Effects of Nitrogen Application Rates on the Compensatory Response of Winter Rapeseed to Water Stress during the Regreening Stage: Postprint

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Abstract

To determine the optimal nitrogen application rate for winter rapeseed (Brassica napus) under water stress conditions during the regreening stage and its compensatory effect on water stress, a pot experiment was conducted. During the regreening stage, five nitrogen application levels of pure nitrogen per pot were established: 0 g (N0), 0.2 g (N1), 0.4 g (N2), 0.6 g (N3), and 0.8 g (N4) (equivalent to 0 $kg \cdot hm^{-2}$, 30 $kg \cdot hm^{-2}$, 60 $kg \cdot hm^{-2}$, 90 $kg \cdot hm^{-2}$, and 120 $kg \cdot hm^{-2}$), and two water treatments: water deficit (D, soil water content of 50% to 55% field capacity) and adequate water supply (W, soil water content of 70% to 80% field capacity), to investigate the compensatory effects of nitrogen application rate on growth indicators, chlorophyll content, photosynthetic rate, seed yield, and water use efficiency in winter rapeseed after rewatering from water stress during the regreening stage, and to evaluate these indicators under different treatments using principal component analysis. The results showed that under the same water conditions, above-ground dry matter, chlorophyll content, photosynthetic rate, seed yield, and water use efficiency all exhibited a trend of initially increasing and then decreasing with increasing nitrogen application rate, reaching maximum values at N3. After rewatering following drought stress during the regreening stage, above-ground dry matter, chlorophyll content, photosynthetic rate, yield, and yield components of winter rapeseed under all nitrogen treatments exhibited certain compensatory effects. The compensatory effect initially increased and then decreased with increasing nitrogen application rate, with the best compensation observed at the N3 level. At the N3 nitrogen level, growth indicators, chlorophyll content, and seed yield of winter rapeseed under the D treatment showed no significant differences from the W treatment, exhibiting equivalent compensatory effects, whereas the photosynthetic rate at the initial flowering stage under the D treatment was significantly greater than that under the W treatment, demonstrating overcompensatory effects. The N3D treatment reduced yield by 2.2% but increased water use efficiency by 3.8% compared with the N3W treatment. Nitrogen partial factor productivity and grain oil content both decreased with increasing nitrogen application rate, while grain protein content increased. Compared with N0, the N3 treatment under both water regimes reduced average nitrogen partial factor productivity by 6.2% and grain oil content by 13.0%, but increased yield by 87.6%, water use efficiency by 32.9%, and grain protein content by 24.6%. Principal component analysis of all indicators revealed that the N3D treatment achieved the highest comprehensive score. Therefore, the N3D treatment demonstrated the best overall performance in promoting winter rapeseed growth, improving yield and water use efficiency, and ensuring quality.

Full Text

Compensative Impact of Winter Oilseed Rape (Brassica napus L.) Affected by Water Stress at Re-greening Stage Under Different Nitrogen Rates

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Abstract

Oilseed rape is one of the most important oil crops cultivated on over 6.5 million hectares of land in China. Although mainly cultivated in the Yangtze River Basin, rising winter temperatures in northern China in recent years have made it possible to expand the cultivation area of oilseed rape northward and westward. The planting area of winter oilseed rape in Northwest China has increased year by year. Irrigation and nitrogen supply at re-greening stage is important for flower bud differentiation and branch number increase of oilseed rape. However, drought stress is usually frequent at re-greening stage in most regions of Northwest China. Local farmers apply irrigation and nitrogen to oilseed rape fields for high seed yields, but such effect has not been obvious, resulting in various environmental problems. Therefore determining an appropriate nitrogen dose under drought at re-greening stage is important for the production of oilseed rape in Northwest China.

Barrel experiments, including 5 nitrogen application rates [0 g (N0), 0.2 g (N1), 0.4 g (N2), 0.6 g (N3) and 0.8 g (N4)] and two water treatments [full water (W, 70%-80% of field water capacity) and deficit water (D, 50%-55% of field water capacity)] at re-greening stage were conducted to measure growth and physiological index, yield components, water use efficiency (WUE) and quality traits of oilseed rape. The study used principal component analysis (PCA) to analyze and evaluate the parameters under different treatments. Results showed that aboveground dry matter, chlorophyll content, photosynthetic rate, seed yield and WUE first increased and then decreased with increasing nitrogen application rate. Then aboveground dry matter, chlorophyll content, photosynthetic rate, seed yield and WUE all reached the maximal level under N3 treatment with the same water conditions. After drought stress and re-watering, shoot dry matter weight, chlorophyll content, photosynthetic rate, yield and yield components of all nitrogen treatments showed certain degree of compensative effect. The compensative effect intensified first and weakened then with N application rate, which was best under N3 treatment. No significant differences were noted in growth indexes, chlorophyll content and seed yield between W and D treatments. Photosynthetic rate under D treatment was significantly higher than that under W treatment with N3. Seed yield reduced by 2.2% and WUE increased by 3.8% in D treatment compared to that of W treatment with N3 nitrogen application. Nitrogen partial factor productivity and seed oil content decreased with increasing nitrogen amount, while seed protein content showed the reverse trend. Compared with N0, average partial factor productivity and seed oil content in N3 treatment decreased by 6.2% and 13.0%, but yield and WUE increased by 87.6% and 32.9%, respectively. Based on PCA for each indicators, we found that the highest PCA score occurred in N3D treatment. Therefore, the N3D treatment was optimized measure for increasing WUE, yield and quality of oilseed rape in northwest China.

