Postprint: Effects of Water and Nitrogen Management on Soil and Leaf Nutrient Content in Rainfed Spring Wheat

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Abstract

Soil moisture and nutrients are critical factors affecting crop growth. Rational water-fertilizer coupling can not only improve soil nutrient supply conditions but also enable high and stable crop yields. To further investigate the effects of water-nitrogen regulation on soil and leaf nutrient contents, stoichiometric ratios, and yield of spring wheat, this study took spring wheat in the arid land of the Loess Plateau in central Gansu as the research object, and analyzed the variation characteristics of soil and leaf organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) contents under different irrigation amounts (W1: 50 mm, W2: 100 mm, W3: 150 mm, W4: 200 mm) and different nitrogen application rates (N1: 62.5 $kg \cdot hm^{-2}$, N2: 102.5 $kg \cdot hm^{-2}$, N3: 152.5 $kg \cdot hm^{-2}$), as well as the correlations among soil nutrient content, leaf nutrient content, and yield. The results showed that: (1) Soil OC, TN, and TP contents all decreased layer by layer with increasing soil depth. Soil OC and TN contents both exhibited a trend of first increasing and then decreasing with increasing irrigation amount and nitrogen application rate, reaching maximum values under the W3N2 treatment; whereas soil TP content showed little change. The ranges of C:N, C:P, and N:P ratios were 5.81–8.24, 8.35–13.75, and 1.23–1.95, respectively, all lower than the national average values. (2) Leaf TN content at the maturity stage of spring wheat showed a trend of first increasing and then decreasing with increasing irrigation amount, and a gradually increasing trend with increasing nitrogen application rate, reaching a maximum value under the W3N2 treatment; whereas OC and TP contents showed little change. (3) Spike number and grains per spike of spring wheat both exhibited a trend of first increasing and then decreasing with increasing irrigation amount, and a gradually increasing trend with increasing nitrogen application rate; thousand-grain weight and yield both showed a trend of first increasing and then decreasing with increasing irrigation amount and nitrogen application rate, reaching maximum values under the W3N2 treatment, indicating that W3N2 is the optimal

water-nitrogen coupling pattern for spring wheat growth and development. (4) Correlation analysis revealed that there were significant correlations between spring wheat yield and soil and leaf nutrient contents, and that yield could be improved by altering water-fertilizer supply conditions. In summary, controlling irrigation amount and nitrogen application rate at the levels of W3 (150 mm) and N2 (102.5 kg · hm^{-2}) can meet the nutrient content requirements during spring wheat growth, thereby increasing yield, representing an optimal water-nitrogen combination suitable for local production conditions.

Full Text

Effects of Water and Nitrogen Regulation on Soil and Leaf Nutrient Contents of Dryland Spring Wheat

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Abstract

Soil moisture and nutrients are key factors affecting crop growth. A rational combination of water and fertilizer can not only improve soil nutrient supply conditions but also ensure high and stable crop yields. To further investigate the effects of water and nitrogen regulation on soil and leaf nutrient contents, stoichiometric ratios, and yield of spring wheat, this study examined dryland spring wheat in the Loess Plateau of central Gansu Province using a combination of field sampling and laboratory experiments. We analyzed the changing characteristics of soil and leaf organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) contents under different irrigation amounts (50 mm, 100 mm, 150 mm, and 200 mm) and nitrogen application rates (62.5 kg · hm^{-2}, 102.5 kg · hm^{-2}, and 152.5 kg · hm^{-2}), and explored the correlations between soil and leaf nutrient contents and yield.

The results showed that: (1) Soil OC, TN, and TP contents all decreased layer by layer with increasing soil depth. Soil OC and TN contents initially increased and then decreased with increasing irrigation and nitrogen application amounts, reaching maximum values under the 150 mm irrigation and 102.5 kg · hm^{-2} nitrogen treatment. Soil TP content showed little change. The C:N, C:P, and N:P ratios ranged from 5.81–8.24, 8.35–13.75, and 1.23–1.95, respectively, all lower than national averages. (2) At the mature stage, spring wheat leaf TN content first increased and then decreased with increasing irrigation amount, while gradually increasing with nitrogen application rate, reaching its maximum under the 150 mm irrigation and 102.5 kg · hm^{-2} nitrogen treatment. Leaf OC and TP contents showed little variation. (3) Spike number and grains per spike initially increased and then decreased with irrigation amount, while gradually increasing with nitrogen application rate. Both thousand-grain weight and yield first increased and then decreased with increasing irrigation and nitrogen amounts, reaching maximum values under the 150 mm irrigation and 102.5 kg · hm^{-2} nitrogen treatment, indicating this was the optimal water-nitrogen coupling model for spring wheat growth and development. (4) Correlation analysis revealed significant relationships between spring wheat yield and soil and leaf nutrient contents, suggesting that yield could be improved by altering water and fertilizer supply conditions. In conclusion, controlling irrigation at 150 mm and nitrogen application at 102.5 kg · hm^{-2} can meet the nutrient content requirements of spring wheat during growth and improve yield, representing an optimal water-nitrogen combination for local production conditions.

