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Evaluating the Combined Effects of Water and Fertilizer Coupling Schemes on Pear Vegetative Growth and Quality in North China

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Abstract: Unreasonable fertilizer and irrigation applications and dosages in orchards in northern China result in poor vegetative growth and fruit quality. To reveal the combined effect of water and fertilizer coupling on vegetative growth and fruit quality, this study used pear as a field experiment material, considering: (1) irrigation lower limits (55%, 65%, 75%θ_f, θ_f is field capacity) and (2) nitrogen fertilizer application (162, 324, 486 kg·ha^{-1}). Nine coupling schemes and a control treatment (C) were set up in the orthogonal combination. The results showed that, under the higher irrigation rate and nitrogen dose, the spring shoot length, base diameter, and leaves relative chlorophyll content values were increased by 36.77%, 31.86% and 12.91%, respectively. The response of each coupling scheme was different. However, selected water and nitrogen coupling schemes improved the fruit quality. The evaluation results indicated that medium irrigation and high fertilizer scheme were optimal. In conclusion, integrating the vegetative growth and fruit quality, it is recommended that the water and fertilizer coupling scheme for pear in the northern China is as follows: a lower irrigation limit of 65%θ_f and a nitrogen fertilizer amount of 486.00 kg·ha^{-1}.

Keywords: golden pear tree; drip irrigation; water and fertilizer coupling schemes; vegetative growth; fruit quality; comprehensive evaluate

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1. Introduction

Improving global agriculture for food and water security to satisfy burgeoning population growth and mitigate environmental impacts has become an important goal in recent years [1–5]. With the improvement of people's living standards, demand for fruits in China has significantly increased [6], and people's requirements are more demanding in terms of both fruit quantity and quality. Fresh fruit plays a significant role in the daily diet and is a good source of vitamins [7], various carbohydrates, and microelements [8]. China has been the world's largest pear producer since 1977; the fruit cultivation area has increased by approximately 25% in the last two decades, and pear is one of the main fruit trees planted in China [9,10]. According to the FAO's statistical data, the pear production of China accounts for approximately 68.4% of the world production [11]. The Beijing-Tianjin-Hebei region is one of the main pear production regions [12,13].

The pear tree consumes large amounts of water and has high nutrient requirements. Precipitation and pear tree requirements are not well aligned temporally or spatially [14,15], and inaccurate water and fertilizer management schemes and other problems have caused soil moisture and nutrients to fail meeting the requirements of tree growth, severely restricting the development of the pear industry. In addition, the traditional 'abundant water and fertilizer' production and management model is predominant [16], resulting in low water and fertilizer availability rates and even causing serious soil and water environmental problems. Irrigation and fertilization are two important controllable factors that affect crop yields. The fertilizer application rates were beyond the safer limits according to the investigations by Chinese Ministry of Agriculture [17].

Many scholars have reported that water and fertilizer coupling technology can maintain soil moisture and nutrient contents at optimal levels for crop absorption [17–20], fruit tree vegetative growth [21], yield increases [22–24], and improved efficiency of irrigation water and fertilizer use [25,26]. Additionally, it remains extremely important to improve fruit quality [27] and increase fruit photosynthetic capacity. Water and fertilizer coupling technology can increase the average fruit weight in shallow-rooted densely planted 'Fuji' apples, with better fruit flavour quality and a high fruit rate [28]. There is a critical threshold for the optimal effects of water and fertilizer coupling [29]. When the value is lower than the critical value, the effect of increasing water and fertilizer inputs is expected to increase as well, and excessive application of water and fertilizer may result in insignificant or even reduced production [21,30,31].

Although previous researchers have made many achievements in terms of identifying fertilizer application rates and irrigation amount for fruit trees, especially pear trees, there is relatively less research in this area. Many scholars have conducted research on yield and utilization rate of water and fertilizer based on a certain aspect of irrigation or fertilization. However, there are few studies on vegetative growth process and fruit quality in mature areas of pear trees under water and nitrogen coupling schemes with different irrigation lower limits and nitrogen application rates, and no comprehensive evaluation has been carried out. Thus, further research is needed to help formulate water and fertilizer schemes for the pear tree.

To investigate the combined effect of water and fertilizer coupling schemes on pear tree vegetative growth and fruit quality, we took pear trees (*Pyrus pyrifolia* cv. 'Whangkeumbae') as the field experimental material. We used an evaluation tool to comprehensively evaluate the schemes to provide support for pear production in North China.

2. Materials and Methods

2.1. Experimental Site Description

The experiments were conducted during March-October 2018 in a pear orchard at Beijing Daxing Manor (39°37′ N, 116°25′ E), China. The average annual precipitation is 556.4 mm, and the average sunshine duration is 2459 h. The annual average temperature is 11.6 °C, the frost-free period is 185 d, and the warm temperate zone has a semi-humid continental monsoon climate. The soil is a sandy loam with uniform texture. The soil bulk density is 1.59 $g \cdot cm^{-3}$, and field capacity θ_f (volume water content) in the moist layer is 35%. The meteorological data such as max and min temperature (°C), wind speed ($m \cdot s^{-1}$) and relative humidity (%) (Figure 1) were obtained from an automatic weather station (HOBO U30, Onset, Bourne, MA, USA). Irrigation and fertilizer coupling practices are based on drip irrigation and fertilization integrated systems. The first hub of fertigation technology was equipped with a set of proportional fertilizing pumps and fertilizing barrels. The local irrigation mode of the experimental orchard was drip irrigation with a single line, and the irrigation water was groundwater. Laboratory analyses, including of fruit quality, were carried out at the 'Weishanzhuang' Station of Beijing Engineering Technology Research Center of National Water Saving Irrigation.

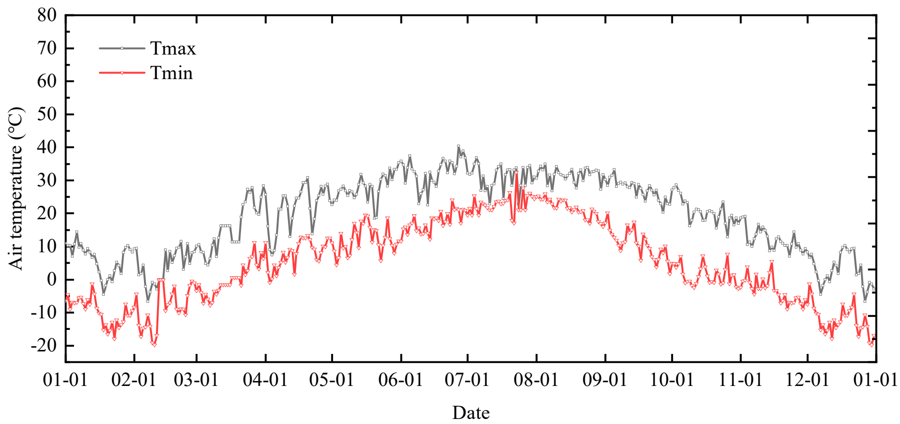


Figure 1. Meteorological data map of the field experiment site. The black line expresses the maximum air temperature (T_{max}); the red line is the minimum air temperature (T_{min}).

2.2. Experimental Treatments

Ten-year-old golden pear trees (*P. pyrifolia* cv. 'Whangkeumbae') were used as the test material, and the rootstock is *Pyrus betulifolia* 'Bunge'. Because the nutrient reserve of the tree in the previous growing season is the basis for flowering, fruit setting, leafing and develop shoots in the following growing season, we chose fruit trees with the same appearance, such as tree height and crown, for the first experimental design. The two factors of the experiment were: (1) irrigation lower levels: I_H (75%θ_f), I_M (65%θ_f), and I_L (55%θ_f), and the irrigation upper limit was field capacity (θ_f) in all treatments; and (2) nitrogen fertilizer amounts were set to three levels: N_H (486 kg·ha^{-1}), N_M (324 kg·ha^{-1}), and N_L (162 kg·ha^{-1}). Nine water and fertilizer coupling schemes were set by orthogonal combination (Table 1). Figure 2 shows irrigation amount and precipitation at each growth stage. In this study, the local irrigation and fertilizer mode of drip irrigation with a single line was used as a C. The control treatment did not include fertilizer application, and the irrigation system was managed by the manor based on experience.