Keywords: Winter oilseed rape; Re-greening stage; Nitrogen application rate; Water stress; Seed quality; Water use efficiency; Compensative effect

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Oilseed rape (Brassica napus) is a traditionally important oil crop in China, with a planting area exceeding 6.5 million hm^2, making it the country' s largest oil crop. Strengthening research on rapeseed production technology is crucial for ensuring China' s edible oil security. In recent years, China' s climate has undergone significant changes, with the northern boundary of winter oilseed rape cultivation shifting noticeably northward in a "northward and westward expansion" trend, moving cultivation areas toward higher latitudes and altitudes, and continuously expanding the planting area in Northwest China. Water and nitrogen supply during the re-greening stage affects subsequent flower bud differentiation and branch number, thereby influencing rapeseed yield. During the re-greening period of winter oilseed rape, rainfall is scarce in most areas of Northwest China. Local farmers often apply large-volume spring irrigation with substantial nitrogen fertilizer, yet traditional irrigation and fertilization methods have not increased rapeseed yield and have instead caused severe disruption to ecosystem nitrogen cycling, soil compaction, and tremendous resource waste. Therefore, determining appropriate nitrogen application rates under drought stress conditions to achieve synergistic water-fertilizer effects and incentive mechanisms that maximize water and nutrient use efficiency is of great practical significance for sustainable agricultural development in China' s arid and semi-arid northwestern regions.

The compensatory effect of water stress refers to the capacity of crops, after experiencing water stress within a threshold, to exhibit favorable physiological, biochemical, and agronomic indicators for growth, yield improvement, and quality enhancement when recovery factors (re-watering) and processes (time) are present. Super-compensatory effect refers to the extraordinary improvement in growth indicators, physiological indicators, and yield exhibited by crops after experiencing certain water deficit conditions. Water deficit is a common environmental stress in crop growth, but not every crop, growth stage, or degree of water deficit causes damage and yield reduction. Moderate water stress during a specific growth stage followed by re-watering can provide certain regulatory effects on crop physiological and biochemical metabolism and growth development, resulting in temporary rapid growth that can partially or super-compensate for losses incurred during the water stress period. Previous studies have shown that water stress can enhance the sensitivity of Illicium lanceolatum seedlings to strong light, and photosynthetic capacity can temporarily recover after re-watering. Moderate drought stress during the seedling stage of peanut (Arachis hypogaea) followed by re-watering can rapidly restore leaf photosynthetic performance, reduce water consumption without affecting yield, and improve water use efficiency. Crop compensatory effects occur not only under drought and re-watering conditions but also after drought through increased fertilizer application such as nitrogen. Supplementing soil nutrients through fertilization can not only alleviate the effects of water stress factors but also effectively improve crop yield and water use efficiency by regulating crop physiological processes, compensating for losses caused by insufficient water. Li et al. demonstrated that water stress increases stomatal resistance and significantly decreases chlorophyll content and net photosynthetic rate. However, applying nitrogen fertilizer during stress reduces transpiration rate while increasing chlorophyll content, leaf light absorption intensity, and net photosynthetic rate, thereby significantly improving short-term water use efficiency. Nevertheless, some studies have indicated that under limited soil water conditions, increasing nitrogen application can exacerbate crop water stress and adversely affect yield. Currently, there remains considerable disagreement regarding the effects of fertilization on crop growth, development, and yield formation after drought and re-watering, likely due to differences in crop species, timing and degree of water stress, and fertilizer application rates. Therefore, determining the appropriate nitrogen application rate after re-watering for different crops experiencing varying degrees of water stress at different growth stages is crucial for water-saving and yield increase.

Although studies on crop physiological ecology under different nitrogen supply levels and water regulation conditions have been reported, few have focused on winter oilseed rape. This study used Brassica napus 'Shanyou 107' as experimental material under barrel cultivation conditions to investigate the compensatory effects of different nitrogen application rates during the re-greening stage on physiological growth, yield, and quality traits of winter oilseed rape after water stress and re-watering, aiming to provide a theoretical basis for determining reasonable nitrogen application rates under regulated deficit irrigation conditions during the re-greening stage of Brassica napus.