Keywords: water and nitrogen regulation; spring wheat; carbon, nitrogen and phosphorus; stoichiometry

1 Introduction

Ecological stoichiometry is an important indicator for evaluating plant health status and characterizing soil nutrient supply conditions for plant growth. Carbon (C), nitrogen (N), and phosphorus (P) are the main chemical elements for plant growth, among which C is the most important element and constitutes the main component of plant dry matter. N is an important element that plays a significant role in the composition of various proteins and genetic materials. Plant growth rate can be indicated by the N:P ratio, and the efficiency of plant utilization of soil nutrients can be reflected by the C:N ratio. The nutrient element that limits productivity can be identified by the C:P ratio. Through the study of ecological stoichiometry, we can deeply understand the nutrient regulation factors of plant-soil interactions, which is important for revealing the interactions among elements, regional soil nutrient management, and sustainable land use.

Currently, research on ecological stoichiometry in China' s farmland ecosystems has mainly focused on rice, tobacco, and maize, but studies on the combined effects of water and nitrogen on wheat soil and plant nutrient contents are relatively scarce and show regional differences. The Loess Plateau in central Gansu is an important agricultural region in Northwest China, with an extremely fragile ecological environment, low rainfall, and frequent drought conditions in spring and winter. Unreasonable irrigation and fertilization have led to serious waste of water resources and nitrogen loss, limiting the efficient and sustainable development of local agriculture and severely damaging the ecosystem. Spring wheat, due to its strong drought resistance, short growth period, and considerable yield, is considered an excellent preferred crop in this region. Current research on spring wheat has mainly focused on tillage measures, sowing dates, and cultivation patterns, but the characteristics of soil and leaf nutrient content and yield changes under water and nitrogen regulation modes in this region remain unclear.

Farmland ecosystems in this region are mainly limited by water and nitrogen. The relationship between water and nutrients in the soil of semi-arid spring wheat areas in the Loess Plateau of central Gansu needs to be studied to achieve comprehensive regulation and management through fertilizer adjustment and water promotion. This will help realize the positive effects of water and nitrogen regulation, comprehensively improve water and nitrogen use efficiency, and promote efficient agricultural production. This study selected dryland spring wheat in the Loess Plateau of central Gansu as the research object to analyze the dynamic changes of soil and leaf C, N, and P contents and stoichiometric ratios and spring wheat yield under water and nitrogen regulation. We aimed to explore the response mechanism of spring wheat soil and leaf nutrient contents to water and nutrient changes, reveal the optimal water-nitrogen combination for spring wheat growth, and provide theoretical support and scientific basis for achieving efficient agricultural production, reducing water and nitrogen resource waste, and preventing soil environmental pollution in this region.

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2 Materials and Methods

2.1 Study Area

The experiment was conducted from March to July 2020 at the Anjiapo Experimental Station in Anding District, Dingxi City, Gansu Province (35°64 N, 104°64 E). The site is located in the hilly and gully region of the Loess Plateau in central Gansu, classified as a soil and water conservation area. The region has an average altitude of 2000 m, mean annual temperature of 6.4 °C, annual precipitation of 375.44 mm, annual evaporation of 1531 mm, and sunshine duration of 2476.6 h. Precipitation shows strong seasonal patterns, with greater rainfall during the crop growth period, while spring and winter droughts occur frequently. Before sowing, the 0–40 cm soil layer had a bulk density of 1.30 $g \cdot cm^{-3}$, organic matter content of 12.01 $g \cdot kg^{-1}$, total nitrogen content of 0.76 $g \cdot kg^{-1}$, and total phosphorus content of 0.32 $g \cdot kg^{-1}$.