Table 1. Irrigation water and nitrogen fertilizer applications in different treatment schemes during different growth stages.

	Irrigation Treatment				Nitrogen Application/(kg·ha^{-1})			
	Lower Limit	**Upper Limit**	**Total Amount/ (m^3·ha^{-1})**	**Times**	**Pre-Bloom**	**Young Leaves Stage**	**Fruit Expansion**	**Total Amount**
C	-	-	3040.0	6	0.0	0.0	0.0	0.0
I_LN_H	55.0%θ_f	100.0%θ_f	790.0	5	194.4	97.2	194.4	486.0
I_LN_M	55.0%θ_f	100.0%θ_f	790.0	5	129.6	64.8	129.6	324.0
I_LN_L	55.0%θ_f	100.0%θ_f	790.0	5	64.8	32.4	64.8	162.0
I_MN_H	65.0%θ_f	100.0%θ_f	860.0	6	194.4	97.2	194.4	486.0
I_MN_M	65.0%θ_f	100.0%θ_f	860.0	6	129.6	64.8	129.6	324.0
I_MN_L	65.0%θ_f	100.0%θ_f	860.0	6	64.8	32.4	64.8	162.0
I_HN_H	75.0%θ_f	100.0%θ_f	1140.0	7	194.4	97.2	194.4	486.0
IHN_M	75.0%θ_f	100.0%θ_f	1140.0	7	129.6	64.8	129.6	324.0
I_HN_L	75.0%θ_f	100.0%θ_f	1140.0	7	64.8	32.4	64.8	162.0

Where: θ_f is the field water capacity, and CK follows conventional management.

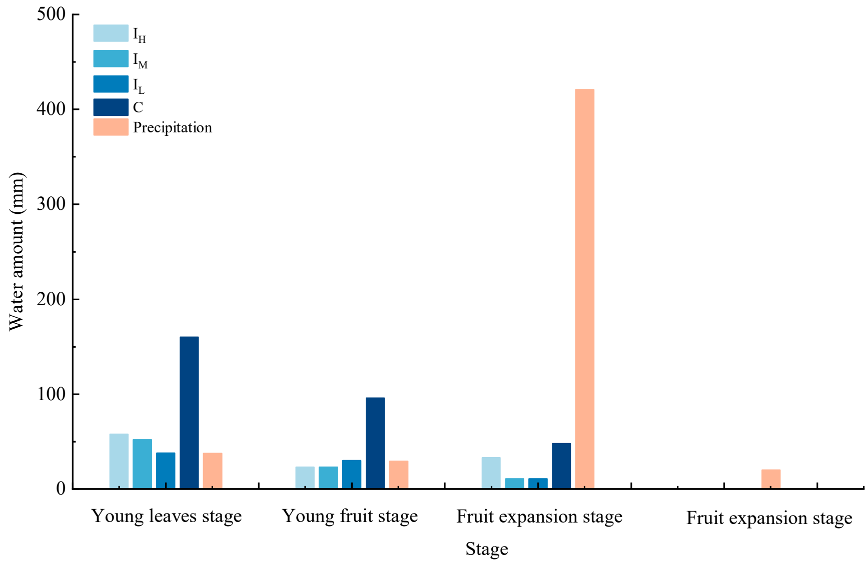


Figure 2. Irrigation amount and precipitation value in each stage.

Each experimental scheme area was equally divided into three plots, each plot as a trial replicate, with a total of three replicates set for each scheme, and they measured 45 m $\times$ 4 m. There was one row of pear trees planted for each treatment, with 15 pear trees in each row, and trees were planted at a row spacing of 4 m and plant spacing of 3 m. A total of 150 tree were selected, and 30 trees were select to be measured. The drip irrigation pipes were arranged on the west side of the pear trees, 20 cm away from the trees, and the spacing between the drip emitters was 0.25 m. (Figure 3). $CO(NH_2)_2$ with 46% nitrogen was applied to fulfil the nitrogen requirements. In addition, field management measures, such as pruning, plant disease and insect pest control, and flower and fruit thinning, were applied based on conventional methods.

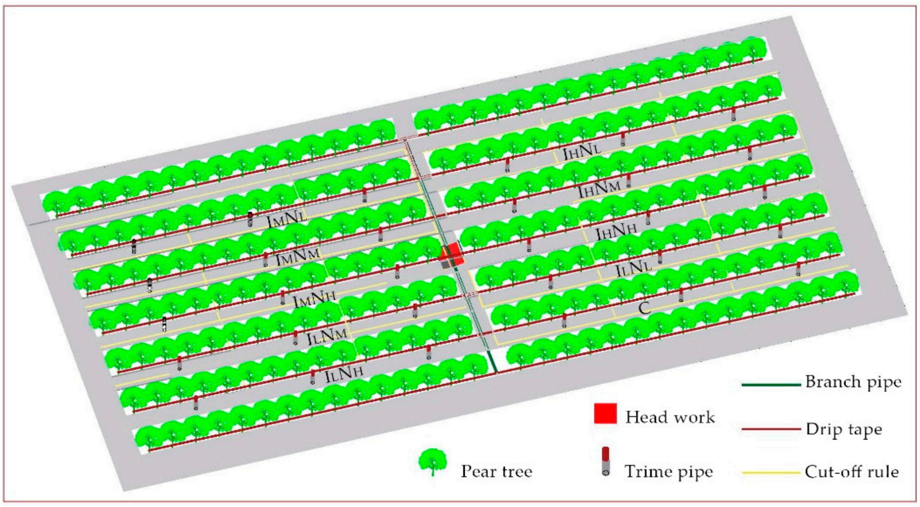


Figure 3. Layout of the experimental area.

2.3. Pear Tree Irrigation and Fertilizer Application

Soil moisture monitoring was performed by TRIME-PICO-IPH (IMK0, Germany) at three-day intervals. TRIME-PICO-IPH was calibrated for the experimental soil before data collection. TRIME-PICO-IPH was used to measure the soil moisture content in the pear tree moist layer, and one test point was measured three times for each scheme. A trime pipeline was arranged in each test repetition area to monitor soil moisture status, with three trime pipes arranged for each scheme (Figure 3). The measurement results were averaged within the experimental treatment. When the average soil water moisture was below the irrigation lower limit, irrigation was applied, and the irrigation water amount was calculated as follows:

$$m = 0.1 \cdot p \cdot h \cdot (\theta_f - \theta_t)/\eta \quad (1)$$

In the calculation formula of the irrigation amount, m is the irrigation quota (mm): γ p is the soil wetting ratio (0.8 in this experiment); and h is the planned wet layer depth (cm). According to the distribution range of the root system of fruit trees and the distribution of soil moisture after a period of monitoring, the planned depth of the moist layer is 100 cm; θ_f is the field water capacity, θ_t is the soil water content at time t, and the irrigation water limit is determined according to the plan. The upper limit of irrigation is the field water capacity; and η is the surface irrigation water utilization factor (0.9 under this test condition).

During the growth period of the pear trees, fertilization was carried out three times, namely, the pre-bloom (3 April, 40%), the young leaves stage (6 May, 20%), and the fruit enlargement stage (20 July, 40%). The irrigation and fertilization system are shown (Table 1).

2.4. Experimental Indicators and Methods

2.4.1. Spring Shoot Length and Base Diameter

Three plants were randomly selected in each scheme. We used a tape to measure the spring shoot length and a Vernier calliper to measure the spring shoot base diameter. One pear tree was selected in each experimental plot, and three branches were selected in each of the four directions of the selected pear tree. Taking the average value after the measurement, the above two indicators were measured every two weeks during the growth period.

2.4.2. Leaf Area and SPAD Values

In each experiment replicate, a pear tree was randomly selected, and three spring shoots were randomly selected in four directions. Three leaves were randomly selected to measure the leaf area and chlorophyll (SPAD). A ruler was used to determine the maximum length and width of the blade. In the first measurement, 60 leaves from each treatment were randomly selected and brought back to the laboratory to determine the length and width, and the actual leaf area was scanned with an instrument to obtain fitting (Equation (2)):

$$\mathrm{A} = 0.7186 \cdot b \cdot l + 0.7153 \quad (2)$$

where A is the fitted blade area (cm^2); l is the maximum length of the blade (cm); and b is the maximum width of the blade (cm).