1.1 Experimental Site

The barrel cultivation experiment of winter oilseed rape was conducted from September 12, 2013, to May 22, 2014, under a rain shelter at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University. The experimental site is located at 34°20 N, 108°24 E, with an altitude of 521 m, belonging to a warm temperate monsoon semi-humid climate zone, with an average annual sunshine duration of 2,163.8 h and a frost-free period of 210 days. The test soil was taken from the 0–20 cm cultivated layer of farmland at the experimental station, with a loam texture, field water capacity of 24% (mass water content, the same below), and wilting water content of 8.5%. The soil was naturally air-dried, ground, and passed through a 5 mm sieve before use. The basic physicochemical properties of the test soil were: organic matter 11.36 $g \cdot kg^{-1}$, total nitrogen 0.83 $g \cdot kg^{-1}$, nitrate nitrogen 60.27 $mg \cdot kg^{-1}$, available phosphorus 18.30 $mg \cdot kg^{-1}$, available potassium 135.73 $mg \cdot kg^{-1}$, and pH 8.13.

1.2 Experimental Materials and Design

The winter oilseed rape variety tested was 'Shanyou 107' , provided by the College of Agriculture, Northwest A&F University. The nitrogen fertilizer used was urea (containing N$ 46*{2}O*{5}$$ $16%). The plastic barrels used in the experiment had specifications of: upper inner diameter 29.5 cm, lower inner diameter 22.5 cm, and height 25.2 cm.

Two factors were established during the re-greening stage of winter oilseed rape: nitrogen (N) application amount and water treatment. Five nitrogen application levels were set: 0 g, 0.2 g, 0.4 g, 0.6 g, and 0.8 g of pure N per barrel, equivalent to 0 $kg \cdot hm^{-2}$, 30 $kg \cdot hm^{-2}$, 60 $kg \cdot hm^{-2}$, 90 $kg \cdot hm^{-2}$, and 120 $kg \cdot hm^{-2}$, respectively, denoted as N0, N1, N2, N3, and N4. Two water levels were established: full water supply (W, soil water content maintained at 70%–80% of field water capacity) and water stress (D, soil water content maintained at 50%-55% of field water capacity during the stress period). The stress stage was the re-greening period (150–182 DAS, DAS: days after sowing). Each treatment was replicated 9 times in a completely randomized block design. After the stress period ended, soil water content was restored to 70%–80% of field water capacity. All treatments received basal applications of 0.6 g of pure N and P_2O_5.

Before the experiment, 9 small holes with a radius of about 0.5 cm were uniformly drilled at the bottom of each barrel, covered with gauze and 500 g of fine sand to regulate lower soil aeration and moisture conditions. Soil and fertilizer were loaded 2 days before sowing, with 13 kg of dry soil per barrel. Basal fertilizer was mixed evenly with dry soil in proportion, and soil dry bulk density was controlled at 1.35 $g \cdot cm^{-3}$ during loading. Two PVC pipes (15 cm long, 1.5 cm in diameter) were inserted for irrigation, with uniform holes drilled around the pipes and a layer of gauze wrapped along the pipe walls. After soil loading, the barrel surface was covered with 500 g of vermiculite to prevent rapid soil compaction. On September 12, 2013, 5 seeds were uniformly sown in the center of each barrel at a depth of 5 cm, and water was applied to reach 85% field water capacity after sowing. After the winter oilseed rape developed 3 true leaves (September 25, 2013), seedlings were thinned to 1 vigorous plant per barrel. One day before water treatment, the top-dressed nitrogen fertilizer for each barrel was dissolved in irrigation water and uniformly applied along the PVC pipes. Winter oilseed rape was harvested on May 22, 2014 (253 days after sowing, 253 DAS).

1.3 Measurement Items and Methods

1) Soil water content: The weighing method was used to determine irrigation amount and timing to maintain soil water content within the set range. At harvest, soil water content was measured using the drying method, with 3 measurement points uniformly selected per barrel and one soil sample taken every 5 cm along the soil depth direction, totaling 20 cm.

Water use efficiency was calculated using the formula WUE = Y/ET, where WUE is crop water use efficiency ($kg \cdot m^{-3}$), Y is grain yield at harvest (kg), and ET is water consumption during the entire growth period (m^3). ET = M - Wt, where M is the total irrigation amount during the growth period and Wt is soil water storage at harvest.

2) Chlorophyll content and photosynthetic rate: On the initial flowering day (208 DAS), the net photosynthetic rate and chlorophyll content of the third leaf from the top of winter oilseed rape were measured. The Li-6400 portable photosynthesis system was used to measure the net photosynthetic rate of the third leaf from the top of winter oilseed rape in each barrel between 10:00–12:00. After extracting leaf pigments with 96% ethanol, chlorophyll content was determined using a spectrophotometer colorimetric method.

3) Growth indicators and yield traits: At harvest, plant height, main raceme length, and height of the first effective branch of each winter oilseed rape plant were measured with a tape measure; taproot diameter was measured with a vernier caliper; and branch number was recorded. After measurement, the stems of winter oilseed rape were placed in an oven, killed at 105 °C for 30 min, then dried at 70 °C to constant weight to determine aboveground dry matter weight.

4) Yield traits: At harvest, the number of pods in the main raceme and branch racemes of each winter oilseed rape plant were measured sep-

arately. After sun-drying, the seed yield of main raceme and branch racemes were measured separately, along with seed number per pod and 1000-seed weight.

