Postprint: Irrigation Water Infiltration and Stratified Water Uptake by Maize in the Qingtongxia Yellow River Irrigation Area

Authors: Ma Guorong, Zhuang Haoran, Xu Dehao, Ma Yongcheng, Zhao Mengyang, Feng Kepeng, Feng Kepeng

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Abstract

Maize is one of the principal crops in irrigated agriculture within arid regions. Investigating the infiltration of irrigation water and the stratified water uptake patterns of maize is crucial for understanding water transport processes in the Soil-Plant-Atmosphere Continuum (SPAC) of maize agroecosystems. This study was conducted in the Qingtongxia Yellow River Irrigation District of Ningxia, situated in an arid climatic zone. Samples of precipitation, irrigation water, groundwater, maize stem water, and soil from seven distinct layers within a 1 m profile were collected throughout the maize growing season. The isotopic variations of \$ \$2H and \$ \$18O were analyzed, and under the guidance of hydrogen and oxygen stable isotopes, combined with soil volumetric water content measurements, the infiltration process of irrigation water following field application was investigated. Subsequently, both the direct comparison method and Bayesian mixing model were employed to quantify the proportional contribution and uptake patterns of water from different soil layers. The results demonstrated that: (1) Hydrogen and oxygen isotopes in precipitation, irrigation water, and groundwater exhibited progressive enrichment, whereas those in maize stem water showed gradual depletion. Soil water isotopes were enriched in the shallow layer (0–30 cm) and stabilized below this depth. (2) The local meteoric water line was \$ $2H = 6.67$ \$18O − 9, indicating significant sub-cloud evaporation. Both precipitation and irrigation water experienced intense evaporation at the soil surface after entering the field, with groundwater being recharged by these sources. (3) Irrigation water infiltrated rapidly within five days of application, with piston flow identified as the dominant infiltration mechanism in the irrigation district. (4) Maize primarily utilized shallow soil water from the 0–30 cm layer, which accounted for 44.70% of total water uptake during the entire growth period. The primary water uptake zone remained unchanged following irrigation events, with the shallow layer providing the greatest contribution. (5) Stratified water uptake by maize was closely correlated with soil temperature and volumetric water content. Elevated shallow soil temperatures and reduced volumetric water content due to transpiration and evaporation prompted increased utilization of middle and deep soil water. Shallow soil moisture is critical for maize growth; under drought conditions, timely irrigation is essential to replenish water in the primary root zone to ensure normal growth and development.

Full Text

Water Infiltration and Maize Root Water Uptake Patterns in the Qingtongxia Yellow River Irrigation District

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MA Guorong[1], ZHUANG Haoran[1], XU Dehao[1], MA Yongcheng[1], ZHAO Mengyang[1], FENG Kepeng[1],[2],[3]

[1]School of Civil and Hydraulic Engineering, Ningxia University, Yinchuan 750021, Ningxia, China
[2]Key Laboratory of the Internet of Water and Digital Water Governance of the Yellow River in Ningxia, Yinchuan 750021, Ningxia, China
[3]Ningxia Engineering Research Center for Water Saving Irrigation and Water Resources Control, Yinchuan 750021, Ningxia, China

Abstract

Maize is a key crop in irrigated agriculture in arid regions, and understanding the infiltration of irrigation water and stratified water uptake patterns of maize is crucial for studying the soil-plant-atmosphere continuum water transfer processes within maize field systems. This study was conducted in the Qingtongxia Yellow River irrigation district in the arid climatic conditions of Ningxia, China. During the maize growing season, samples of precipitation, irrigation water, groundwater, maize stems, and soil from seven depths within 1 meter were collected. The isotopic variations of δ^2H and δ^{18}O were analyzed. Using the guidance of hydrogen and oxygen stable isotopes combined with soil moisture content analysis, the infiltration process of irrigation water into the field was investigated. The absorption proportions and patterns of maize water uptake from various soil layers were examined using both the direct comparison method and Bayesian mixture models. The results indicate that: (1) The hydrogen and oxygen isotopes of successive precipitation, irrigation water, and groundwater in the Qingtongxia Yellow River irrigation district show an enrichment trend, while those of maize stem water gradually deplete; isotopes of soil water are enriched in the shallow layers (0–30 cm) and stabilize below this depth. (2) The atmospheric precipitation line in the irrigation district is represented by $\delta^2\text{H} = 6.67\delta^{18}\text{O} - 9$, with precipitation significantly influenced by secondary evaporation under clouds. After entering the field, both precipitation and irrigation water undergo intense surface evaporation, while groundwater is replenished by both. (3) Irrigation water rapidly infiltrates into the field within five days of application, with piston flow as the primary infiltration mechanism in the irrigation district. (4) Maize predominantly absorbs water from the shallow soil layer (0–30 cm), with the absorption proportion reaching 44.70% over the entire growth period; following irrigation, there is no significant change in the main water absorption layer of maize, with the shallow layer contributing the most. (5) The stratified absorption and utilization of soil water by maize are closely correlated with soil temperature and moisture content. The increase in shallow soil temperature and the decrease in soil moisture content due to transpiration and evaporation promote enhanced utilization of water from the middle and deep soil layers. Adequate moisture in the shallow soil layer is crucial for maize growth, and under arid conditions, timely irrigation is necessary to replenish water in the main soil layer to ensure normal growth and development.