The relative content of chlorophyll was measured using a SPAD-502. Leaf area and SPAD values were measured every two weeks.

2.4.3. Fruit Volume and Weight Measurement

One tree was randomly selected in each repetition, and ten fruits were randomly selected for each pear tree, and we used a 15 cm Vernier calliper to measure the longitudinal diameter of the fruit once and the transverse diameter twice in opposite directions and calculated the average. The fruit's horizontal and vertical diameters were measured every three weeks. The actual volume was measured by the drainage method. According to the fruit volume measured by the drainage method and the horizontal and vertical diameters of the fruit, fitting equations were generated. Since the fruit growth speed of the pears at different growth stages was different, fitting Equations (3) and (4) were obtained:

$$V_1 = 0.58\ c + 0.315\ d - 14.271 \quad (3)$$

$$V_2 = 4.582\ c + 2.783\ d - 312.269 \quad (4)$$

where V is the fitted fruit volume (cm^3); c is the average diameter of the fruit (cm); and d is the longitudinal value of the fruit (cm).

During the harvest period, one tree was randomly selected in each test plot, and 15 fruits were randomly selected from each plant, and we used a balance to measure the fruit weight and calculated the average.

2.4.4. Fruit Quality

During the harvest period, one tree was randomly selected in each repetition, and 15 fruits were randomly selected from each plant. Three fruits were randomly selected in each plot. The fruits showed similar sizes, no mechanical damage, no pests, or other diseases, and they had typical characteristics. After picking, they were stored in a fresh ice box and shipped back to the laboratory at low temperature and stored frozen at −80 °C; the 2,6-dichlorophenol indophenol titration method was used to determine the content of ascorbic acid (AA); a handheld refractometer (RHBO-90) was used to determine the total soluble solids content (TSS) of the fruit; and the NaOH standard solution titration method was used to determine the titratable acidity content (TA) of the fruit.

2.5. TOPSIS Analysis

The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is a useful method to evaluate schemes by multiple factors. Many scholars use it to judge which process is optimal for the user's aims [32–36]. This method can yield order preferences by similarity to obtain ideal solutions. This article focuses on the analysis of spring shoot length, base diameter, leaf area, leaf SPAD value and fruit quality, and the changes of each index with the amount of irrigation and nitrogen, as well as the coupling effect of water and nitrogen, but not all indicators were considered altogether. Therefore, we used TOPSIS method to evaluate the comprehensive effect of coupling schemes on golden pear tree spring shoot length, base diameter, leaf area and SPAD, and fruit quality.

Vector normalization was performed by the following relationship to obtain a normalized decision matrix:

$$r_{ij} = \frac{X_{ij}}{\sum\limits_{j=1}^{m} X_{ij}} \tag{5}$$

where r_{ij} is the normalized performance value, X_{ij} is the factor to normalize, and m = 8.

The Euclidean distance for the ideal best value was calculated by using Equation (5).

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2} \tag{6}$$

where $S_i{}^+$ is the Euclidean distance for the ideal best value, $V_j{}^+$ is the ideal best value from the weighted normalized matrix, m = 8, and w is the weight factor constant for individual fruit quality parameters to obtain the weight normalized decision matrix.

The Euclidean distance for the ideal worst value was calculated by using Equation (7).

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2} \tag{7}$$

where $S_i{}^-$ is the Euclidean distance for the ideal worst value, and $V_j{}^+$ is the ideal best value from the weighted normalized matrix.

The overall performance score was calculated by using Equation (8).

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{8}$$

where P_i (from 0 to 1) is the quality index (performance score); the greater the index value is, the superior the performance of the treatment.

2.6. Statistical Analysis

The spring shoot length, spring shoot diameter, and fruit quality data were recorded by Excel 2019 (Microsoft Office 2019). LSD multiple range tests were applied to compare the mean values of each treatment when significant differences were detected using $p < 0.05$ as a significance level. SPSS version 25 (SPSS, Chicago, IL, USA) was used. Two-way ANOVA was performed using the analysis of variance procedure in SPSS 25 (SPSS, Chicago, IL, USA).

3. Results

3.1. Effect of Different Treatments on Spring Shoot Length and Base Diameter

The slope of the growth curve of spring shoot length of tree changed from steep to gentle, and this indicates that the growth speed of spring shoot length is from fast to slow. (Figure 4), and the increase value of the base diameter of the spring shoot was large in young leaves stage and fruit expansion stage, compared to young fruit stage (Figure 5). Table 2 shows that the last value of the tree spring shoot length under all water and fertilizer coupling schemes except I_LN_L was significantly different when compared to C. The difference between the treatment of the spring shoot base diameter for C and I_LN_L was not significant, but it was significantly different from those of other water and fertilizer coupling schemes. The results of the table show that the last value of the spring shoot length and base diameter of trees under water and fertilizer coupling schemes were greater than the C value and were positively correlated with the amount of water and nitrogen applied (Figures 4 and 5). Increasing irrigation water amount and nitrogen application dose can significantly increase the base diameter of spring shoot, but there was no significant difference in the response of spring shoot length to nitrogen application rates. Irrigation water amount and nitrogen application dose had no significant interaction effect on the increase in spring shoot length and base diameter of spring shoot (Table 3).

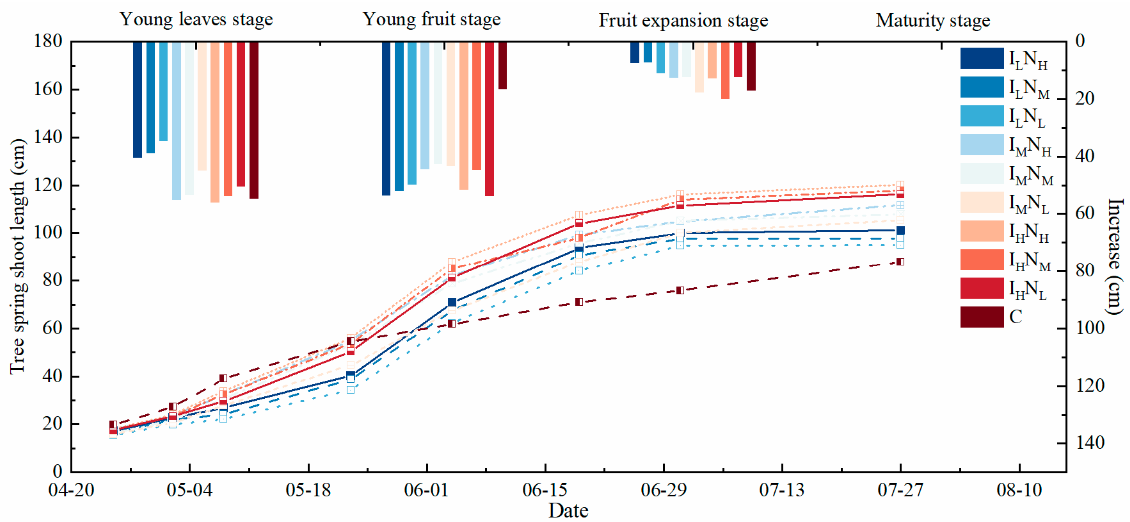


Figure 4. Variation of spring shoot length during the growing season (lines) and increase among development stages (bars) under different water and fertilizer coupling schemes. The data are the mean values measured within the three repetitions (points). The bar is the amount of stage growth increase, the difference between the mean of the next stage, and the mean of the previous stage.