5) Oil and protein content: The oil and protein content of seeds from main and branch racemes of rapeseed were determined using a near-infrared spectroscopy analyzer (Foss, NIRSystem-5000).

6) Nitrogen partial factor productivity ($g \cdot g^{-1}$) = yield (g) / nitrogen application amount (g).

1.4 Data Processing and Analysis

Microsoft Excel 2010 was used to process experimental data; PASW Statistics 18.0 software was used for principal component analysis and variance analysis, with multiple comparisons using Duncan' s new multiple range method at a significance level of $\alpha = 0.05$; OriginPro 8.5 software was used for graphing.

2.1 Effects of Nitrogen Application Rate on Growth Indicators of Winter Oilseed Rape Under Different Water Treatments at Re-greening Stage

Nitrogen application rate had significant effects on plant height, main raceme length, effective branch height, taproot diameter, effective branch number, and aboveground dry matter weight of winter oilseed rape under different water treatments at the re-greening stage (Table 1). Under the same water conditions, except for effective branch height, which decreased with increasing nitrogen application rate, all other indicators first increased and then decreased with increasing nitrogen application rate, reaching maximum values at N3. Under the same nitrogen application level, all growth indicators of winter oilseed rape under full water supply (W) conditions were higher than those under water stress (D) conditions, but the differences between W and D treatments first decreased and then increased with increasing nitrogen application rate, with the smallest difference observed at the N3 nitrogen level.

Under no nitrogen application (N0), except for plant height and taproot diameter, main raceme length, effective branch height, effective branch number per plant, and aboveground dry matter weight under D treatment were significantly lower than those under W treatment, showing insufficient compensation. As nitrogen application rate increased, the compensation effect after re-watering under D treatment improved significantly. Under N1, except for plant height and taproot diameter, other indicators showed insufficient compensation; under N2 and N3, all growth indicators showed equivalent compensation effects. Continuing to increase nitrogen application rate reduced the compensation effect after re-watering under D treatment. Under N4, the effective branch number per plant under D treatment was significantly lower than that under W treatment, showing insufficient compensation. These results indicate that appropriate top-dressing of nitrogen fertilizer during water stress at the re-greening stage is beneficial for compensation of growth indicators after re-watering.

2.2 Effects of Nitrogen Application Rate on Chlorophyll Content and Photosynthetic Rate of Winter Oilseed Rape Under Different Water Treatments at Re-greening Stage

Chlorophyll is the main photosynthetic pigment that plays an important role in light absorption, and chlorophyll content can reflect photosynthetic capacity, which in turn reflects the ability of energy transfer and transformation and dry matter accumulation in crops. Photosynthesis is the physiological basis of plant growth and a primary mechanism directly related to crop yield formation, and photosynthetic rate can reflect the level of photosynthesis to a certain extent. Nitrogen application rate had significant effects on chlorophyll content and photosynthetic rate of winter oilseed rape leaves at flowering stage under different water treatments (Figure 1 [Figure 1: see original paper]).

Analysis of Figure 1a shows that under the same water conditions, chlorophyll content of winter oilseed rape leaves at initial flowering stage first increased and then decreased with increasing nitrogen application rate, with the highest chlorophyll content observed under N3 treatment, which was significantly greater than other nitrogen treatments. No significant difference in chlorophyll content was observed between N2 and N4 treatments, but both were significantly greater than N0 and N1, and N1 was significantly greater than N0. Under the same nitrogen application rate, chlorophyll content under W treatment was greater than that under D treatment, and the difference between the two first decreased and then increased with increasing nitrogen application rate, with the smallest difference observed at N3. Under N0 and N1, chlorophyll content under W treatment was significantly greater than that under D treatment; under N2, N3, and N4, no significant difference in chlorophyll content was observed between the two water treatments. These results indicate that after water stress and re-watering at the re-greening stage, chlorophyll content showed insufficient compensation under N0 and N1, but equivalent compensation under N2, N3, and N4.

Analysis of Figure 1b shows that nitrogen application rate had significant effects on photosynthetic rate of winter oilseed rape leaves at flowering stage under different water treatments. Under the same water conditions, photosynthetic rate first increased and then decreased with increasing nitrogen application rate, with leaf photosynthetic rate under N3 treatment being significantly greater than other nitrogen treatments. Under N0, photosynthetic rate under D treatment was significantly lower than that under W treatment; under N1, N2, and N4, no significant difference in photosynthetic rate was observed between the two water treatments; under N3, photosynthetic rate under D treatment was significantly greater than that under W treatment. These results indicate that after water stress and re-watering at the re-greening stage, photosynthetic rate showed insufficient compensation under N0, equivalent compensation under N1, N2, and N4, and super-compensation under N3.