Keywords: stable isotope; irrigation water infiltration; direct contrast method; MixSIAR model; root water absorption changes; atmospheric precipitation line

Introduction

Global climate warming is increasingly affecting farmland ecosystems, posing significant challenges to normal crop growth, particularly in arid and semi-arid regions where agricultural development is severely constrained by water scarcity. Maize is one of the world's major grain crops and plays a critical role in agricultural production. As the world's second-largest maize producer, China's maize production and planting area account for 20.0% and 22.4% of global totals, respectively. Water and temperature are the primary environmental factors determining maize growth in arid and semi-arid regions, directly influencing growth rates and distribution during different developmental stages. Irrigation can regulate soil moisture and temperature, providing suitable growing conditions for maize and thereby ensuring yield. However, China's farmland irrigation water delivery efficiency is only 57.6%, which still lags behind developed countries, indicating substantial potential for agricultural water savings. In this context, studying farmland irrigation water infiltration processes and maize stratified water uptake characteristics can provide scientific evidence for optimizing irrigation management and improving irrigation water use efficiency, which is significant for promoting sustainable development of farmland ecosystems.

Hydrogen and oxygen stable isotopes (δ^2H and δ^{18}O) are components of water molecules and can serve as natural and effective "tracers" to reveal water transport processes in soils and plants. The isotopic composition of soil water can reflect soil water sources and water movement patterns within soils. Traditional methods for studying plant water sources mainly include root excavation, plant water potential measurement, and moisture monitoring. Root excavation determines potential water sources based on root distribution but is time-consuming, labor-intensive, and highly destructive to plants and soils. Plant water potential methods compare differences in plant water sources by measuring pre-dawn water potential, while moisture monitoring analyzes water uptake from various soil layers through continuous soil moisture content measurements. Although these methods can determine plant water sources to some extent, they cannot quantitatively analyze the utilization proportion of each water source. Previous studies have shown that hydrogen and oxygen stable isotopes do not fractionate during water transport from plant roots upward through the xylem, and water in plant vessels can be considered a mixture of all water sources absorbed by roots. Therefore, by analyzing the hydrogen and oxygen isotopic composition of plant stem water and potential water sources, we can calculate the proportion of different potential water sources utilized by plants. Methods based on hydrogen and oxygen isotope analysis for plant water sources mainly include the direct comparison method and model-based methods.

The direct comparison method is a graphical inference approach that determines plant water sources by comparing the isotopic composition of stem water with potential water sources. Model-based methods can quantify the proportion of potential water sources utilized by plants, including multiple linear mixing models (MixSIR) and Bayesian mixture models (MixSIAR, IsoSource). Among these, IsoSource does not consider uncertainties in water sources when calculating contribution rates, nor does it account for spatial variability in source isotopic composition, leading to high uncertainty in model results. MixSIAR combines the advantages of IsoSource and MixSIR, incorporating fixed and random effects as covariates to explain variability in mixing proportions, significantly improving the accuracy of quantifying potential source contributions to plant growth. Therefore, hydrogen and oxygen stable isotope technology provides a sensitive, effective, and reliable method for studying soil water movement and plant water sources.

Water movement in soil profiles primarily occurs through piston flow and preferential flow. Piston flow refers to “new water” gradually pushing “old water” to move slowly downward, while preferential flow describes “new water” bypassing most of the soil matrix and moving rapidly through open channels such as cracks, wormholes, and crop root holes. Previous studies have shown that deep soil water infiltration patterns are consistent in the north and south mountains of Lanzhou, both following piston flow. Research has found that under homogeneous soil conditions, precipitation infiltration is faster, with piston flow as the main infiltration form, while under heterogeneous soil conditions, preferential flow through macropores may coexist with piston flow.