2.2 Experimental Design

The experiment used a split-plot design with irrigation amount as the main plot treatment and nitrogen application rate as the subplot treatment. Four irrigation levels were established: W1 (50 mm), W2 (100 mm), W3 (150 mm), and W4 (200 mm). Three nitrogen application rates were established: N1 (62.5 $kg \cdot hm^{-2}$), N2 (102.5 $kg \cdot hm^{-2}$), and N3 (152.5 $kg \cdot hm^{-2}$). This created 12 treatment combinations, each replicated three times. Each plot area was 24 m^2, with 0.5 m isolation belts between plots. The test variety was "Dingxi No. 42" spring wheat, sown on March 26, 2020, at a seeding rate of 187.5 $kg \cdot hm^{-2}$. Irrigation was applied three times (at tillering, jointing, and flowering stages) using a water meter to calculate the amount for each treatment. Phosphorus fertilizer (P_2O_5 14%) was applied as basal fertilizer at 150 $kg \cdot hm^{-2}$ before sowing. Nitrogen fertilizer was applied as both basal and topdressing fertilizer, with the nitrogen source being common urea (46.5% N). Basal fertilizer was applied before sowing, and topdressing was applied before jointing stage irrigation. Other field management practices followed local conventional methods.

2.3 Sample Collection and Measurement

On July 20, 2020 (mature stage), soil samples were collected from each plot at different soil layers (0-10 cm, 10-20 cm, and 20-40 cm) using a soil auger with a diameter of 25 cm. After removing debris, soil samples from the same layer were mixed to form composite samples, which were passed through a 2 mm sieve, placed in sealed bags, and taken back to the laboratory. The soil was naturally air-dried and passed through a 0.25 mm sieve for analysis. In each plot, 30 wheat plants with similar growth were randomly selected. After heat inactivation, drying, grinding, and sieving, plant samples were prepared for analysis. The selected wheat yield measurement quadrats were all non-border rows and at least 0.5 m from plot edges. Ten plants were measured for spike number, grains per spike, and thousand-grain weight, and yield was calculated.

Soil and leaf OC, TN, and TP contents were determined using the H_2SO_4-$K_2Cr_2O_7$ heating method. After digestion with H_2SO_4-$K_2Cr_2O_7$ solution at high temperature, semi-micro Kjeldahl method and vanadium molybdenum yellow colorimetric method were used to determine TN and TP contents, respectively. Leaf samples were digested with H_2SO_4-H_2O_2 solution before measurement.

2.4 Data Analysis

SPSS 25.0 software was used for statistical analysis and Origin 2018 for plotting. Pearson correlation analysis was used to examine relationships between variables.

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3 Results

3.1 Effects of Water and Nitrogen Regulation on Soil OC, TN, TP Contents and Stoichiometric Characteristics in 0-40 cm Layer

Soil OC, TN, and TP contents showed an overall trend of first increasing and then decreasing with increasing irrigation and nitrogen application amounts (Figure 1). Soil OC and TN contents under the W3N2 treatment were significantly higher than other treatments ($P < 0.05$) and reached maximum values. Soil TP content showed little overall change with no significant differences among treatments (P > 0.05). All three elements decreased layer by layer with increasing soil depth, with average contents in the 0–20 cm layer being 33.11%, 24.02%, and 14.30% higher than in the 20–40 cm layer, respectively. The ranges of soil C:N, C:P, and N:P ratios were 5.81–8.24, 8.35–13.75, and 1.23–1.95, respectively, all lower than national averages.

[Figure 1: see original paper]

3.2 Effects of Water and Nitrogen Regulation on Leaf OC, TN, TP Contents and Stoichiometric Characteristics at Mature Stage

Leaf TN content first increased and then decreased with increasing irrigation amount, while gradually increasing with nitrogen application rate, reaching its maximum under the W3N2 treatment (Table 1). Leaf OC and TP contents showed little change with irrigation and nitrogen amounts, with no significant differences among treatments (P > 0.05). Leaf C:N ratio first increased and then decreased with irrigation and nitrogen amounts, reaching its minimum under the W3N2 treatment, with significant differences among treatments (P < 0.05). Leaf C:P and N:P ratios showed little change with no significant differences among treatments (P > 0.05).

