Effects of Moisture on Soil Stoichiometric Ratios and Homeostasis of Silage Maize in the Hexi Region: Postprint

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Abstract

To investigate soil nutrient limitations and cycling patterns in the farmland ecosystem of the Hexi irrigation region, and to clarify the homeostasis characteristics of silage corn plants and soil under different water treatments, silage corn under four irrigation treatments in the Hexi irrigation region of Gansu Province—W0 (conventional irrigation), W1 (10% water saving), W2 (20% water saving), and W3 (30% water saving)—was used as the research object. The contents of soil and plant organic carbon (OC), total nitrogen (TN), and total phosphorus (TP), their ecological stoichiometric characteristic changes, and the homeostasis characteristics between plants and soil under different irrigation treatments were analyzed. The results showed that: (1) Under different irrigation treatments, the soil OC, TN, and TP contents of silage corn all reached their highest values in the 0-10 cm soil layer. (2) Under the four irrigation treatments, plant organ nutrient contents were significantly increased under the W0 irrigation treatment; in the 0-30 cm soil layer, soil OC, TN, and TP contents were highest under the W1 irrigation treatment, with TN and TP being significantly higher than those under other irrigation treatments by 6.66%-26.17% and 4.67%-19.21%, respectively; as irrigation amount decreased, soil and plant nutrients decreased significantly. (3) The ranges of variation for soil and plant C:N, C:P, and N:P values were 3.60-61.2, 4.39-53.9, and 1.01-1.24, respectively. Among these, soil C:N values were relatively stable across soil layers and different irrigation treatments. The N:P values of leaves (11.9) and roots (7.58) were both lower than the threshold for plant nitrogen limitation (14), indicating that plant growth was limited by nitrogen. (4) Under the four irrigation treatments, the homeostasis of OC, TP elements and their chemical ratios in plants (roots, leaves) all showed an absolutely stable state, but under the W2 treatment, the homeostasis of leaf N:P showed a sensitive state. It is evident that in the Hexi irrigation region, 10% water saving not only benefits the retention of soil nutrients for silage corn and maintains the stable adaptive capacity of crop growth,

but also achieves the purpose of water saving, thereby alleviating the current situation of water scarcity.

Full Text

Effects of Water Treatment on Stoichiometric Ratio and Homeostasis of Silage Corn Soil in Hexi

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Abstract

To explore soil nutrient limitations and cycling patterns in farmland ecosystems of the Hexi irrigation region and to clarify the homeostatic characteristics of silage corn plants and soil under different water treatments, this study investigated silage corn in the Hexi irrigation area of Gansu Province. We analyzed changes in soil and plant organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) content, along with their ecological stoichiometric characteristics and homeostatic features between plants and soil under different irrigation treatments. The results showed that: (1) Soil OC, TN, and TP concentrations reached their highest values in the 0–10 cm soil layer across all irrigation treatments. (2) Among the four irrigation treatments, plant organ nutrient content was highest under the W0 treatment. However, for the 0–30 cm soil profile, soil TN and TP contents were highest under the W1 treatment (traditional irrigation), exceeding other treatments by 6.66%–26.17% and 4.67%–19.21%, respectively. Soil and plant nutrients decreased significantly with reduced irrigation amounts. (3) The C:N, C:P, and N:P ratios in soil and plants ranged from 3.60–61.2, 4.39–53.9, and 1.01–1.24, respectively. Soil C:N ratios remained relatively stable across soil layers and irrigation treatments. Leaf N:P ratios (11.9) and root N:P ratios (7.58) were below the plant nitrogen limitation threshold (14), indicating that plant growth was limited by nitrogen. (4) Across the four irrigation treatments, plant OC and TP and their stoichiometric ratios remained stable. However, leaf N:P homeostasis exhibited sensitivity under the W2 treatment (20% water-saving irrigation). These findings suggest that 10% water-saving irrigation in the Hexi irrigation area not only promotes soil nutrient retention and maintains stable crop growth adaptability but also achieves water conservation goals, thereby alleviating current water scarcity.