This study focuses on farmland and maize in the Qingtongxia irrigation district of Ningxia, using hydrogen and oxygen stable isotope information from various soil layers to trace the infiltration process of irrigation water after entering the field. Based on hydrogen and oxygen stable isotopes, we employ both direct comparison and MixSIAR models for qualitative and quantitative analysis to examine the characteristics of maize water uptake from different soil layers during the growth period. This research aims to understand water movement at the soil-plant interface in maize farmland ecosystems and provide references for rational water resource management and improved water use efficiency in irrigation districts.

1.1 Study Area Overview

The Qingtongxia irrigation district is located in central-northern Ningxia and represents the largest component of the Ningxia Yellow River irrigation district, with a total land area of approximately 212.5×10^4 hm^2 and an average elevation of 1100 m. The region has a typical mid-temperate continental climate with an average annual temperature of 8.5°C, sunshine duration of 2870–3080 h, and a frost-free period of about 174 days. The district experiences arid conditions with little rainfall and high evaporation, with a multi-year average precipitation of 180–220 mm concentrated in July–September and annual evaporation of 1000–1500 mm. Agricultural production relies year-round on Yellow River water irrigation. The soil type is primarily loam or sandy loam. The experimental farmland is located in Shangqiao Village, Qujing Town, Qingtongxia City (106°05 E, 38°11 N, elevation 1080 m), with maize as the cultivated crop, row spacing of 0.5–0.6 m, plant spacing of 0.2–0.25 m, groundwater depth of 20–25 m, and five irrigation events during the maize growth period (irrigation dates: June 15, July 2, July 23, August 13, and September 1).

1.2 Sample Collection and Data Observation

Soil samples were collected at intervals of 200 m along a straight line in the field. Fresh soil samples from different layers were taken, and simultaneously, a well-growing maize plant was randomly selected near each soil sampling point for stem sampling (Fig. 1). Five sampling points were selected for each sampling event at the seedling stage (June 10), jointing stage (June 30), large trumpet stage (July 20), tasseling stage (August 5), silking stage (August 20), maturity stage (September 10), and continuously for five days after irrigation. Precipitation, irrigation water, and groundwater samples were also collected during the maize growth period.

At each selected sampling point, soil cores were taken at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. The collected soil samples were uniformly mixed and placed in 10 mL glass vials, filled to capacity, sealed with 脱脂 cotton at the bottle mouth, wrapped with Parafilm, and transported back to the laboratory in an incubator.

Maize stem samples were collected by cutting the roots and stems of selected plants with scissors and quickly placing them in 10 mL glass vials sealed with Parafilm. All stem samples were transported back to the laboratory in an incubator.

Precipitation, irrigation water, and groundwater samples were collected using 500 mL bottles after each precipitation or irrigation event. The collected water samples were transferred to 10 mL glass vials in the laboratory and sealed with Parafilm. A groundwater observation well was installed in the experimental field, from which groundwater samples were extracted, placed in 10 mL glass vials, sealed, and brought back to the laboratory.

All samples were immediately frozen in a -15°C freezer after being brought indoors to prevent evaporative fractionation, awaiting subsequent vacuum extraction for hydrogen and oxygen stable isotope analysis.

Precipitation and air temperature were monitored in real-time through the farmland ecosystem observation station in the irrigation district. Soil three-parameter sensors (TEROS12) were placed at 20 cm intervals within the 0–100 cm profile to monitor soil temperature and volumetric water content, with all data recorded at 15-minute intervals.

1.3 Water Extraction and Isotope Determination

An automatic vacuum condensation extraction system (LI-2000, China) was used to extract water from soil and maize stem samples for subsequent hydrogen and oxygen stable isotope determination. Before each extraction, the system's full valve and main valve were tested for air tightness to ensure vacuum conditions. The full valve was pre-cooled to -80°C and the main valve preheated to 198°C for 40–60 minutes and 60–90 minutes, respectively. After pre-cooling and preheating, water was extracted from samples for 60 minutes.

