sole alfalfa. The third cutting in 2022 recorded a 24.8 % WU reduction under the T-20C2 treatment, while in 2023, treatments T-20C1, T-20C3, T-10C1, and T-10C2 resulted in 12.0 %—31.8 % higher WU values when compared with that of sole alfalfa. The fourth cutting in 2023 exhibited a notable 40.8 % WU increase under the T-10C3 treatment relative to sole alfalfa.

The WP of the first cut of intercropped alfalfa in 2022 was significantly elevated under the T-20C1, T-20C2, T-10C1, and T-10C2 treatments, by 22.5 %—43.9 % relative to sole alfalfa. Conversely, in 2023, the T-20C2 and T-20C3 treatments recorded 35.9 %—37.4 % WP reductions relative to the T treatment (Fig. 8). Compared with that of sole alfalfa, the WP of the second cutting of intercropped alfalfa increased by 8.5 %—76.5 % in 2022 and 47.4 %—102.8 % in 2023, while that of the third cutting increased by 19.1 %—84.7 % in 2022 and 12.9 %—76.7 % in 2023.

4. Discussion

4.1. Effect of cutting management in intercropped alfalfa on yield

In many agricultural systems, including those in China, intercropping is primarily adopted to enhance land productivity. However,

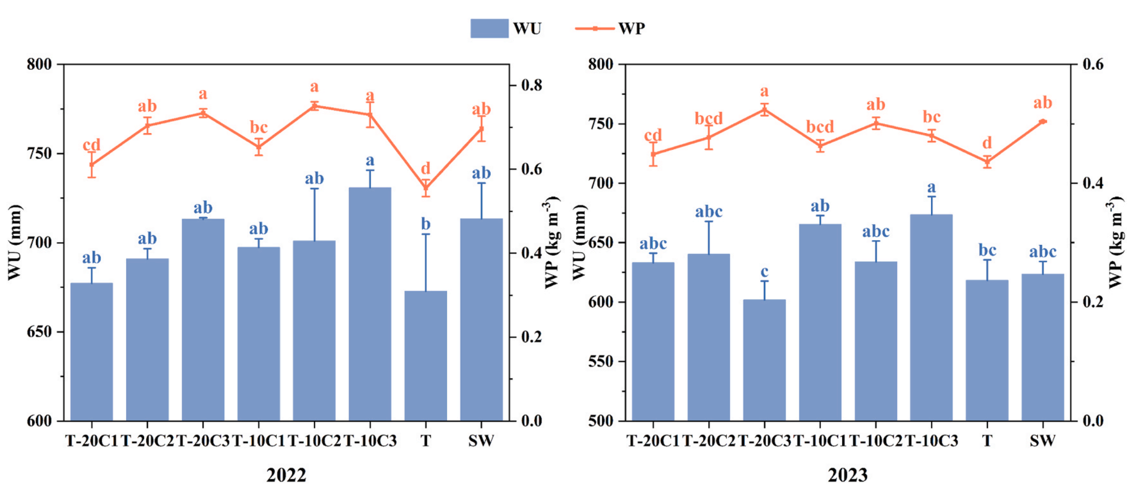

Fig. 6. Water use (WU) and water productivity (WP) of sole and intercropped wheat in 2022 and 2023. WU indicates water use; WP indicates water productivity. Specific details about treatments are shown in Fig. 2; SW, sole wheat. Different lowercase letters above bars indicates significant differences ($p < 0.05$) among different treatments.