Keywords: silage corn; irrigation amount; soil nutrient; stoichiometric ratio; homeostasis; Hexi

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Introduction

Ecological stoichiometry is an emerging ecological field that reveals the coupling relationships and co-variation patterns of nutrient elements in ecological processes, providing a new method for judging plant growth status, nitrogen and phosphorus limitation efficiency, and solving the supply-demand and cycling relationships of plant-soil nutrients in ecosystems. Farmland ecosystems are important components of terrestrial ecosystems, accounting for approximately 10.5% of global land area. Carbon, nitrogen, and phosphorus are not only essential elements for plant growth and development but also key indicators of soil fertility. Soil carbon constitutes the main element of plant dry matter, while nitrogen and phosphorus are important nutrient elements that limit plant growth. These three elements are both coupled and independent of each other. Organisms maintain a relatively stable relationship between internal element content (plant elements) and external environmental conditions. Within the framework of ecological stoichiometry, organisms maintain relatively stable internal element composition when environmental element composition changes—a capability known as stoichiometric homeostasis, which reflects organism adaptability to complex environments. Therefore, investigating crop plant-soil carbon, nitrogen, and phosphorus stoichiometric characteristics and their homeostasis is significant for exploring nutrient retention, resource limitation, and understanding ecosystem structure, function, and stability in farmland ecosystems.

The Hexi region, located in northwestern Gansu Province, features a typical continental arid desert climate and represents an important grain production area in China. Corn is the main grain crop and a high water-consuming crop in this region, with planting area exceeding 20×10^{4} hm^2. In recent years, climate change and overexploitation of groundwater resources have caused reduced river runoff and significant groundwater level decline, exacerbating water scarcity. Consequently, optimizing water-saving irrigation and improving farmland water use efficiency are urgent priorities. Previous studies have shown that different water treatments affect water-nitrogen transport in spring wheat soil and crop root water and nutrient use efficiency, thereby influencing nutrient cycling in wheat farmland systems. Other researchers have found that crops like red jujube require adequate water, and water deficiency affects soil nutrient supply to crops, hindering plant nitrogen and phosphorus absorption and utilization. Water stress reduces crop organ nutrient absorption and accumulation. While extensive research has been conducted on crop yield, plant nutrient characteristics, and irrigation frequency control, the coupling relationship between nutrient cycling and internal stability mechanisms in dryland silage corn-soil systems under different irrigation treatments remains unclear, particularly regarding carbon, nitrogen, and phosphorus nutrient limitation and homeostatic characteristics. Therefore, this study selected four irrigation gradients based on actual irrigation amounts for local silage corn crops to analyze nutrient cycling patterns between silage corn plants and soil and the homeostatic characteristics of plant organs (leaves, roots) in response to soil nutrient changes.

This research contributes to deeper understanding of nutrient cycling patterns and stability mechanisms under different water-saving treatments in ecologically fragile regions, aiming to explore the nutrient balance and homeostatic relationship between crops and soil in arid areas of Hexi, and provide scientific basis for optimizing water-saving irrigation methods and reducing water waste.

1.1 Study Area Overview

The experimental area was located at Huarui Ranch in Minle County, Zhangye City, Gansu Province (100°40 36 E, 38°43 36 N) at an altitude of 1629 m. The region has an average annual temperature of 3.8°C, average annual precipitation of 364 mm, and high evaporation, belonging to a temperate continental desert grassland climate. Agricultural production depends entirely on irrigation. By the end of 2020, the total cultivated land area was 6.25$\times10^{4}$ hm^2, with irrigated land accounting for over 92% of total cultivated area, representing a typical oasis irrigation agriculture region. The soil type is sandy loam with a bulk density of 1.18 $g \cdot cm^{-3}$, containing organic carbon 5.96 $g \cdot kg^{-1}$, total nitrogen 0.65 $g \cdot kg^{-1}$, total phosphorus 0.7 $g \cdot kg^{-1}$, available phosphorus 6.89 $g \cdot kg^{-1}$, and available potassium 272.19 $g \cdot kg^{-1}$.