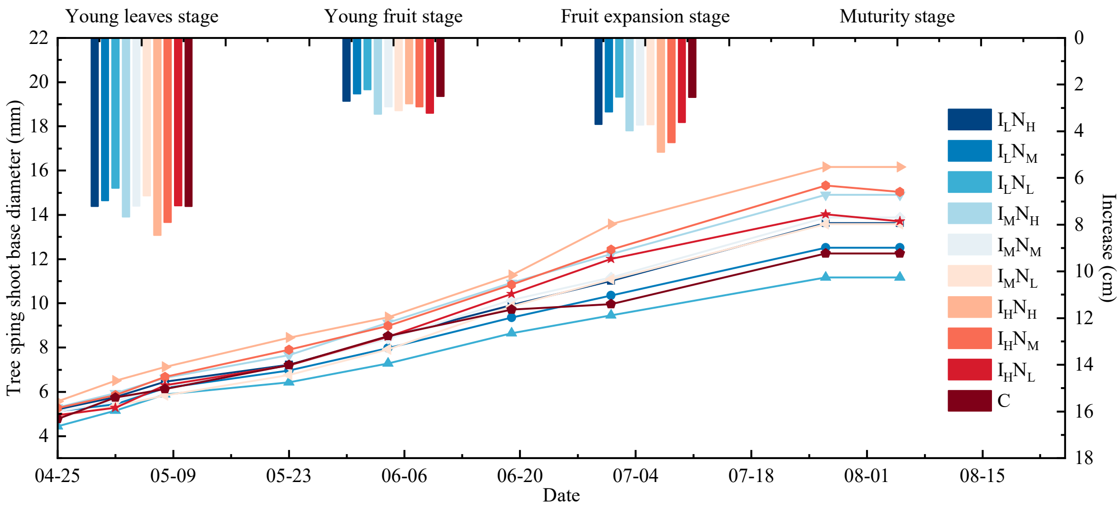


Figure 5. Variation of spring shoot base diameter during the growing season (lines) and increase among development stages (bars) under different water and fertilizer coupling schemes. The data are the mean values measured within the three repetitions (points). The bar is the amount of stage growth increase, the difference between the mean of the next stage, and the mean of the previous stage.

The spring shoot length growth curve during the growing period was S-shaped. The rapid growth period occurred between the young leaves stage and the young fruit stage, and difference between water and nitrogen coupling schemes occurred after the flower leaf stage (Figure 4). After the young fruit stage, the length of the spring shoot of the C and water and nitrogen coupling schemes was significantly different. The spring shoot length under I_HN_H, I_HN_M, I_HN_L and I_MN_H treatments was significantly higher than that under C, I_LN_H, I_LN_M, I_LN_L, I_MN_M and I_MN_L treatments. I_MN_M was significantly higher than that under C, I_LN_H, I_LN_M, and I_LN_L.

Figure 5 shows that the difference in base diameter growth of the spring shoot in schemes were not evident before the young fruit stage and began to differ afterwards. The spring shoot base diameter increased the most in young leaves stage, medium in fruit expansion stage, and the least in young fruit stage. There was no significant difference between I_LN_M and C, although the base diameter of spring shoot decreased under I_LN_M treatment. I_LN_H, I_LN_M, I_LN_L, I_MN_M, I_MN_L, and I_HN_L treatments were significantly different from I_MN_H, I_HN_H, and I_HN_M treatments. I_MN_H, I_HN_H, and I_HN_M treatments significantly increased the base diameter of spring shoot compared with other treatments. There are significant differences between I_LN_H, I_MN_M, I_MN_L and I_LN_M, I_MN_M, I_MN_L, and I_HN_L. The difference between I_LN_M and I_LN_L is significant, and $I_LN_M > I_LN_L$.

Table 2. Spring shoot vegetative traits (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season.

Index	I_LN_H	I_LN_M	I_LN_L	I_MN_H	I_MN_M	I_MN_L	I_HN_H	I_HN_M	I_HN_L	C
Length/cm	101.12 ± 10.33 ^{cd}	97.66 ± 2.57 ^{d}	94.98 ± 3.22 ^{de}	115.49 ± 4.33 ^{a}	107.87 ± 1.43 ^{b}	105.32 ± 1.17 ^{bc}	120.17 ± 5.69 ^{a}	117.88 ± 1.73 ^{a}	116.19 ± 0.72 ^{a}	87.86 ± 3.67 ^{e}
Base diameter/cm	1.36 ± 0.07 ^{b}	1.25 ± 0.04 ^{c}	1.12 ± 0.10 ^{d}	1.52 ± 0.06 ^{a}	1.37 ± 0.00 ^{b}	1.36 ± 0.03 ^{b}	1.62 ± 0.08 ^{a}	1.53 ± 0.01 ^{a}	1.40 ± 0.01 ^{b}	1.23 ± 0.06 ^{c}

Where: Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

Table 3. Leaf area and SPAD (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season.

Index	I_LN_H	I_LN_M	I_LN_L	I_MN_H	I_MN_M	I_MN_L	I_HN_H	I_HN_M	I_HN_L	C
Leaf area/cm^2	67.56 ± 6.56 ^{b}	66.53 ± 2.23 ^{b}	69.24 ± 3.10 ^{ab}	71.48 ± 4.84 ^{ab}	69.99 ± 0.07 ^{ab}	74.86 ± 2.18 ^{a}	74.42 ± 3.93 ^{a}	74.38 ± 1.15 ^{a}	74.58 ± 1.73 ^{a}	73.28 ± 2.65 ^{a}
Leaf SPAD	45.32 ± 1.14 ^{de}	44.78 ± 0.45 ^{de}	44.17 ± 0.74 ^{e}	46.78 ± 0.96 ^{bc}	45.52 ± 0.49 ^{d}	45.70 ± 0.34 ^{cd}	50.12 ± 0.61 ^{a}	47.46 ± 0.56 ^{b}	45.30 ± 0.20 ^{de}	44.39 ± 0.41 ^{e}

Where: Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

3.2. Effect of Different Treatments on Leaf Area and SPAD Values

The change curve and increase in leaf area and SPAD values at each stage are shown in Figures 6 and 7, and the value at the end of the growing season in Tables 3 and 4. The leaf area at the last stage of the I_MN_L treatment was 74.86 cm^2, and that of the I_LN_M treatment was the 66.53 cm^2 (Table 3). The I_MN_L was greater than the I_LN_M by 8.33 cm^2. Increasing the irrigation and fertilizer application rates had no significant effect on the increase in leaf area, and there was no significant interaction (Table 4).

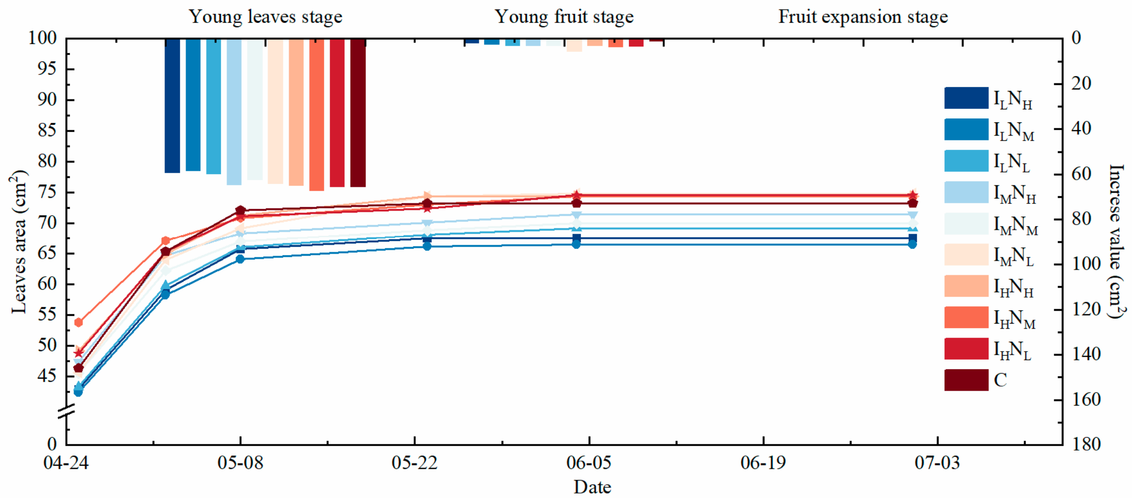


Figure 6. Variation of leaf area during the growing season (lines) and increase among development stages (bars) under different water and fertilizer coupling schemes. The data are the mean values measured within the three repetitions (points). The bar is the amount of stage growth increase, the difference between the mean of the next stage, and the mean of the previous stage.