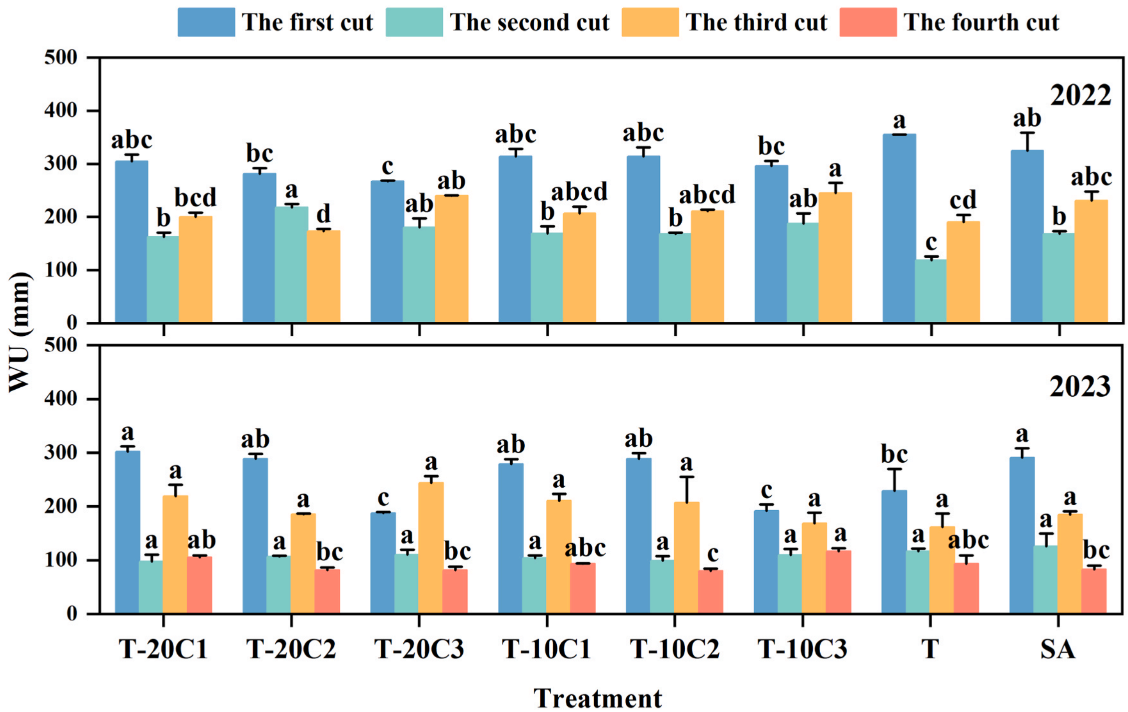

Fig. 7. Water use (WU) of sole and intercropped alfalfa in terms of the different cuts of alfalfa in 2022 and 2023. WU indicates water use. Specific details about treatments are shown in Fig. 2; SA, sole alfalfa. Different lowercase letters above bars indicates significant differences ($p < 0.05$) among different treatments.