Hydrogen and oxygen stable isotopes of extracted water samples were measured using a liquid water isotope analyzer (TLWIA) based on Off-Axis Integrated Cavity Output Spectroscopy (OA-ICOS) technology. This instrument uses GLA431-Internal Temperature Control Technology for higher measurement precision. The measurement results are expressed as per mil (‰) differences relative to Vienna Standard Mean Ocean Water (V-SMOW): $\delta = (R_{sample}/R_{standard} - 1) \times 1000‰$, where R_{sample} and $R_{standard}$ represent the isotope ratios of the water sample and standard, respectively. The measurement precision is $\pm 0.15‰$ for δ^2H and $\pm 0.02‰$ for δ^{18}O.

To eliminate interference from major organic pollutants such as methanol, measured values were corrected using a standard curve. The standard curve was created by first preparing aqueous solutions of different concentrations using chromatographically pure methanol and deionized water, then measuring all samples with the spectrometer to obtain broadband and narrowband spectral effects. A calibration equation was established using the difference between measured and true isotopic values (Fig. 3). For subsequent sample measurements, the difference obtained from the calibration equation was added to the actual measured value to obtain the corrected δ value.

1.4 Root Water Uptake Pattern Analysis Methods

Crop root systems are three-dimensional and can absorb water from different depths. To characterize maize water sources in detail and quantitatively, this study first employed the direct comparison method for qualitative analysis of the main water absorption layers, then used the MixSIAR model for quantitative calculation of the contribution proportions from different soil layers.

When using the direct comparison method, the isotopic values of stem water and soil water from the same period were plotted together. The intersection point of the stem water isotope line and the soil water isotope distribution line was used to determine the main water absorption layer of maize. The MixSIAR model was used to quantitatively calculate the contribution proportions of different soil layers to maize water uptake using dual isotopes (δ^2H and δ^{18}O). The isotopic values of soil water from different layers were used as source data, and stem water isotopic values were used as mixture data. It was assumed that no hydrogen or oxygen isotope fractionation occurs during maize root water uptake to the stem, with fractionation parameters set to 0. The Markov Chain Monte Carlo (MCMC) runtime was initially set to “normal” to confirm proper model operation, with error structure set to residual only. Model convergence was determined using the Gelman-Rubin diagnostic, and if not converged, the runtime was increased to “long” or “very long” until convergence was achieved. Model outputs were expressed as mean values.

The main water sources for maize in the Qingtongxia irrigation district include Yellow River irrigation water and small amounts of precipitation, which infiltrate into different soil layers to form soil water that serves as the potential water source for maize growth. Soil water was divided into three layers: shallow (0–30 cm), middle (30–60 cm), and deep (60–100 cm).

2.1 Isotopic Composition Variation Characteristics of Precipitation and Irrigation Water

During the maize growth period (June 10–September 10), precipitation, air temperature, and the δ^{18}O values of precipitation and irrigation water showed that the total precipitation was 118.5 mm, with the maximum single precipitation event reaching 30.6 mm on July 20. Precipitation was concentrated in July–September, accounting for 44.3% of the total. The daily average temperature was 23.5°C, with maximum and minimum daily temperatures of 37.4°C (July 12) and 3.5°C (September 10), respectively. The variation characteristics of δ^2H and δ^{18}O values were consistent, with precipitation δ^{18}O values continuously increasing and ranging from -11.36‰ to 4.68‰ (mean -4.86‰). The δ^{18}O values of irrigation water showed smaller variation, ranging from -10.37‰ to 6.43‰ (mean -4.68‰). The δ^{18}O values of mixed 0–100 cm soil water first decreased then increased, reflecting the infiltration and evaporation processes after irrigation water entered the field (Fig. 4).

2.2 Isotopic Composition Variation Characteristics of Maize Stem Water and Soil Water

2.2.1 Isotopic Composition Variation of Stem Water and 0–100 cm Mixed Soil Water During the growth period, maize stem water δ^2H values ranged from -88.25‰ to -53.19‰ (mean -71.49‰), and δ^{18}O values ranged from -10.26‰ to -5.80‰ (mean -7.99‰). The 0–100 cm mixed soil water δ^2H values ranged from -81.68‰ to -61.49‰ (mean -72.76‰), and δ^{18}O values ranged from -10.89‰ to -1.44‰ (mean -8.72‰). Although the variation range of stem water differed from that of soil water, their mean values were similar (Table 1). The variation characteristics of maize stem water and 0–100 cm mixed soil water δ^{18}O values were consistent. Figure 5 shows the changes in stem water and soil water δ^{18}O values at different growth stages and five days after irrigation. During the growth period, both stem water and soil water oxygen isotopes continuously depleted, while 0–30 cm soil water isotopes showed enrichment trends after irrigation.