1.2 Experimental Materials and Design

The field experiment was conducted from April to September 2021 using the Jingling 11 silage corn variety. Four irrigation treatments were established: W0 (6150 $m^3 \cdot hm^{-2}$, traditional irrigation), W1 (5535 $m^3 \cdot hm^{-2}$, 10% water-saving), W2 (4920 $m^3 \cdot hm^{-2}$, 20% water-saving), and W3 (4305 $m^3 \cdot hm^{-2}$, 30% water-saving). Specific irrigation amounts for each growth stage are shown in . Each treatment had three replicates, with each plot measuring 1.6 m × 1.5 m. A 1.5 m isolation zone was set between plots to prevent mutual influence. Subsurface drip irrigation was used with patch-type drip tape, 30 cm emitter spacing, and 2.2 $L \cdot h^{-1}$ emitter flow rate. Each plot was equipped with a water meter to strictly control irrigation amounts, with irrigation beginning when soil water content reached 70% of field capacity. Fertilization used a hydraulic proportioning pump, with uniform fertilizer application across all plots applied with irrigation water. Nitrogen fertilizer used urea (46% N), potassium fertilizer used potassium chloride (57% K_2O), and phosphorus fertilizer used urea phosphate (44.06% P_2O_5).

1.3 Soil Water Content Measurement

A TDR soil moisture meter was used to measure soil water content every 7 days in each experimental plot at three soil layers (0-10 cm, 10-20 cm, and 20-30 cm).

1.4 Soil and Plant Sampling and Measurement

At corn maturity, five representative plants were randomly selected from each plot. Soil samples were collected using a soil auger at three locations: directly below the corn plant, between two plants, and near the drip tape side at 10 cm depth. Samples were taken from 0-10 cm, 10-20 cm, and 20-30 cm layers. Soil clods and litter were removed, and samples from the same layer within each plot were mixed. Samples were divided into two portions: one passed through a 2 mm sieve for physicochemical property determination, and another air-dried for storage. Five healthy plants were selected per plot, with root sampling conducted directly below the plant. Leaves and roots from the same plot were mixed separately in ziplock bags, brought to the laboratory, washed to remove dust and weeds, oven-dried at 105°C for 30 minutes, then at 75°C to constant weight for dry mass determination. Samples were ground and passed through a 0.25 mm sieve for leaf and root physicochemical property determination.

Soil and plant (leaf, root) organic carbon (OC) content was determined using the potassium dichromate external heating method. Total nitrogen (TN) content was measured using the semi-micro Kjeldahl method after digestion. Total phosphorus (TP) content was determined using the molybdenum antimony colorimetric method after H_2SO_4-H_2O_2 digestion. Soil bulk density was measured using the ring knife method.

1.5 Yield Measurement

Aboveground silage corn yield was measured using the quadrat method. A 1.6 m × 1.5 m quadrat was established in each plot along the drip tape direction to select representative corn plants. Plant height, stem diameter, leaf area, and root-shoot ratio were measured for five plants. Plant height was measured with a tape measure and stem diameter with vernier calipers. Grain was manually threshed and oven-dried at 75°C, with yield per unit area measured using an electronic balance. Yield per hectare was calculated from the unit area yield.

1.6 Data Processing and Statistical Analysis

The homeostasis index (H) was calculated using the following equation:

$$H = \frac{1}{1 + 10^c}$$

where H is the homeostasis index; the dependent variable y represents leaf or root nutrient content or stoichiometric ratio; the independent variable x represents the corresponding soil nutrient content or stoichiometric ratio; and c is the integration constant. According to Persson et al.' s classification, when the equation fit was significant, H values of >10, 4-10, 1.33-4, and <1.33 were classified as absolute homeostasis, weak homeostasis, weak sensitive state, and sensitive state, respectively. When the equation fit was not significant, it was considered absolute homeostasis.