2.3 Effects of Nitrogen Application Rate on Yield, Nitrogen Partial Factor Productivity, and Water Use Efficiency of Winter Oilseed Rape Under Different Water Treatments at Re-greening Stage

Appropriate water conditions and reasonable nutrient supply are fundamental guarantees for high yield and good quality of crops and important ways to promote crop growth and improve water-nitrogen use efficiency. Nitrogen application rate had significant effects on yield, yield components, and nitrogen partial factor productivity of winter oilseed rape under different water treatments at the re-greening stage (Table 2). Under the same water conditions, main raceme pod number, branch pod number, seeds per pod, 1000-seed weight, main raceme yield, branch raceme yield, and total yield all showed a trend of first increasing and then decreasing with increasing nitrogen application rate. Except for main raceme pod number (which peaked at N2), yield and other yield components all reached maximum values at N3. Under N0 and N1, branch pod number, branch yield, and total yield under D treatment were significantly lower than those under W treatment, and under N0, 1000-seed weight under D treatment was also significantly lower than that under W treatment; under N2, branch yield under W treatment was significantly greater than that under D treatment; under N3, no significant difference was observed in any yield component between W and D treatments; under N4, branch yield and total yield under W treatment were significantly greater than those under D treatment. These results indicate that only under N3 nitrogen level could yield and yield components of winter oilseed rape after water stress and re-watering show equivalent compensation. Under N1, N2, N3, and N4 nitrogen levels, the average yield of winter oilseed rape under the two water treatments increased by 9.0 g (37.1%), 14.1 g (58.1%), 21.3 g (87.6%), and 14.4 g (59.4%) compared with N0, respectively. Moreover, at N3 level, the difference in yield between W and D treatments was smallest (1.0 g), significantly smaller than at N0 (3.5 g), N1 (2.9 g), N2 (1.9 g), and N4 (3.3 g) nitrogen levels.

Nitrogen partial factor productivity is an indicator reflecting the combined effects of soil basic nutrient level and chemical fertilizer application amount. Under the same water conditions, nitrogen partial factor productivity under N1 was slightly greater than that under N0, with no significant difference between them, but both were significantly greater than other nitrogen treatments. Compared with N1, nitrogen partial factor productivity under N3 decreased by 8.8%, while yield increased by 36.8%. Under the same nitrogen application level, nitrogen partial factor productivity under W treatment was greater than that under D treatment. Under N0 and N1 conditions, nitrogen partial factor productivity under W treatment was significantly greater than that under D treatment, while under N2, N3, and N4 conditions, no significant difference in nitrogen partial factor productivity was observed between the two water treatments, and under N3 conditions, the difference in nitrogen partial factor productivity between the two water treatments was smallest, with D treatment only 2.2% lower than W treatment.

Crop water use efficiency is an important indicator for evaluating water-saving effects. Under the same water conditions, both water consumption and water use efficiency showed a trend of first increasing and then decreasing with increasing nitrogen application rate, both reaching maximum values at N3 level (Figure 2 [Figure 2: see original paper]). Water consumption under N2, N3, and N4 (with no significant difference among them) was significantly greater than under N0 and N1 (with N1 water consumption significantly greater than N0). Compared with N0, the average water consumption and average water use efficiency under the two water treatments at N1, N2, N3, and N4 levels increased by 5.8 L (23.1%), 10.1 L (40.1%), 10.4 L (41.3%), and 9.8 L (38.9%), and by 0.11 $kg \cdot m^{-3}$ (11.4%), 0.13 $kg \cdot m^{-3}$ (12.9%), 0.32 $kg \cdot m^{-3}$ (32.9%), and 0.14 $kg \cdot m^{-3}$ (14.7%), respectively. The difference in water use efficiency between W and D treatments first decreased and then increased with increasing nitrogen application rate. At N2 level, water use efficiency was equivalent between the two treatments; at N3 level, water use efficiency under D treatment was greater than that under W treatment (increase of 3.8%). Although water consumption under N4 treatment showed no significant difference from N3 treatment, yield under N4 treatment was significantly lower than that under N3 treatment, resulting in lower water use efficiency under N4 treatment.

2.4 Effects of Nitrogen Application Rate on Oil and Protein Contents of Winter Oilseed Rape Under Different Water Treatments at Re-greening Stage

Oil and protein contents are two important indicators for evaluating rapeseed quality. Nitrogen application rate had significant effects on oil and protein contents of rapeseed after water stress and re-watering at the re-greening stage (Table 3). Oil content decreased with increasing nitrogen application rate, while protein content showed the opposite trend. Oil and protein contents of seeds from branch racemes were greater than those from main racemes. Under the same nitrogen application rate, oil and protein contents under D treatment were higher than those under W treatment, but the differences were not significant.

Compared with N0, the average oil contents of main raceme and branch raceme seeds under N1, N2, N3, and N4 treatments decreased by 1.9%, 3.5%, 5.3%, and 5.8%, and by 1.9%, 3.4%, 6.0%, and 7.6%, respectively. The average protein contents of main raceme and branch raceme seeds under N1, N2, N3, and N4 treatments increased by 1.2%, 2.6%, 5.2%, and 5.7%, and by 1.0%, 2.4%, 5.0%, and 5.8%, respectively, compared with N0. The average oil and protein contents of branch raceme seeds were 1.4% and 0.7% higher than those of main raceme seeds, respectively. The average oil and protein contents of rapeseed under D treatment were 0.5% and 0.2% higher than those under W treatment, respectively.