2.2.2 Isotopic Composition Variation Characteristics of Soil Water in Vertical Profiles Overall, soil water hydrogen and oxygen stable isotope values gradually decreased with increasing soil depth (Table 2). The 0–10 cm layer had the highest mean values at -57.48‰ for δ^2H and -6.06‰ for δ^{18}O, while the 60–80 cm and 80–100 cm layers had the lowest mean values. Within the vertical profile, the 10–20 cm layer showed the largest variation in isotope values, with δ^2H ranging from -79.42‰ to -35.22‰ and δ^{18}O ranging from -10.18‰ to -3.51‰. The 80–100 cm layer showed the smallest variation, with δ^2H ranging from -75.82‰ to -72.80‰ and δ^{18}O ranging from -10.89‰ to -8.78‰. Figure 6 shows the changes in soil water δ^2H and δ^{18}O values at different depths during the growth period. The 0–30 cm layer soil water hydrogen and oxygen isotopes showed enrichment trends during the growth period. The isotopic composition distribution of the 0–30 cm layer at the jointing stage (June 30) and large trumpet stage (July 20) showed different trends from other growth stages, mainly because precipitation events with negative isotopic values occurred before these sampling dates, mixing with existing soil water and reversing the isotopic distribution trend.

Linear fitting of δ^2H-δ^{18}O values for the 30–100 cm layer yielded regression equation slopes for each growth stage: seedling stage (3.89), jointing stage (3.76), large trumpet stage (3.75), tasseling stage (3.78), silking stage (3.77), and maturity stage (3.82). These results indicate similar hydrogen and oxygen isotope distribution trends across growth stages, with slopes for the 30–100 cm layer all around 3.8. In contrast, the 0–30 cm layer showed smaller variation ranges, and comparison with the slope variation range of the 30–100 cm layer indicates that the shallow layer experienced intense evaporation.

2.3 Hydrogen and Oxygen Isotope Distribution Characteristics of Different Water Bodies in the Qingtongxia Irrigation District

Linear fitting of hydrogen and oxygen isotope values for precipitation, irrigation water, and groundwater yielded the local meteoric water line (LMWL: $\delta^2\text{H} = 6.67\delta^{18}\text{O} - 9$), irrigation water line ($\delta^2\text{H} = 5.43\delta^{18}\text{O} - 10.82$), and soil water line ($\delta^2\text{H} = 5.21\delta^{18}\text{O} - 10.26$). Compared to the global meteoric water line (GMWL: $\delta^2\text{H} = 8\delta^{18}\text{O} + 10$), the LMWL has smaller slope and intercept, indicating that precipitation in the irrigation district is affected by strong secondary evaporation under clouds due to arid conditions, high temperatures, and low precipitation. After entering the field, both precipitation and irrigation water undergo intense surface evaporation. Groundwater hydrogen and oxygen isotope values plot near the intersection of precipitation and irrigation water lines, indicating that groundwater is recharged by both sources. Maize stem water isotope values plot near the soil water line, indicating that soil water is the main water source for maize.

At the seedling stage, stem water isotope values deviate from other growth stages (shown in the black ellipse in Fig. 7), mainly because shallow soil water absorbed during the seedling stage is enriched by evaporation, resulting in corresponding enrichment of stem water isotopes with higher δ^2H and δ^{18}O values.

2.4 Maize Water Source Tracing

2.4.1 Direct Comparison Method Analysis of Main Water Absorption Layers Results from the direct comparison method for determining maize main water absorption layers are shown in Fig. 8. Intersection points for the jointing, large trumpet, tasseling, silking, and maturity stages were located at 10–20 cm, 20–30 cm, 10–20 cm, 10–20 cm, and 10–20 cm, respectively. Overall, direct comparison method results indicate that maize primarily absorbs water from the shallow layer (0–30 cm) throughout the growth period, with no change in the main water absorption layer after irrigation. At the seedling stage (Fig. 8a), no intersection point existed, making it impossible to determine the main water absorption layer, demonstrating a limitation of the direct comparison method.

Figure 9 shows the changes in maize absorption proportions from different soil layers after irrigation. On the first day after irrigation, contribution proportions for the 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm layers were 12.15%, 10.05%, 15.20%, 16.67%, 15.23%, 13.33%, and 16.30%, respectively. On the fifth day after irrigation, contribution proportions were 15.65%, 16.20%, 14.55%, 13.50%, 12.80%, 12.90%, and 15.60%, respectively. The contribution proportions of the 0–10 cm and 10–20 cm layers increased by 3.08% and 6.62%, respectively, while other layers decreased, indicating that maize increased water uptake from shallow soil layers after irrigation.