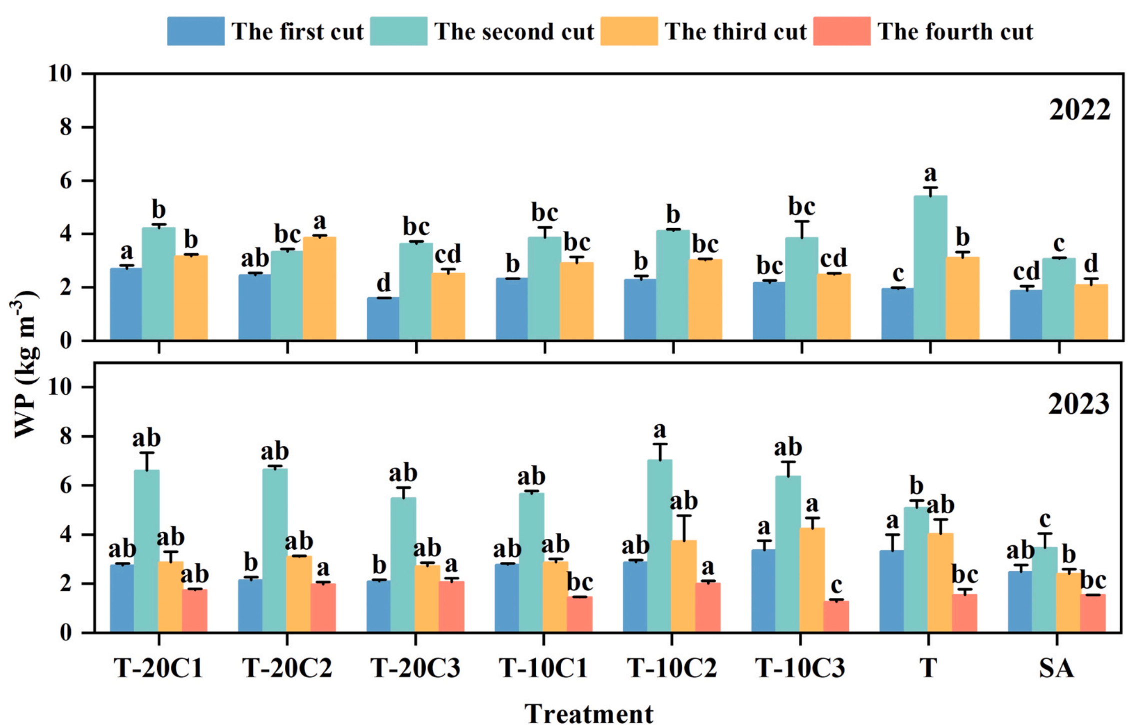

Fig. 8. Water productivity (WP) of sole and intercropped alfalfa in terms of the different cuts of alfalfa in 2022 and 2023. WP indicates water productivity. Specific details about treatments are shown in Fig. 2; SA, sole alfalfa. Different lowercase letters above bars indicates significant differences ($p < 0.05$) among different treatments.

cultivated grasslands under ecological restoration programs (e.g., alfalfa in the Grain-for-Green initiative) often degrade over time owing to economically driven management neglect (Li et al., 2024). Although studies confirm that wheat/alfalfa intercropping outperforms monocultures in terms of productivity—offering potential for sustainable grassland rehabilitation—realizing this potential requires balanced interspecies relationships, as well as balance between the border-row effect and recovery growth. Crop combinations, row ratios, and strip spacing are the examples of optimized spatial configurations that can reduce niche competition (Brooker et al., 2015; Chen et al., 2024; Wang et al., 2023), but established systems lack adaptability to dynamic field conditions, ultimately constraining yield stability and optimization. This limitation motivated our investigation into spatiotemporal management through alfalfa cutting schedules as an alternative yield-regulation approach. Our two-year field experiment demonstrated that strategic early cutting of alfalfa (particularly in the T-20, T-10C1, T-10C2, and T-10C3 treatments before first flowering) significantly boosted system yields relative to monocultures without compromising wheat production (Table 1, Fig. 3). Although alfalfa was cut in advance at the first harvest and did not obtain the maximum yield, the yield increase derived exclusively from enhanced alfalfa productivity, revealing that intercropped alfalfa requires management that is distinct from monoculture regimes. Compared with conventional intercropping (T treatment), optimized first-cut timing preserved wheat yields while increasing alfalfa output (Fig. 3), maintaining the land use advantage of the system (LER>1). These results demonstrate that modification of cutting schedules is both necessary and effective to unlock the full yield potential of wheat/alfalfa intercropping systems.