Statistical analysis was performed using SPSS 22.0 software. One-way ANOVA was used for significance analysis, with Duncan' s multiple comparison method for post-hoc tests. Pearson correlation analysis was used to examine relationships between soil nutrient indicators and leaf/root carbon, nitrogen, phosphorus, and their stoichiometric ratios.

Results

2.1 Soil Profile Moisture Changes Under Different Irrigation Treatments

As shown in [Figure 1: see original paper], soil water content in each layer was higher under W0 and W1 treatments. The 10–20 cm layer showed sharp water content changes, while the 20–30 cm layer remained relatively stable across treatments. Under W3 treatment, water content was only 12.89%. Overall, soil water content increased with soil depth under all treatments, with the 0–10 cm layer showing the highest values.

2.2 Plant-Soil OC, TN, and TP Contents Under Different Irrigation Treatments

Changes in soil and plant (leaf, root) nutrients under different irrigation treatments are illustrated in [Figure 2: see original paper]. Soil OC, TN, and TP concentrations in the 0–10 cm layer reached maximum values across all treatments. Soil OC concentrations fluctuated within a certain range across 0–30 cm layers, while TN and TP contents were significantly higher under W1 treatment ($P < 0.05$). In the entire 0–30 cm profile, soil TN and TP contents under W1 treatment exceeded other treatments by 6.66%–26.17% and 4.67%–19.21%, respectively. Plant (leaf, root) nutrient contents decreased with reduced irrigation amounts. Under W0 treatment, plant leaf OC content ($448.00\ g \cdot kg^{-1}$), TN content ($6.67\ g \cdot kg^{-1}$), and TP content ($6.31\ g \cdot kg^{-1}$) were significantly higher than other treatments, while root OC content ($60.00\ g \cdot kg^{-1}$) was also higher than other treatments. Under W3 treatment, plant leaf OC, TN, and TP contents were significantly lower than other treatments, while root nutrient differences were minimal and not significant.

2.3 Plant-Soil Element Stoichiometric Ratios Under Different Irrigation Treatments

Due to different dominant factors affecting soil and plant (root, leaf) nutrient content, significant differences were observed under the irrigation gradient factor. One-way ANOVA results (Table 2) showed that mean C:N, C:P, and N:P ratios in the 0–30 cm soil layer and plant organs differed significantly among irrigation treatments ($P < 0.05$). Soil and plant (root, leaf) C:N ratios showed no significant differences, while soil C:P and N:P ratios reached maximum values under W1 treatment, showing significant differences from other treatments ($P < 0.05$). The ranges of C:N, C:P, and N:P ratios in soil and plants were 3.60–61.2, 4.39–53.9, and 1.01–1.24, respectively. Soil C:N ratios remained relatively stable across soil layers and irrigation treatments. Leaf N:P ratios (11.9) and root N:P ratios (7.58) were below the plant nitrogen limitation threshold (14), indicating plant growth was limited by nitrogen.

2.4 Silage Corn Yield Changes Under Different Irrigation Treatments

As shown in [Figure 3: see original paper], silage corn yield ranged from 85–69 $t \cdot hm^{-2}$ across different irrigation treatments. W0 and W1 treatments showed no significant yield difference, while W2 and W3 treatments were significantly lower ($P < 0.05$). From the perspective of silage corn yield, W1 treatment (10% water-saving) maintained stable yield while achieving water conservation.

2.5 Correlations Between Plant-Soil Stoichiometric Characteristics and Elements

Soil water content showed linear correlations with soil OC, TN, and TP contents. As shown in [Figure 4: see original paper], soil OC, TN, and TP contents were extremely significantly positively correlated with soil water content ($P < 0.01$). Table 3 shows that soil OC, TN, and TP contents were extremely significantly positively correlated with leaf and root OC, TN, and TP contents ($P < 0.01$). Leaf C:N and C:P ratios showed extremely significant positive correlations with root C:N and C:P ratios ($P < 0.01$). Root C:N and C:P ratios showed significant positive correlations with soil OC and TN contents at the same level, while root N:P ratio showed significant positive correlation with soil TN content ($P < 0.05$).