2.5 Principal Component Analysis and Evaluation of Various Indicators of Winter Oilseed Rape Under Different Water and Nitrogen Treatments at Re-greening Stage

Principal component analysis was conducted using growth indicators, physiological indicators, yield traits, water consumption, water use efficiency, and quality indicators of winter oilseed rape under different water and nitrogen treatments as evaluation objects. Table 4 shows that the eigenvalue of principal component 1 was 17.668, with a contribution rate of 84.132%, and the eigenvalue of principal component 2 was 2.336, with a contribution rate of 11.124%. The cumulative contribution rate of the first two principal components reached 95.256%, which could explain 95.256% of the variation.

Through the initial factor loadings of principal component analysis (Table 5), the two columns of data in the initial factor loading matrix were input into the data editing window (as variables B1 and B2). Then, using "Transformation Compute Variable," "A1=B1/SQR(17.668)" was entered in the Compute Variable dialog box (for the second principal component, 2.336 was filled in the parentheses after SQR) to obtain eigenvectors A1 and A2 (Table 5).

The relationship expressions of each principal component expressed by standardized variables can be written through the eigenvectors given in Table 5. Since the first two principal components already reflected 95.256% of the total information, the weighted mean was calculated using the contribution rates of the two principal components as weights to obtain the comprehensive principal component score (E):

$E = 0.8413 \times \text{Prin1} + 0.1112 \times \text{Prin2}$ (1)

This comprehensive score can serve as a comprehensive evaluation index for the effects of different water and nitrogen treatments on winter oilseed rape physiological growth, yield traits, water consumption, water use efficiency, and quality. The comprehensive principal component scores obtained by substituting parameters from different water and nitrogen treatments into this formula are shown in Table 6 .

Combined with the comprehensive evaluation scores of different water and nitrogen treatments on winter oilseed rape physiological growth, yield composition, water consumption, water use efficiency, and quality, the higher the comprehensive score of a treatment, the greater its impact on the measured parameters. Considering the specific positive and negative effects of the parameters, the optimal treatment can be evaluated. As shown, N3D treatment had the highest comprehensive score, while N0D treatment had the lowest. This indicates that N3D treatment had the best comprehensive effect on promoting winter oilseed rape physiological growth, improving yield and water use efficiency, and ensuring quality, while N0D treatment had the worst effect.

3.1 Rewatering Compensatory Effect

In semi-arid regions, crop growth and development are often in environments with alternating wet and dry conditions and variable low water availability. Water deficit can cause damage to crops, but not every growth stage or degree of water shortage reduces crop yield. Often, after moderate water deficit at a certain growth stage is relieved, crop growth and development and even final grain yield formation can produce compensatory effects. Compensatory effects after re-watering are manifested in growth and development, photosynthesis, water use, material transport, and grain yield. The degree to which crop yield and quality are affected by water deficit depends on the timing, duration, and severity of the water deficit. Ding et al. found that after maize (Zea mays) experienced different degrees of drought stress at the seedling stage and was re-watered, dry matter accumulation, transpiration rate, and root activity all showed varying degrees of compensatory growth effects. Liu et al. studied drought stress at the peanut seedling stage followed by re-watering and found that photosynthetic performance of leaves decreased during the drought period but rapidly recovered to normal levels after re-watering, reducing water consumption without affecting yield, and increasing average water use efficiency of peanut by 43.9%. Yan et al. showed that drought stress increased abscisic acid and indoleacetic acid content and decreased gibberellin and zeatin content in pea (Pisum sativum) roots at each growth stage, with greater changes under more severe drought stress. Re-watering after drought could produce compensatory effects on endogenous hormone content in pea roots at each growth stage, with the compensation amount depending on pea growth stage, drought stress intensity, and re-watering duration. Li et al. studied the effects of partial water stress followed by re-watering on maize root growth and found that moderate stress followed by re-watering was beneficial for increasing total root surface area but had no significant effect on total root length or root dry weight, with root compensatory effects related to stress intensity and re-watering time. This study obtained similar results regarding the compensatory effects of growth, physiology, and yield of winter oilseed rape after water stress and re-watering at the re-greening stage under different nitrogen application rates. Aboveground dry matter weight, seeds per pod, and 1000-seed weight under all nitrogen treatments showed equivalent compensatory effects; chlorophyll and pod number per plant showed insufficient compensation under N1 but equivalent compensation under other nitrogen treatments; photosynthetic rate showed super-compensation under N3 but equivalent compensation under other nitrogen treatments; yield under N1 and N4 was significantly lower than that under full water supply conditions, while yield under N2 and N3 showed no significant difference from full water supply. These results demonstrate that appropriate water stress at the re-greening stage of winter oilseed rape followed by re-watering can produce certain compensatory effects on growth, physiology, and grain yield under all nitrogen treatments.