3.3 Effects of Water and Nitrogen Regulation on Spring Wheat Yield and Yield Components

Spike number and grains per spike first increased and then decreased with irrigation amount, while gradually increasing with nitrogen application rate, reaching maximum values under the W3N2 treatment (Table 2). Thousand-grain weight and yield first increased and then decreased with both irrigation and nitrogen amounts, reaching maximum values under the W3N2 treatment and minimum values under the W1N1 treatment, with significant differences among the 12 treatments (P < 0.05).

3.4 Correlations Between Soil and Wheat Leaf C, N, P Contents and Yield

Correlation analysis showed that soil TN content was extremely significantly positively correlated with yield (P < 0.01) and significantly positively correlated with soil OC and leaf TN contents (P < 0.05). Leaf TN content was extremely significantly positively correlated with yield (P < 0.01). Soil OC content was significantly positively correlated with yield (P < 0.05). Other nutrient indicators showed varying degrees of positive correlation with yield.

4 Discussion

4.1 Effects of Different Water and Nitrogen Treatments on Soil OC, TN, TP Contents and Stoichiometric Characteristics

Soil is an important component of terrestrial ecosystems, and soil C, N, and P contents and their stoichiometric ratios are important indicators of organic matter composition, soil fertility, and nutrient balance status. This study showed that soil OC, TN, and TP contents decreased layer by layer with increasing soil depth because litter is an important source of nutrients for surface soil, and soil can absorb root exudates and litter from surface plants, leading to nutrient accumulation first in the soil surface layer before migration and diffusion to lower layers through water or other media. With increasing soil depth, the influence of litter and humus on soil element accumulation gradually decreases. This study found that soil OC and TN contents showed consistent changes because soil TN mainly originates from organic matter formed by plant residue decomposition and synthesis. Additionally, soil OC and TN contents first increased and then decreased with increasing irrigation and nitrogen amounts, reaching maximum values under the W3N2 treatment. This may be because appropriate irrigation and nitrogen application increase soil water content, help dissolve nitrogen fertilizer, improve fertilizer utilization efficiency, and enhance soil fertility. At this point, microbial activity is enhanced, decomposition is strengthened, and soil carbon and nitrogen mineralization rates accelerate, thereby increasing soil OC and TN contents. However, excessive irrigation and fertilization reduce soil porosity, aeration, and tillage quality, inhibit soil respiration and microbial activity, cause soil compaction, lead to resource waste and even secondary salinization, and disrupt the carbon-nitrogen balance, resulting in decreased OC and TN contents.

Soil TP content showed little change with increasing irrigation and nitrogen amounts because phosphorus is a sedimentary mineral mainly influenced by soil parent material with low mobility. Therefore, soil TP content remains relatively stable in the short term with environmental changes. The soil C:N ratio ranged from 5.81–8.24, lower than the national average, indicating that the study area is more deficient in soil nitrogen, which may be an important reason for the low C:N ratio. This suggests that the carbon source in this region' s soil is relatively small, and the rates of organic matter decomposition and mineralization are relatively fast, which is beneficial for crop growth and development to a certain extent. The soil C:P ratio ranged from 8.35–13.75, and the N:P ratio ranged from 1.23–1.95, both lower than national averages, further indicating that the study area' s soil is deficient in phosphorus and confirming previous research results on soils in the Loess Hilly Region.

4.2 Effects of Different Water and Nitrogen Treatments on Leaf OC, TN, TP Contents and Stoichiometric Characteristics at Mature Stage

Spring wheat leaves are the main organs for respiration and transpiration, and their primary function is photosynthesis to produce organic matter. Leaf growth is important for forming large spikes, increasing grain weight, and improving yield. This study showed that leaf OC and TP contents changed little with irrigation and nitrogen amounts because these are structural substances that constitute the plant body, are less affected by the environment, and have relatively stable contents. Leaf TN content first increased and then decreased with increasing irrigation amount and gradually increased with nitrogen application rate, reaching its maximum under the W3N2 treatment. This is because appropriate irrigation and nitrogen application promote plant absorption and dissolution of fertilizer. Photosynthesis enables nutrient accumulation in plants, with erect branches and leaves and normal root development that can fully absorb available nitrogen from different soil depths and transport it to aboveground parts, thereby increasing leaf TN content. Additionally, balanced and effective soil nutrients can enhance plant mineralization and immobilization.