2.6 Homeostasis Analysis of Leaves and Roots in Response to Soil Nutrient Changes

The homeostatic characteristics of leaf and root nutrients and their stoichiometric ratios in response to soil nutrient changes under different irrigation treatments showed that leaf and root OC, TN, TP, and their ratios remained stable across the four irrigation treatments. However, leaf N:P homeostasis was more sensitive under W2 treatment (20% water-saving irrigation) compared to W0 treatment. The regression equations for plant leaf and root nutrients and stoichiometric ratios with soil nutrients were not significant, indicating absolute homeostasis. This suggests that under different irrigation treatments, soil carbon and phosphorus elements could regulate plant element contents and ratios, maintaining relatively stable conditions. Under W2 irrigation, plant leaf N:P showed significant fitting results with homeostasis indices of 1.01 and 1.24 (H

< 1.33), belonging to the sensitive state type, reflecting that leaf nutrients were easily affected by soil nutrient changes under W2 irrigation.

Discussion

3.1 Plant Leaf/Root-Soil Nutrient Contents and Ecological Stoichiometric Characteristics Under Different Irrigation Treatments

Carbon, nitrogen, and phosphorus are essential elements for plant growth and development, and their contents can predict soil and plant nutrient saturation and limitation status. This study found that water-saving irrigation (W1) effectively increased soil OC, TN, and TP contents, consistent with previous research. On one hand, water-saving treatment can promote downward migration of soil moisture to some extent. Under W1 treatment, soil water content was lower than W0 treatment, and lower water content helped promote soil nutrient accumulation. Additionally, although water-saving treatment slowed water transport velocity, it accelerated fertilizer dissolution and organic fertilizer mineralization, improving soil productivity and nutrient decomposition rates, thereby promoting nutrient release and increasing soil nutrient content. However, excessive water-saving (W3) caused soil compaction and deep water infiltration, leading to nutrient leaching to deeper soil layers and accelerating nutrient loss.

Under equal fertilizer application but different irrigation amounts, soil OC, TN, and TP contents generally decreased with soil depth, consistent with Wang Jiancheng' s research. Soil organic carbon primarily originates from plant residues, humus decomposition, and mineralization of microorganisms and root secretions. Soil nitrogen mainly comes from biological nitrogen fixation, rainfall, and fertilizer application, while soil phosphorus primarily comes from fertilization and crop residue return. The study found that soil OC, TN, and TP contents were extremely significantly positively correlated with soil water content, indicating that increased surface organic matter content promoted microbial activity, further promoting nitrogen and phosphorus accumulation. Additionally, surface input of exogenous nitrogen and phosphorus fertilizers led to nutrient concentration in the surface layer, resulting in relatively high nutrient content in the 0–10 cm layer of silage corn fields.

Soil C:N ratio reflects the nutritional balance status of carbon and nitrogen elements and can indicate their sensitivity to soil quality. This study found that in the 0–30 cm soil layer under silage corn maturity, soil C:N ratios (5.42–7.28) were lower than national farmland soil levels (11.45), indicating relatively fast carbon and nitrogen mineralization rates in this region. Soil C:P ratio represents the mineralization potential of soil phosphorus and serves as a diagnostic indicator for predicting soil nutrient limitation and nitrogen saturation status. This study found that soil C:P ratios in the 0–30 cm layer under different irrigation treatments were 60.66–71.44, far below the national level (136), indicating nitrogen deficiency and high phosphorus availability in the region' s soils, with large potential for phosphorus release from organic matter.