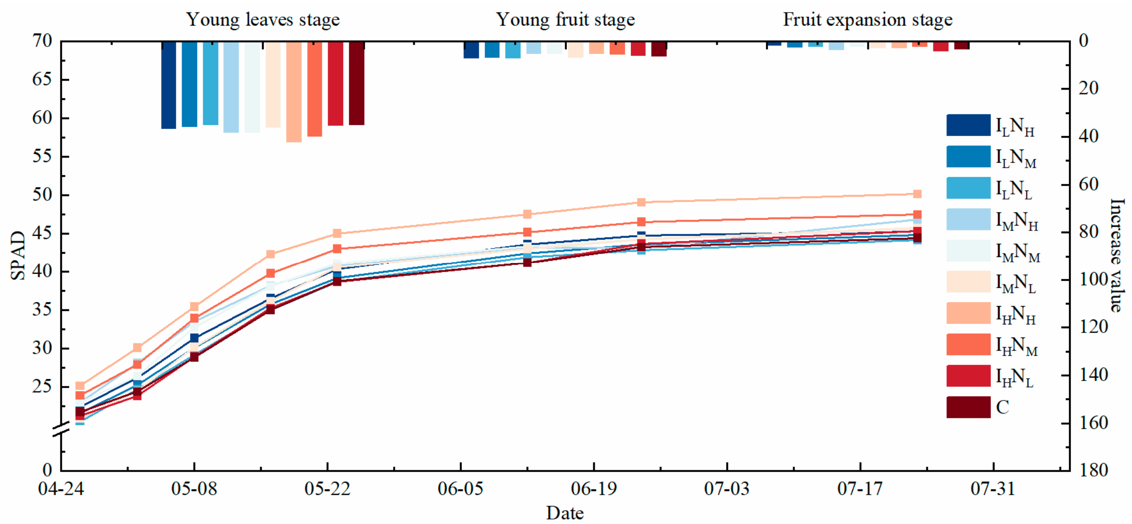


Figure 7. Variation of leaf SPAD during the growing season (lines) and increase among development stages (bars) under different water and fertilizer coupling schemes. The data are the mean values measured within the three repetitions (blocks). The bar is the amount of stage growth increase, the difference between the mean of the next stage, and the mean of the previous stage.

Table 4. Two-way ANOVA results.

Index	Spring Shoot Length	Spring Shoot Base Diameter	Leaf Area	SPAD	Fruit Volume	Fruit Weight	TSS	TA	AA
Irrigation lower limit	***	***	ns	***	ns	ns	ns	ns	*
Nitrogen fertilizer application	ns	***	ns	***	*	*	*	ns	*
Interaction I × N	ns	ns	ns	**	ns	**	*	ns	ns

Where: ns: not significant; *, ** and *** represents significance at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

The leaf area rapidly Increased before mid-May; however, after mid-May, the increase in the leaf area slowed. The leaf area of I_LN_H and I_LN_M treatment was significantly lower than that of C, which was reduced by 7.81% and 9.21%, respectively. There was no significant difference in leaf area between I_LN_L, I_MN_H, I_MN_M, I_MN_L, I_HN_H, I_HN_M, and I_HN_L treatments and C treatments. In addition, I_MN_L, I_HN_H, I_HN_M, I_HN_M, and I_HN_L treatments were significantly different from I_LN_H, I_LM_N treatments.

The change curve and increase in leaf SPAD values at each stage are shown in Figure 7. The SPAD value increased mainly at young leaves stage, but less at young fruit stage. The maximum SPAD value (I_HN_H) was 50.12. Except I_LN_L, the SPAD value of pear leaves under the water and nitrogen coupling schemes was higher than that of C, but I_LN_L treatment was not significantly different from C. I_MN_H, I_MN_M, I_MN_L, I_HN_H, and I_HN_M treatments were significantly different from C, and the corresponding five treatments increased by 12.91%, 6.92%, 5.38%, 2.95%, and 2.55%, respectively (Table 3). However, there was no significant difference between I_LN_H, I_LN_M, and I_HN_L treatments and C. There are significant differences between I_HN_H and other water–nitrogen coupling schemes. SPAD under I_HN_M treatment was significantly higher than I_LN_H, I_LN_M, I_LN_L, I_MN_M, I_MN_L, and I_HNL. The SPAD under I_MN_H, I_MNM and I_MN_L treatments was significantly higher than that of I_LN_L. The response of the SPAD value to increasing nitrogen fertilizer and irrigation rates separately was highly significant, and the interaction was significant (Table 4).

3.3. Effect of Different Treatments on Fruit Volume and Weight

Figure 8 shows the change curve for fruit volume during the growth period and the increases at each stage under the different drip water and fertilizer coupling schemes. Fruits volume expanded slowly at the young leaves stage and the young fruit stage, but they grew rapidly at the fruit expansion stage and slowed down at the mature stage. There was no difference between the treatments at the young leaves stage and the young fruit stage. After the fruit expansion period, the difference of fruit volume between water and fertilizer coupling schemes and C gradually appeared. Drip water and fertilizer coupling treatments significantly promoted fruit volume expansion, but the growth rate under the C in the fruit expansion period was reduced compared with that under the treatments, while the large increase in fruit volume in the C treatment in the maturity period was greater than that under the water and fertilizer coupling treatments (Figure 8).

The fruit volume under I_MN_H was 308.46 cm^3, and the minimum fruit volume under C was 255.27 cm^3. Except I_LN_L treatment, the other water and nitrogen coupling treatments significantly increased fruit volume, which was significantly different from C. I_MN_H, I_HN_H, I_HN_M, I_LN_H, I_MN_M, I_LN_M, I_HN_L, and I_MN_L were increased by 20.84%, 18.83%, 17.45%, 17.09%, 15.80%, 15.12%, 13.09%, and 12.90%, respectively, compared with C treatment (Figure 9a). In addition, some water and fertilizer coupling schemes were also significantly different. For example, I_HN_H differs significantly from I_MN_L and I_MN_M.

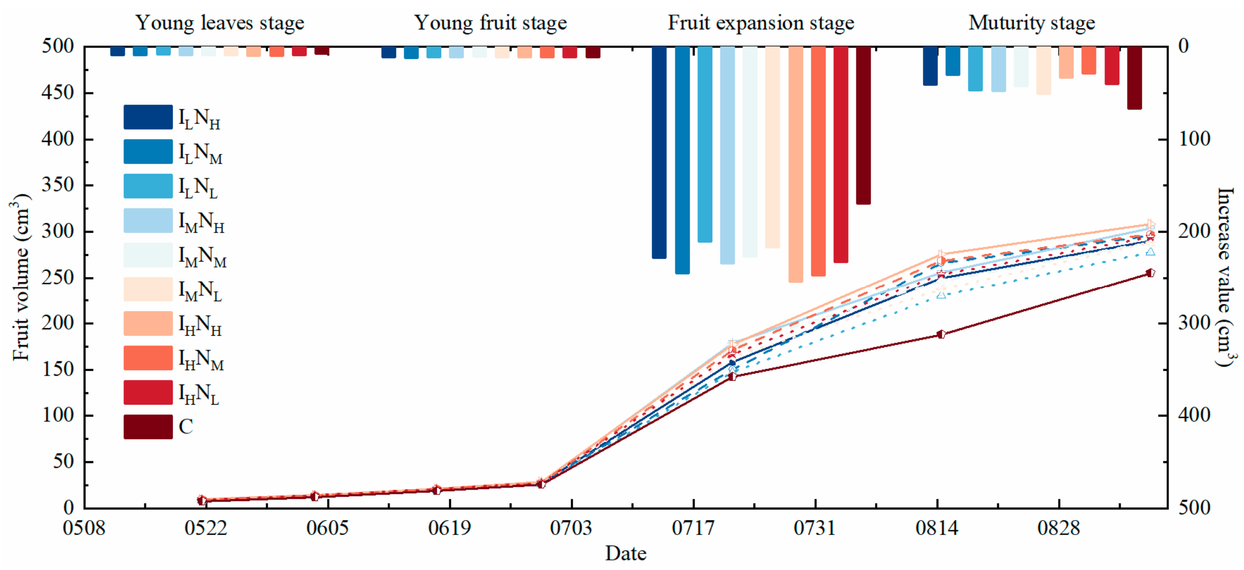
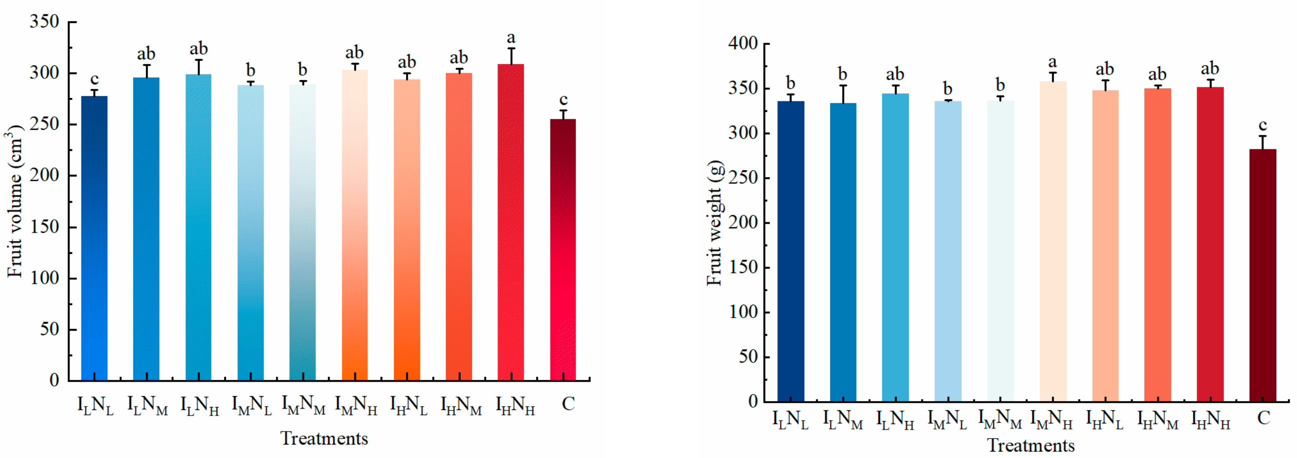