Leaf C:N ratio first decreased and then increased with irrigation and nitrogen amounts, reaching its minimum under the W3N2 treatment, because leaf TN content affects the C:N ratio while OC, as a structural element, is generally high in plants with small environmental variation. Therefore, TN content change is the main factor affecting the C:N ratio. Leaf C:P and N:P ratios showed little change with irrigation and nitrogen amounts and no significant differences because plant phosphorus sources are relatively single with low mobility, making it difficult for crops to absorb and utilize effectively. The N:P ratio can intuitively reflect the limiting effect of soil nitrogen and phosphorus nutrients on plant growth. This study found that the wheat leaf N:P ratio showed no significant change, indicating that spring wheat growth in this study area is mainly limited by nitrogen element. This is because nitrogen is an essential macronutrient for plants and a structural component element. We should fully consider the optimal nitrogen application rate for spring wheat at different growth stages and appropriately increase nitrogen application while further optimizing the water and nitrogen coupling model to supply the plant body for growth and development.

4.3 Relationships Between Soil Nutrients, Wheat Leaf C, N, P Contents and Yield

Soil nutrient and water conditions directly affect plant nutrient absorption and utilization, thereby influencing plant stoichiometric characteristics. Soil OC and TN contents showed consistency in change, with a significant positive correlation between them because soil and plant are closely linked and show relatively unified changes in element storage and consumption processes. Additionally, soil nutrients and water play important roles in plant nutrient absorption. When soil TN content is high and soil internal aeration is good, plant nutrient absorption and utilization are enhanced, root absorption of mineral elements is improved, and absorbed soil nutrients are transported to aboveground parts. Therefore, soil TN content is significantly correlated with leaf TN content and yield. Soil OC content is extremely significantly positively correlated with leaf TN content and yield because aboveground plant growth also promotes soil nutrient accumulation, which in turn promotes plant growth. Additionally, added nitrogen fertilizer can increase soil effective nitrogen content, provide a good living environment for plants, enhance microbial activity, and further improve plant root activity, thereby enhancing the ability to absorb soil OC and transport it upward.

Both leaf TN content and yield showed extremely significant positive correlations with yield, indicating that TN content in leaves significantly affects wheat yield. This is because increased irrigation enhances the yield-increasing ability of fertilizer on crops, and increased fertilization improves the yield-increasing effect of irrigation on crops. Crop productivity is improved, wheat' s ability to absorb and utilize nutrients is further enhanced, and final yield increases.

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5 Conclusion

Based on the analysis of soil and leaf C, N, and P stoichiometric characteristics and yield of dryland spring wheat under water and nitrogen regulation modes in the hilly and gully region of the Loess Plateau in central Gansu, this study revealed the response characteristics of spring wheat soil and leaves to water and nutrients. The main conclusions are as follows:

1. Soil OC and TN contents decreased layer by layer with soil depth and showed a trend of first increasing and then decreasing with increasing field irrigation and nitrogen application amounts, reaching maximum values under the W3N2 treatment. Soil TP content showed no obvious change with field irrigation and nitrogen application amounts. The C:N, C:P, and N:P ratios were lower than national averages, indicating that the study area' s soil is deficient in nitrogen and phosphorus.

2. Spring wheat leaf OC and TP contents showed little change with field irrigation and nitrogen application amounts. Leaf TN content first increased and then decreased with irrigation amount and gradually increased with nitrogen application rate. Leaf C:N ratio first decreased and then increased with irrigation and nitrogen amounts, reaching its minimum under the W3N2 treatment, while leaf C:P and N:P ratios showed little change. The leaf N:P ratio indicated that spring wheat growth in this study area is mainly limited by nitrogen element.

3. Spike number and grains per spike first increased and then decreased with field irrigation amount and gradually increased with nitrogen application rate. Thousand-grain weight and yield first increased and then decreased

with both field irrigation and nitrogen application amounts, reaching maximum values under the W3N2 treatment.

4. Correlation analysis showed significant relationships between spring wheat soil and leaf nutrients and yield. By regulating water and fertilizer supply modes, soil and plant nutrient status can be changed to improve yield.

In summary, controlling irrigation at 150 mm and nitrogen application at 102.5 kg · hm^{-2} can meet the nutrient content requirements of spring wheat during growth, improve yield, and represents an optimal water-nitrogen combination for local production conditions. In practice, nitrogen application rates should be ensured during each growth period of spring wheat in this study area to guarantee normal growth and enable better management of spring wheat fields.

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Note: Figure translations are in progress. See original paper for figures.