The yield increase observed in this study primarily stems from the compensatory growth mechanisms within the intercropping system, especially for treatments involving the advance cutting of one or two rows of alfalfa. Our earlier study (Wan et al., 2024) demonstrated the recovery growth of wheat, and herein we observed the recovery growth of alfalfa. We infer that this coupled recovery growth of two crops synergistically enhanced system productivity. Such recovery growth patterns are well established in intercropping systems. When early maturing crops are harvested, the reduction in both aboveground and belowground competition enables late maturing crops to access more resources, thereby reducing yield penalties and potentially increasing overall productivity (Ma et al., 2020b; Wu et al., 2022). This temporal resource complementarity effectively optimizes growth conditions for both crop components. Our findings corroborate previous research that demonstrated similar patterns in other systems. In wheat/maize intercropping, maize typically exhibits recovery growth after wheat harvesting (Ma et al., 2020b), while in our wheat/alfalfa system, where alfalfa is the dominant species (Magid et al., 1991), the dynamic is reversed. Following early cutting, wheat exhibited significant recovery growth (Wan et al., 2024), ultimately resulting in wheat yields that matched or exceeded sole cropping yields (Table 1). Compared with the complete cutting of intercropped alfalfa strips, reducing the number of pre-cut alfalfa rows offers dual advantages—maximizing alfalfa yield retention during the first harvest while simultaneously supporting wheat regrowth. This phenomenon can be attributed to niche differentiation and border-row effects. Border-row effects of dominant crops have been widely observed in various strip intercropping systems, including wheat/maize, maize/soybean, and maize/peanut intercropping (Li et al., 2020; Shen et al., 2023; Wang et al., 2020). By selectively cutting one or two rows of the competitively dominant alfalfa, this practice effectively removes the border-row effect, with this strategic removal stimulating recovery growth in both species. This dual effect is clearly reflected in LER values, with the T-20C2 and T-10 treatments achieving the highest ratios (Fig. 3), confirming their superior system-level performance. This approach enhances overall system productivity more effectively than treatments involving the complete cutting of intercropped alfalfa strips. Our results also demonstrate that the 6:6 wheat—alfalfa row ratio configuration represents a compact planting system. Typically, the wheat proportion may be increased or the row spacing widened during initial planting to eliminate or mitigate competition during the co-growth period. However, this approach can result in an excessively low proportion of alfalfa after wheat harvesting, leading to large areas of idle land and inefficient resource utilization. This markedly reduces the yield in subsequent growth cycles, ultimately causing a decline in total productivity and a lower LER. We define such pre-determined adjustments (e.g., species composition, field management, and row-spacing ratios) as external regulation of intercropping systems, which operates outside of the crop growth process. In contrast, we define human interventions that directly influence the growth of crops in intercropping systems as internal regulation. The different cutting methods proposed herein serve as internal regulation, allowing flexible adjustments to row ratios and overcoming the inflexibility and rigidity of external regulation.

The optimal cutting treatments exhibited effectiveness in response to the interannual variability (Table 1). Cooler temperatures and altered precipitation patterns in 2023, particularly during the key growth stages, had a substantial impact on influenced crop responses to cutting regimes. This climate dependent variation highlights the need for adaptive management strategies in grain forage intercropping systems, where optimal cutting schedules may require adjustments based on seasonal conditions. Climatic conditions across different years variably affect the growth performance of wheat and alfalfa, necessitating strategic cutting during their peak competition phase to optimize resource utilization. For example, low temperatures during the early growing season can inhibit wheat growth, delaying the period of intense interspecies competition between wheat and alfalfa. In such cases, premature cutting or excessive removal may lead to resource wastage, because the wheat cannot fully utilize the available resources. An optimal cutting strategy can be determined based on climatic conditions and growth performance during the early co-growth phase. Such management flexibility represents a crucial mechanism to enhance system resilience to climate variability, including temperature fluctuations, precipitation changes, and periodic droughts. Future research should focus on quantifying these climate—treatment interactions to develop predictive models that can inform decision making under variable environmental conditions.

4.2. *Effects of cutting management in intercropped alfalfa on water use advantage*

In arid and semi-arid regions, water scarcity is a critical limiting factor for ecosystem productivity (Wang et al., 2025a). Efficient water resource utilization is therefore essential to maintain the stability of these ecosystems. The wheat/alfalfa intercropping system studied here demonstrates how niche differentiation can enhance WP while supporting ecosystem resilience. Intercropping increases biodiversity, creating temporal and spatial niche separations between species (Schmutz and Schöb, 2023; Yu et al., 2022). This enables more efficient use of available resources, including limited water supplies (Wang et al., 2023). The improved WP in intercropping systems not only sustains productivity (Ma et al., 2024) but also enhances the capacity of the system to withstand environmental stresses (Tao et al., 2024; Wang et al., 2025b), a key aspect of long-term stability in water-limited ecosystems.