Plant C:N:P ratios reflect nutrient levels in plants and can indicate nutritional status and environmental adaptability under different irrigation treatments. This study found that water-saving irrigation reduced plant organ (leaf, root) nutrient contents, possibly because leaf and root nutrients and their stoichiometric ratios showed different levels of correlation, indicating that nutrients absorbed by leaves and roots originated not only from soil and plant nitrogen fixation but also from complex synergistic relationships between different elements, which may be related to plant types and their growth strategies for environmental adaptation. Additionally, excessive water-saving (W3) reduced soil and root environment nutrients, decreasing root nutrient absorption and metabolic intensity. Since aboveground plant organ growth is closely related to root water and nutrient absorption capacity, this further reduced leaf stomatal opening, weakened photosynthesis, and decreased aboveground dry matter accumulation and nutrients.

Plant C:N and C:P ratios reflect the balance between plant growth rate and nutrient utilization efficiency. This study found that root and leaf C:N ratios showed no significant differences with reduced irrigation, indicating a relatively stable coupling structure between the two. However, root C:P ratio under W3 treatment was significantly higher than other treatments, indicating that reduced irrigation significantly decreased plant carbon assimilation capacity and carbon fixation rate, further increasing the proportion of effective phosphorus content in roots. This may occur because phosphorus is a sedimentary mineral with low mobility in soil and is easily adsorbed and fixed. Root phosphorus acquisition depends more on root morphological changes. Under water deficit, roots easily extend to deeper soil layers, changing the root-shoot ratio. Accelerated root growth enables roots with large surface area and many branches to occupy more soil volume, increasing contact area with soil phosphorus and providing relative advantages in phosphorus acquisition, leading to significantly reduced root C:P ratio.

3.2 Plant Leaf and Root Responses to Soil Nutrient Changes and Their Homeostatic Characteristics

Soil nutrient changes directly affect plant growth, functional operation, and nutrient absorption and utilization. When soil nutrients change, plant leaves and roots can maintain relatively stable internal chemical elements through homeostatic regulation. This theory represents the intrinsic attribute of plant nutrient absorption and comprehensive reflection of soil nutrient supply status. Plant homeostasis level is closely related to nutrient limitation. This study found that under W0, W1, and W3 treatments, plant leaf and root homeostasis showed absolute homeostasis, while under W2 treatment, leaf N:P showed sensitive state. This occurred mainly because the experimental area soil was nitrogen-limited, and plant N:P ratios (7.58–11.9) were below the nitrogen limitation threshold

(14), indicating nitrogen limitation during silage corn growth.

The homeostasis model for plant leaf and root nutrients and stoichiometric ratios showed absolute homeostasis under W0, W1, and W3 treatments, but partial sensitivity under W2 treatment. This indicates that silage corn soil and plant (leaf, root) nutrient stoichiometric characteristics have coupling relationships with absolute stability under W0, W1, and W3 treatments (with traditional irrigation W0 as control). Therefore, different irrigation amounts affect nutrient cycling and the feedback mechanism between plant and soil nutrients, and silage corn has a conservative nutrient utilization strategy that enables survival in arid, nutrient-poor soils.

Conclusion

Based on the response of silage corn plant-soil stoichiometry and its homeostasis to water regulation for stable production in the Hexi region, this study investigated silage corn characteristics under different irrigation treatments. The conclusions are as follows:

1. Under different irrigation treatments, soil OC, TN, and TP contents decreased with soil depth, and water-saving irrigation (W1) promoted soil nutrient accumulation, but excessive water-saving (W3) reduced soil and plant organ (leaf, root) nutrient contents.
2. Soil C:N and C:P ratios were relatively stable, with low soil organic matter decomposition rates, nitrogen deficiency, and high phosphorus availability. Plant root C:P ratio decreased significantly with reduced irrigation, reducing plant carbon assimilation capacity and carbon fixation rate, thereby increasing the proportion of effective phosphorus content in roots. Silage corn growth was limited by soil nitrogen elements during its growth process.
3. With traditional irrigation (W0) as control, water-saving irrigation (W1) enabled silage corn plant leaf and root nutrient contents to have relatively high homeostasis and good environmental adaptability to soil nutrient changes.

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