3.2 Water-Fertilizer Synergistic Compensatory Effect

Water and nutrients are both the greatest obstacles to dryland agricultural production and the most easily controlled material inputs for humans. In actual production, water and nutrients are inseparable, and the interaction between the two factors can be transformed through human regulation measures. The fundamental problem of plant nutrition in dryland agriculture is how to rationally use fertilizers under water-limited conditions to achieve the goal of "regulating water with fertilizer," improve crop water use efficiency, enhance drought resistance, promote full utilization of limited water resources by crops, prevent soil and water pollution caused by unreasonable fertilization, and obtain optimal ecological and economic benefits. Liu et al. showed that water stress could significantly increase malondialdehyde and soluble sugar content in spring maize leaves and reduce peroxidase and superoxide dismutase activities, while nitrogen application could maintain high levels of soluble sugar content, peroxidase, and superoxide dismutase activities in leaves before the tasseling stage. Hao et al. found that high water and high fertilizer did not necessarily produce high yield, and that mild drought and low nitrogen had obvious synergistic interaction effects, achieving water-saving while maintaining yield. Ma et al. showed that wheat (Triticum aestivum) under compound fertilizer + organic fertilizer treatment did not experience significant effects on photosynthetic rate during water deficit periods, and photosynthetic rate showed super-compensatory effects after re-watering, with yield stability significantly higher than that under no fertilizer treatment. Chu et al. found that the compensatory or super-compensatory effects of soybean (Glycine max) yield were the result of combined water stress and nitrogen nutrition, and that the absence of either condition would affect yield compensation effects. Wang et al. found that under drought stress, the yield-increasing effect of fertilization on rapeseed was significantly higher than under timely irrigation conditions, and that fertilization was an effective measure for normal growth and yield improvement of rapeseed under drought stress.

In this study, under no nitrogen application (N0), aboveground dry matter weight, chlorophyll content, photosynthetic rate, yield, and water use efficiency under water stress (D) treatment at the re-greening stage were all significantly lower than those under full water supply (W) treatment, showing obvious insufficient compensation effects. As nitrogen application rate increased, the compensation effects of aboveground dry matter weight, chlorophyll content, photosynthetic rate, yield, and water use efficiency under D treatment increased significantly. Especially under N3, growth indicators, yield traits, quality indicators, and chlorophyll content under D treatment showed equivalent compensation effects; photosynthetic efficiency and water use efficiency showed super-compensation effects. Further increasing nitrogen application rate (N4) significantly reduced the compensation effects of various indicators. This may be because appropriate nitrogen application increased nutrient content near the root system, alleviated the decline in rhizosphere soil nutrients caused by drought stress, and the appropriate nutrient supply increased root activity and aboveground productivity of winter oilseed rape, further strengthening the plant' s ability to absorb and utilize nutrients, thereby more effectively increasing the yield increase magnitude. However, both low and excessive nitrogen application could not improve yield and water use efficiency of winter oilseed rape under water stress and re-watering conditions at the re-greening stage, possibly because chlorophyll content and photosynthetic rate of winter oilseed rape leaves after re-watering under low and excessive nitrogen application could not obtain sufficient compensation effects, resulting in insufficient compensation of pod number, seeds per pod, and 1000-seed weight.

Under water stress conditions, crop water use efficiency can be significantly improved through reasonable fertilization and measures to promote deeper root growth. The effects of water stress on crops are caused to some extent by the root system. Therefore, the root characteristics of winter oilseed rape under different nitrogen application rates and water treatments at the re-greening stage require further research.

The results of this study indicate that appropriate nitrogen application during water stress at the re-greening stage of winter oilseed rape can significantly improve compensation effects on growth, physiology, yield, and water use efficiency, while low or excessive nitrogen application shows no obvious compensation effects. In this study, nitrogen application rate N3 (equivalent to 90 $kg \cdot hm^{-2}$) showed the best compensation effect. Under N3 nitrogen level, all growth indicators, chlorophyll content, and grain yield of winter oilseed rape under D treatment showed no significant difference from those under W treatment, showing equivalent compensation effects; photosynthetic rate at initial flowering stage under D treatment was significantly greater than that under W treatment, showing super-compensation effects; yield under D treatment was 2.2% lower than that under W treatment, while water use efficiency increased by 3.8%. Principal component analysis of various growth, physiological, yield, and quality indicators showed that N3D treatment had the highest comprehensive score. Therefore, N3D treatment had the best comprehensive effect on promoting winter oilseed rape physiological growth, improving yield and water use efficiency, and ensuring quality. This study can provide a theoretical basis for determining reasonable nitrogen application rates under regulated deficit irrigation conditions at the re-greening stage of Brassica napus.