Our results show that wheat/alfalfa intercropping improves WP compared with that seen in sole cropping systems (Fig. 5). All intercropping systems achieved WP values similar to or significantly higher than monocultures. Early cutting of alfalfa further optimized WU (Figs. 7 and 8), with the T-20C2 and T-10C3 treatments increasing ΔWU by 13.1 % and 14.3 % in 2022 and 2023, respectively (Table 2). The interannual variation in optimal cutting regimes (e.g., delayed cutting in 2023 owing to poor wheat growth) highlights how adaptive management can reduce niche overlap and improve system stability under variable conditions. Soil evaporation represents a major component of WU in these systems (Yin et al., 2019). In 2023, cold spells impaired wheat growth, resulting in unused resources after alfalfa cutting and increased evaporative losses. Despite higher WU, the intercropping system maintained a WP comparable to or better than that of sole cropping. This demonstrates the inherent stability of the system—the ability to maintain function despite climatic disturbances. These findings suggest that the adjustment of alfalfa cutting during co-growth with wheat can significantly improve WP. Such management strategies optimize both the productivity and sustainability of intercropping systems under variable climatic conditions (Liu et al., 2025), offering valuable insights for the maintenance of stable ecosystems in arid regions, where water scarcity is a persistent challenge.

Previous studies have demonstrated that WU in intercropping systems is influenced by environmental conditions and crop species (Li et al., 2023a, 2001a, 2001b; Ma et al., 2020a). In wheat/alfalfa intercropping systems, wheat serves as the subordinate crop (Magid et al., 1991). Under conventional cutting practices, the WP of intercropped wheat is generally lower than that of sole wheat owing to competitive suppression by alfalfa during the co-growth period. However, early cutting of alfalfa alters this dynamic, with some intercropped wheat treatments exhibiting WP values comparable to or even exceeding those of sole cropping (Fig. 6). This shift likely stems from reduced interspecies competition, thereby allocating increased water resources to wheat during its critical growth stages. A detailed analysis of WP revealed a notable contrast: while the T treatment significantly reduced WP in intercropped wheat (by 20.4 % in 2022 and 15.6 % in 2023) relative to sole cropping, modified treatments markedly improved efficiency. In 2022, WP under the T-20C2, T-20C3, T-10C1, T-10C2, and T-10C3 treatments increased by 17.7 %—35.3 % relative to the standard T treatment. Similarly, in 2023, the T-20C3, T-10C2, and T-10C3 treatments sustained this positive trend, enhancing WP by 10.1 %—20.2 %. These findings highlight the potential of targeted treatment combinations to significantly enhance WP in intercropping systems, offering valuable insights for sustainable water management in cultivated grasslands.

Optimal alfalfa cutting strategies should be adjusted according to interannual climate variability during the co-growth period. In wet years with sufficient precipitation, increasing the number of pre-cut alfalfa rows can effectively reduce water competition pressure on wheat. Conversely, under drought conditions, decreasing the number of pre-cut rows may help maintain the adequate growth of alfalfa as a high water-demand crop. In conclusion, early cutting of alfalfa during the critical growth stages of wheat can optimize the allocation and utilization of limited water resources in wheat/alfalfa intercropping systems, thereby maximizing overall system benefits.