Figure 8. Variation of fruit volume during the growing season (lines) and increase among development stages (bars) under different water and fertilizer coupling schemes. The data are the mean values measured within the repetition (points). The bar is the amount of stage growth increase, the difference between the mean of the next stage, and the mean of the previous stage.



(**a**) Fruit volume (**b**) Fruit weight

Figure 9. Fruit volume (**a**) and weight (**b**) (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season. Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

The fruit weight under water and fertilizer coupling schemes was greater than the value under C (Figure 9b), and the difference was significant. In I_MN_H treatment, the maximum fruit weight was 357.83 g, which was 26.72% higher than that under C. There was no significant difference between the I_MN_H, I_LN_H, I_HN_H, I_HN_M, and I_HN_L treatments ($p > 0.05$) (Figure 9b). The change in lower irrigation limit had no significant difference in fruit weight. However, the effect of nitrogen application rate on fruit weight was significant (Table 4). In addition, interaction of both factors on fruit weight was significantly different.

The results showed that a suitable water and nitrogen coupling scheme has a significant effect on increasing fruit volume and fruit weight (Table 4). When the nitrogen application rate was lower than medium level, the fruit weight gradually increased with increasing irrigation amount, and the fruit weight increase was accelerated. When the irrigation amount was lower than 950 $m^3 \cdot ha^{-1}$ and the nitrogen application rate was higher than medium level, the fruit weight increased significantly with the increase in the nitrogen application rate, and the change rate in fruit weight was faster than when the irrigation amount was higher than 950 $m^3 \cdot ha^{-1}$.

3.4. Effects of Different Treatments on Fruit Quality

Comparing treatments in this experiment, I_LN_L, I_LN_M, I_LN_H, I_MN_H, I_HN_H, I_HN_M, and I_HN_L are significantly different from C. The total soluble solid content under I_HN_M treatment was 13.50% (Figure 10). When the nitrogen application rate is less than 250 $kg \cdot ha^{-1}$, it changed into a 'V' shape with the irrigation amount (Figure 11b). For fruit TSS, there was no unidirectional increase or decrease with the amount of irrigation and nitrogen application. TSS can only achieve the maximum value at the appropriate irrigation and nitrogen application rate. The minimum TSS value appeared in the elliptical area where the irrigation rate was greater than 1000 $m^3 \cdot ha^{-1}$ and the nitrogen application rate was less than 200 $kg \cdot ha^{-1}$. However, due to the interaction of the irrigation amount and the nitrogen application rate, when the irrigation amount was 900 $m^3 \cdot ha^{-1}$ and the nitrogen application rate was medium level, as shown in the elliptical area, the TSS value was relatively low.

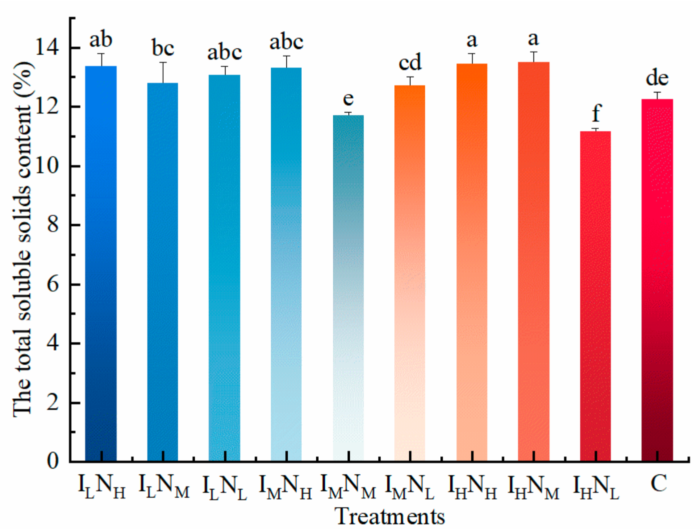
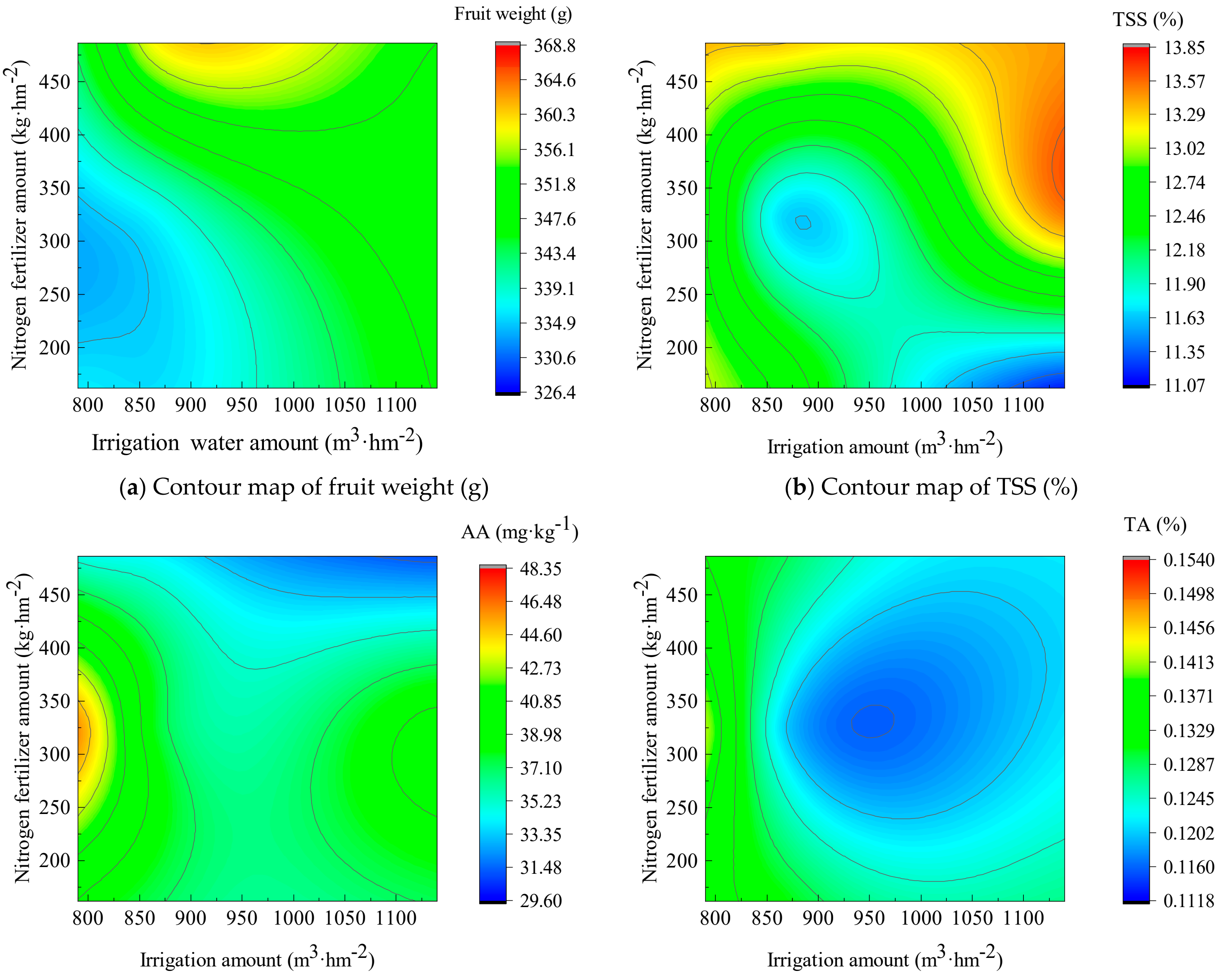