References

[1] Wang H Z. Strategy for rapeseed industry development based on the analysis of rapeseed production and demand in China[J]. Chinese Journal of Oil Crop Sciences, 2007, 29(1): 101–105

[2] Zhang S J, Wang H Z. Policies and strategies analyses of rapeseed production response to climate change in China[J]. Chinese Journal of Oil Crop Sciences, 2012, 34(1): 114–122

[3] Yin Y, Liao X, Yu B, et al. Regional distribution evolvement and development tendency of Chinese rapeseed production[J]. Chinese Journal of Oil Crop Sciences, 2010, 32(1): 147-151

[4] Guo X P, Zhang L J, Wang Q, et al. Advances compensatory effects response to water stress[J]. Journal of Hohai University: Natural Sciences, 2005, 33(6): 634-637

[5] Kou D, Su D R, Wu D, et al. Effects of regulated deficit irrigation on water consumption, hay yield and quality of alfalfa under subsurface drip irrigation[J]. Transactions of the CSAE, 2014, 30(2): 116-123

[6] Reynolds J F, Kemp P R, Ogle K, et al. Modifying the 'pulse-reserve' paradigm for deserts of North America: Precipitation pulses, soil water, and plant responses[J]. Oecologia, 2004, 141(2): 194-210

[7] Xue H Y, Zhang Y J, Liu L T, et al. Responses of spectral reflectance, photosynthesis and chlorophyll fluorescence in cotton during drought stress and rewatering[J]. Scientia Agricultura Sinica, 2013, 46(1): 2386-2393

[8] Acevedo E, Hsiao T C, Henderson D W. Immediate and subsequent growth responses of maize leaves to changes in water status[J]. Plant Physiology, 1971, 48(5): 631-636

[9] Cao Y H, Zhou B Z, Chen S L, et al. Photosynthetic response of different ecotype of Illicium lanceolatum seedlings to drought stress and rewatering[J]. Acta Ecologica Sinica, 2012, 32(23): 7421-7429

[10] Liu J L, Zhao C X, Wu N, et al. Effects of drought and rewatering at seedling stage on photosynthetic characteristics and water use efficiency of peanut[J]. Scientia Agricultura Sinica, 2011, 44(3): 469-476

[11] Zhao L Y, Deng X P, Shan L. A review on types and mechanisms of compensation effect of crops under water deficit[J]. Chinese Journal of Applied Ecology, 2004, 15(3): 523-536

[12] Li S Q, Tian X H, Li S X. Physiological compensation effects of nutrient on winter wheat in dryland[J]. Acta Botanica Boreali-Occidentalia Sinica, 2000, 20(1): 22-28

[13] Zhang Y J, Zhou Y R, Du B, et al. Effects of nitrogen nutrition on grain yield of upland rice and paddy rice under different cultivation methods[J]. Acta Agronomica Sinica, 2008, 34(6): 1005-1013

[14] Chu L L, Zhang Z X. Effects of nitrogen nutrition and water stress on compensation effect of the yield of soybean[J]. Acta Ecologica Sinica, 2010, 30(10): 2665-2670

[15] Xu J Z, Peng S Z, Wei Z, et al. Characteristics of rice leaf photosynthetic light response curve with different water and nitrogen regulation[J]. Transactions of the Chinese Society of Agricultural Engineering, 2012, 28(2): 72-76

[16] Gao J F. Experimental Guidance for Plant Physiology[M]. Beijing: Higher Education Press, 2006: 74-77

[17] Jia Z H, Yi J H, Sun Z J. Effects of different mulches on rhizosphere temperature, growth, and physiological properties of flue-cured tobacco[J]. Chinese Journal of Applied Ecology, 2006, 17(11): 2075-2078

[18] Lou C H, Wang X C. Physiology Base of Crop Yield Formation[M]. Beijing: China Agriculture Press, 2001: 138

[19] Cai H J, Kang S Z, Zhang Z H, et al. Proper growth stages and deficit degree of crop regulated deficit irrigation[J]. Transactions of the CSAE, 2000, 16(3): 24-27

[20] Ding D F, Cai H J, Wang J, et al. A study on compensative growth of maize under regulated deficit irrigation[J]. Agricultural Research in the Arid Areas, 2006, 24(3): 64-67

[21] Yan Z L, Xuan C X, Niu J Y, et al. Effect of drought stress and water recovery on endogenous hormone content in roots of pea[J]. Chinese Journal of Eco-Agriculture, 2009, 17(2): 306-310

[22] Li R, Hu T T, Niu X L, et al. Effect of partial root-zone drought stress on root growth of maize[J]. Chinese Journal of Eco-Agriculture, 2013, 21(11): 1371-1376

[23] Liu X B, Wang G H, Jin J, et al. Physiological Research of Crop Rhizosphere and Production[M]. Beijing: Science Press, 2010: 324-356

[24] Liu X G, Zhang F C, Yang Q L, et al. Effect of regulated deficit irrigation and nitrogen fertilization on maize leaf protective system[J]. Chinese Journal of Eco-Agriculture, 2009, 17(6): 1080-1085

[25] Hao S R, Zheng J, Feng Y Z, et al. Aftereffects of water-nitrogen interaction on rice at jointing stage[J]. Transactions of the CSAM, 2013, 44(3): 92-96

[26] Ma S C, Zhang X C, Duan A W, et al. Regulated deficit irrigation effect of winter wheat under different fertilization treatments[J]. Transactions of the CSAE, 2012, 28(6): 139-143

[27] Wang Y, Lu J W, Li X K, et al. Effects of drought stress on fertilizer use efficiency of rapeseed during wintering[J]. Plant Nutrition and Fertilizer Science, 2010, 16(5): 1203-1208

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