4.3. Implications

In recent years, water shortages have attracted widespread global attention (Grafton et al., 2015; Zhang et al., 2023). Given this water shortage condition, intercropping represents an effective approach for fostering sustainable ecosystems. This study represents a novel approach to systematically regulating growth dynamics during co-growth phases in intercropping systems. Our results establish that optimized alfalfa cutting management during wheat/alfalfa co-growth of wheat and alfalfa significantly improves overall system productivity (Durodola et al., 2025; Thakur et al., 2016). This innovative approach delivers dual agricultural benefits, simultaneously enhancing alfalfa biomass production while maintaining wheat yields at or above monoculture levels. Crucially, we demonstrate that temporal cutting regulation dramatically improves water use efficiency, with most treatments achieving WP values that match or exceed those of conventional sole cropping systems. These findings address pressing challenges in the rehabilitation of degraded grasslands, particularly in the context of managed cultivated grasslands. In the Loess Plateau, where extensive grassland restoration has yielded ecological improvements but encountered socioeconomic constraints, our methodology provides a balanced solution for ecological restoration and agricultural productivity. The proven climate resilience associated with our methodology makes it particularly valuable for drought-prone regions experiencing increased climatic variability. This research advances sustainable ecosystem management through the simultaneous optimization of production and resource efficiency. Future studies should focus on elucidating the integrated mechanisms governing nutrient, light, and thermal resource utilization within such systems, which will be essential to develop scalable implementation frameworks.

Herein, we have innovatively proposed a novel approach to enhance the productivity and WP of cultivated grasslands and agricultural ecosystems through intercropping system regulation. The scientific feasibility of this approach is undeniable, however, its practical implementation may encounter skepticism from agronomists and crop specialists. They may contend that it considerably increases management complexity, potentially leading to cost increases relative to yield gains and ecological benefits. The emergence of smart agriculture, leveraging the intelligence and automation aspects of Industry 4.0, will facilitate a swift transition of traditional agriculture from stage 1.0 and 2.0 to the Agriculture 4.0 characterized by flexible and controllable practices. Here, we take intercropping as an example and divide it into four stages: stage 1.0 refers to the intercropping model when compared with sole cropping systems; stage 2.0 involves the external regulation of intercropping, including water and nutrient management, row ratios, and species (variety) combinations; stage 3.0 emphasizes internal regulation during the growth process of intercropping systems (this study belongs to this stage); and stage 4.0 integrates smart agriculture to harness the biodiversity advantages of intercropping systems. According to resource conditions, it enables flexible and precise adjustments, markedly enhancing system productivity and resource-use efficiency. Our proposed approach maximizes ecological benefits, strengthens environmental conservation, and minimizes the negative impacts of agricultural production on the environment.

Currently, intercropping systems still adhere to traditional simplistic cultivation practices, crop varieties and water—fertilizer management. With the advent of 'Industry 4.0' and the advancement of smart agriculture, there is an urgent need to develop more intelligent and efficient management approaches for intercropping systems. The internal regulation proposed herein elevates intercropping systems to a new level. This study implements zonal alternation and dynamic adjustment of grassland through partial cutting, thereby enhancing the productivity of intercropping systems Future integration of this approach with intelligent, unmanned, and miniaturized agricultural machinery may lead to the emergence Agriculture 4.0 in intercropping systems, defined by cost-effectiveness and high production efficiency.

5. Conclusions

This study demonstrates the dual benefits of optimized alfalfa cutting management in wheat/alfalfa intercropping systems. The findings indicate that optimized cutting regulation not only substantially enhances system productivity but also achieves efficient water resource utilization by improving WP and reducing WU. This approach provides an innovative solution for ecological restoration and sustainable development in cultivated grasslands within arid regions. Through coordinated management of cutting timing and row arrangement, it maintains forage yield is maintained while synergistic optimization between agricultural WU and ecological water requirements is achieved. Observed interannual variations highlight the adaptability of this technical system to different climatic conditions, providing a scientific basis for the development of region-specific grassland management strategies. Ultimately, this research offers a practical pathway to balance agricultural production and ecological conservation in water-limited ecosystems.

CRediT authorship contribution statement

Longshuai Ma: Writing – review & editing, Writing – original draft, Project administration. **Guanrong Dai:** Writing – review & editing, Visualization, Investigation. **Fangru Wan:** Writing – original draft, Investigation. **Xiaozheng Wang:** Writing – review & editing. **Yinjuan Li:** Writing – review & editing. **Baoqing Zhang:** Writing – review & editing, Supervision.

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.

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Data availability

Data will be made available on request.

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