Figure 10. The total soluble solid content (TSS) (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season. Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

The highest AA value was observed in the I_LN_M treatment, an increase of 30.85% compared with the C value, while the I_HN_H treatment had the lowest value, which was 10.87% lower than that of C (Figure 12). The AA under I_LN_M treatment was 14.58 $mg \cdot kg^{-1}$ more than I_HN_H, and the different was significant. Comparing all schemes in this experiment, the I_LN_M, I_LN_L, and I_HN_H treatments were significantly different than C. When compared with C, I_LN_M, I_LN_L, and I_HN_M treatments increased AA in fruit, but AA of I_HN_H was significantly lower than C. Compared with other water and nitrogen coupling treatments, AA was significantly increased by I_LN_M treatment. The irrigation lower limit and nitrogen fertilizer amount significantly affected the AA of fruit, but the interaction on AA was not significant.



(**c**) Contour map of AA (mg·kg⁻¹)　　(**d**) Contour map of TA (%)

Figure 11. Contour map of fruit quality with irrigation amount and nitrogen application rate. (**a**): Change curve of fruit weight with irrigation amount and nitrogen application rate; (**b**): Change curve of the total soluble solid content (TSS) with irrigation amount and nitrogen application rate; (**c**): Change curve of AA with irrigation amount and nitrogen application rate; (**d**): Change curve of TA with irrigation amount and nitrogen application rate.

The fruit titratable acidity content (TA) is shown in Figure 13. Compared with C treatment, I_MN_M, I_HN_H, and I_HN_M treatment significantly reduced TA. TA content under I_LN_M treatment was significantly higher than the I_MN_M, I_HN_H, and I_HN_M schemes. The results showed that there was no significant difference in the effect of lower irrigation limit, nitrogen application rate, and interaction on TA. Too low or high irrigation and nitrogen application were unfavorable for reducing the titratable acid content in the fruit (Figure 11d). After the appropriate value (Fertilizer amount is medium level.), the titratable acid content of the fruit gradually increased. A suitable water and nitrogen coupling scheme can reduce the titratable acid content, and when the scheme is not suitable, it will lead to an increase in the titratable acid content of the fruit. The I_HN_M treatment was 0.1213, which was 13.05% lower than that of C.

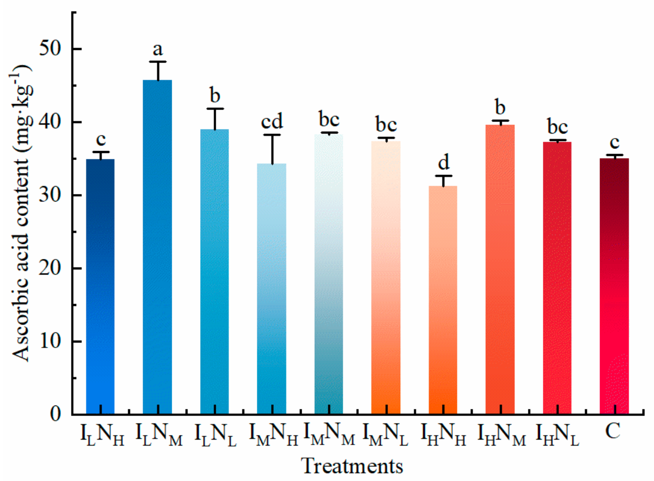


Figure 12. The ascorbic acid content (AA) (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season. Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

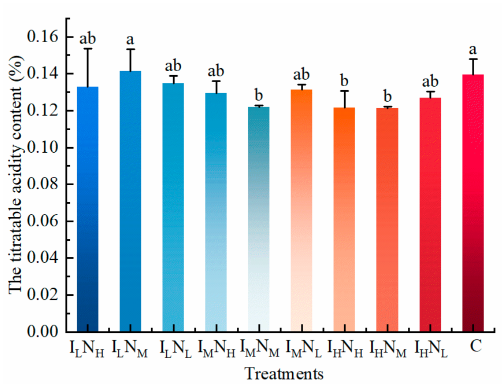


Figure 13. The titratable acidity content (TA) (mean ± standard deviation) under different water and fertilizer coupling schemes at the end of the growing season. Values within the same rows followed by different lowercase letters are significantly different at $p < 0.05$ according to the LSD test.

3.5. Evaluating Water and Fertilizer Coupling Schemes by TOPSIS Analysis

The TOPSIS method was selected to process, analyze, and evaluate the eight indexes of pear physiological growth and quality altogether. There is a significant correlation between some variables (Table 5), as is also the case between spring shoot length and leaf area, leaf SPAD value, and other parameters. However, we cannot substitute one variable for the other in the decision making, despite the correlation between indicators. This is because each variable represents a different aspect. For example, although there is a significant relationship between spring shoot length and TA, they represent physiological growth and fruit quality, respectively. Therefore, spring shoot length and base diameter, leaf area and SPAD, fruit weight, and quality variables should be used as evaluation indicators.

Table 5. Correlation analysis results.

	Spring Shoot Length	Spring Shoot Base Diameter	Leaf Area	SPAD	TSS	TA	AA	Fruit Weight
Spring shoot length	1.000							
Spring shoot base diameter	0.927 **	1.000						
Leaf area	0.773 *	0.615	1.000					
SPAD	0.793 *	0.866 **	0.571	1.000				
TSS	−0.230	0.212	−0.121	0.419	1.000			
TA	−0.809 **	−0.748 *	−0.674 *	−0.668 *	0.103	1.000		
AA	−0.552	−0.613	−0.456	−0.626	−0.121	0.558	1.000	
Fruit weight	0.809 **	0.797 *	0.453	0.666	0.307	−0.512	−0.640	1.000

Where: * and ** represents significant at $p < 0.05$ and $p < 0.01$, respectively.

Table 6 shows the evaluation results and the corresponding rankings. The highest comprehensive evaluation value was 0.599 for I_MN_H (Table 6). The evaluation values for each scheme were as follows: $I_MN_H > I_HN_H > I_HN_M > I_HN_L > I_LN_M > I_MN_L > I_LN_H > I_LN_L > I_MN_M$.

Table 6. Comprehensive evaluation results of tree vegetative growth and fruit quality by the TOPSIS method.

Treatments	I_LN_H	I_LN_M	I_LN_L	I_MN_H	I_MN_M	I_MN_L	I_HN_H	I_HN_M	I_HN_L
S_i^+	0.237	0.278	0.285	0.170	0.298	0.243	0.216	0.215	0.224
S_i^-	0.165	0.222	0.156	0.253	0.108	0.176	0.279	0.239	0.198
Pi	0.410	0.444	0.354	0.599	0.266	0.420	0.563	0.527	0.469
Rank	7	5	8	1	9	6	2	3	4

4. Discussion

Ben Colpaert et al. research show that spring application of N was most efficiently partitioned to leaves, fruits, and buds at the time of harvest [37]. Wu et al. found that fertilizer application could increase the dry weight and nitrogen absorption of pear trees and increase the residual amount of fertilizer nitrogen in soil. One time fertilization behind petal falls reduced fertilizer utilization [13,38]. Wu Yang et al. found that, together with routine fertilization management, changing the fertilization time promoted the growth of pear trees in rain-fed orchards and increased the quality of dry weight [39]. The number of soluble solids in heavy fruits greater than 400 g was reduced relative to control treatment [40]. Zhang et al. found that 2 g/L of mixed water increased the soluble solid content of the fruit [41].

4.1. Tree Spring Shoot Length and Base Diameter Dynamics

The vegetative growth is an important representation of the nutritional status of pear trees and an important guarantee of fruit growth and quality [42]. The spring shoot length and base diameter are the most direct indicators to measure the vegetative growth of golden pear trees. The results show that, under the appropriate water and nitrogen coupling scheme, the spring shoot length and base diameter value of pear trees were significantly increased compared with those under the conventional farming scheme. The spring shoot length increased rapidly; to a certain extent, this can enhance photosynthesis, promote nutrient levels, and improve the fruit quality. Comparing the results of nine water and nitrogen coupling schemes, adding nitrogen fertilizer, or increasing the irrigation water limit, can significantly increase the spring shoot length and base diameter, but some results show that the pear trees spring shoots length and base diameter were decreased with the irrigation water amount application. This phenomenon may be due to the increase in irrigation amount leading to deep leakage of nutrients in the soil, which further leads to insufficient nutrients in the soil and is not the growth of spring shoots [43]. A small amount of water applied multiple times is more conducive to the growth of spring shoots of pear trees [44]. Under the same irrigation limit, increasing the amount of nitrogen fertilizer had a greater impact on the increase in the base diameter of spring shoots than the length of shoots. However, applying too much water and nitrogen fertilizer will lead to overgrowth of the plant and the use more water and nutrients, which will lead to insufficient water and nutrients for fruit growth. The growth of the two forms a competitive relationship, which is not conducive to pear production. Similarly, when insufficient water and nitrogen fertilizer is applied, spring shoots and fruit growth will be limited due to insufficient water and nutrients in the soil. For example, the base diameter of I_LN_L treatment spring shoots was significantly lower than that of C shoots. This may have been due to too little irrigation, and the increased application of nitrogen fertilizer failed to compensate for the reduced irrigation. The effect of the increase in diameter led to the base diameter of the spring shoots under the I_LN_L treatment being lower than under C. However, although the irrigation amount was significantly reduced, the spring shoot growth of pear trees under the water and nitrogen coupling scheme was increased compared with C, except for the I_LN_L treatment. Water and nitrogen coupling schemes promoted the water absorption and utilization of pear trees, further promoted the growth of spring shoots of pear trees, and guaranteed the growth state of pear trees. Therefore, the water and nitrogen coupling scheme can ensure the spring shoot growth of pear trees while reducing the irrigation amount and improving the water use efficiency.

4.2. Leaf Area and SPAD Dynamics

Leaf growth status is particularly important for evaluating the vegetative organs of pear trees. The size of the leaf area and SPAD value can directly reflect the growth status of the leaf [45,46]. Similarly, the size of the leaf area and SPAD values are significantly related to crop photosynthesis. The results show that the effect of the irrigation limit on the leaf area is more significant than increasing the amount of nitrogen application [47], the water–nitrogen coupling scheme significantly reduced the irrigation water amount, which resulted in a relatively low soil water content, and soil water content became the main factor limiting leaf growth. A larger amount of irrigation will help increase the leaf area, but the effect of nitrogen application is not in accordance with Duan et al. This phenomenon may be due to the application of nitrogen fertilizer contributing to the leaf interior material, which is not obvious for increasing the leaf area [48]. In comparison, the mid-water and low-fertilization scheme resulted in the largest leaf area but was generally close to I_HN_H, I_HN_M, I_HN_L, and C; the SPAD values were positively correlated with water and nitrogen inputs, and the fertigation scheme was excellent. The value under C was comparatively the highest under the I_HN_H treatment, and the coupling of higher irrigation and nitrogen application amounts helped to increase the chlorophyll content, which is in line with the results of Lu Chao's research on chlorophyll supplies in relation to water and nitrogen [49], which suggests that, by ensuring soil water and nutrient content, leaf SPAD increases, and soil moisture and nutrients significantly affect the plant chlorophyll content [50].The application of nitrogen fertilizer could alleviate the limiting effect of water deficit, and, to same extent, low fertilization level showed better results.

4.3. Fruit Volume and Weight Dynamics

The volume and weight of fruit were higher under the water and nitrogen coupling schemes than under C (Figure 9), and our results differ from other studies, and this is because, although the irrigation water was reduced, using N fertilizer helps the absorption and utilization of water in pear trees [51]. Water and fertilizer coupling technology is helpful to increase yield, fruit volume, and weight. Fruit volume has a significant relationship with average per fruit weight. Cui et al. found that reducing the irrigation water did not reduce the fruit weight [52]. When the amount of nitrogen applied was appropriate, too much irrigation water caused nutrients to leach down with water, reducing the availability of nutrients for the fruits. This renders the nutrient content in the soil unable to meet the needs of fruit growth; the greater the amount of nitrogen applied, the higher the probability that the fruit growth needs are met, but amounts exceeding the fruit growth requirements will cause waste and even increase agricultural nonpoint source pollution [53] without increasing per fruit volume and weight. Excessive water inputs will cause fruit drop [54], resulting in reduced yield and reduced irrigation water productivity. Therefore, a fertigation scheme that can meet the water and nutrients required for fruit growth without causing deep leakage and excessive residual material is the most suitable. Although the water and nitrogen coupling scheme reduced the irrigation amount, the spring shoot growth, pear fruit enlargement, and average fruit weight were guaranteed during the growing period, which indicated that the water and nitrogen coupling scheme played an important role in regulating the competition between vegetative growth and reproductive growth and in ensuring growth.

4.4. Fruit Quality Dynamics

Fruit quality is not only an important factor restricting Chinese fruit exports, but it also affects the price of fruit in the market [29]. The quality of fruit mainly includes nutrient content and taste. In this study, the TSS, AA, and TA were selected for analysis. The effect of the water and nitrogen coupling scheme on various indicators was not completely consistent. The interaction of the nitrogen application rate on various indicators was especially complex, and there was no single factor for increase or decrease. Xie et al. found that lower soluble solids under water and fertilizer coupling than conventional schemes, which may be related to fruit quantity [40]. The water and fertilizer coupling method significantly improved the fruit quality, and the effects of irrigation amount, fertilizer application amount, and interaction on fruit quality were significantly different [55]. The former study has clarified the influence of water and fertilizer on fruit quality. In this study, however, the effects of irrigation water amount and fertilizer dose on above indexes were different, which may be due to the difference between the environment and the fertilizer type. A suitable water and fertilizer coupling scheme can improve fruit quality, but an unsuitable one will produce antagonistic effects and reduce fruit quality. In terms of fruit grading, among the 10 schemes in this experiment, the I_MN_H, I_HN_H, and I_HN_M treatments all met the premium fruit standard of the Technical Supervision Bureau. The TSS, TA and AA in fruit was improved by medium nitrogen application rate. Under the medium nitrogen application rate, increasing irrigation amount was helpful to improve fruit quality.

4.5. Optimal Drip Water and Fertilizer Coupling Scheme

Irrigation and fertilization are two important controllable factors that determine the growth and production of fruit trees and improve fruit quality. Leaf area and SPAD values are important indicators of basic physiological activities and yield formation of fruit trees. Fruit quality is the bottleneck in market pricing and sales and an important factor affecting the import and export of fruits. Through the correlation analysis, it is not difficult to find a correlation between pear tree vegetative growth and fruit quality indicators [56]. The evaluation of all together showed that I_MN_H was the closest to the optimal value, and the degree of closeness was the highest. However, different evaluation results may be produced under different index systems.

5. Conclusions

We monitored the pear tree vegetative growth and fruit quality parameters during the growth period. The results show that proper water and fertilizer coupling schemes can guarantee the tree vegetative and improve fruit quality. The growth indicators had significant responses to the water and fertilizer coupling schemes. Irrigation amount was significantly affected spring shoot length. The increase in irrigation amount and nitrogen application significantly increased the growth of spring shoot base diameter. Increased nitrogen fertilization contributed to the improvement of SPAD values. Comprehensively considering vegetative grows and fruit quality, it is recommended that the water and fertilizer coupling scheme for golden pear in the North China area throughout the growing season is an irrigation water limit of 65%θ_f and a nitrogen fertilizer amount of 486.00 kg·ha^{-1}.

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