2.4.2 MixSIAR Quantitative Analysis of Maize Water Sources The MixSIAR Bayesian mixture model was used with dual isotopes (δ^2H and δ^{18}O) to quantitatively calculate the contribution proportions of each soil layer to maize water uptake during different growth stages (Fig. 9). Throughout the growth period, the average contribution proportions for the 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm layers were 15.63%, 14.21%, 14.88%, 14.24%, 14.11%, 13.76%, and 13.24%, respectively. The shallow layer (0–30 cm) had the highest average contribution proportion, which decreased sequentially with increasing soil depth.

The contribution proportions of shallow soil water (0–30 cm) at different growth stages were: seedling stage (52.2%), jointing stage (40.73%), large trumpet stage (46.45%), tasseling stage (37.40%), silking stage (45.68%), and maturity stage (44.72%), with an average contribution of 44.70%. Therefore, shallow soil water provided the main water source for maize growth throughout the growth period. From seedling to tasseling stage, the contribution proportion of shallow soil water gradually decreased, then continuously increased after tasseling stage, showing a pattern of first decreasing then increasing.

3.1 Comparison of Direct Comparison Method and MixSIAR Model Results

The main water absorption layers determined by the direct comparison method are basically consistent with the results calculated by the MixSIAR model. However, the direct comparison method only determines the main water absorption layer through intersection points between stem water and soil water isotopes. At the seedling stage, no intersection point exists, and multiple intersection points exist on the fifth day after irrigation, making it impossible to determine the main water absorption layer. The existence of multiple intersection points may be due to irrigation effects, as maize roots increase water absorption after irrigation, and infiltrating irrigation water mixes with existing soil water, changing the isotopic composition of each soil layer. The water uptake from various soil layers is in a dynamic process, making stem water isotopic information complex. This demonstrates that while the direct comparison method is intuitive and simple, its accuracy is limited because it may not capture all influencing factors in the system. When multiple water sources exist or stem water isotopic information becomes complex, its results have limitations and uncertainties.

The MixSIAR model, based on dual stable isotopes, considers uncertainties in water sources and multi-source mixing effects, enabling accurate quantification of the contribution proportions of multiple water sources to maize growth. It can avoid errors when no intersection or multiple intersections exist between stem water and soil water, making it suitable for complex systems. As a Bayesian statistical model, MixSIAR can better handle complex water systems by considering multiple possible sources, which aligns better with reality. Additionally, MixSIAR can account for uncertainties in source proportions, providing more comprehensive results suitable for situations where source proportions are uncertain or variable. However, MixSIAR has high requirements for input data, requiring detailed isotopic characteristic data that necessitate more experimental and analytical work.

3.2 Irrigation Water Infiltration Patterns from a Stable Isotope Perspective

Soil moisture content and isotopic composition changes in the soil profile can reflect the infiltration process after irrigation water enters the field. Figure 10 shows changes in soil volumetric water content at different depths during the growth period. After the second irrigation, the 0–40 cm layer soil water content decreased rapidly, with the 0–20 cm and 20–40 cm layers decreasing by 27.05% and 29.08%, respectively, while deeper layers decreased slowly and the 80–100 cm layer remained almost unchanged.

Figure 11 shows changes in soil water δ^{18}O values at different depths during the five days after irrigation. Linear fitting equation slopes were used to represent isotopic distribution changes in the 0–100 cm soil profile. Analysis of soil water isotope distribution patterns at different growth stages reveals that without irrigation, the 30–100 cm soil water isotope distribution slopes were all around -0.02. After irrigation, the slopes became positive and only returned to pre-irrigation values on the fifth day, indicating that soil water isotope values gradually decreased with increasing soil depth. The main reason for the change in 30–100 cm soil water isotopic composition after irrigation is that irrigation water isotopes are more depleted than existing soil water isotopes, mixing with original soil water during infiltration and affecting the isotopic composition distribution in the vertical profile.

Soil water infiltration is influenced by soil type, properties, and land use patterns. The rapid decrease in 0–40 cm layer soil water content and the trend of first decreasing then increasing isotopic values in the soil vertical profile after irrigation indicate that irrigation water undergoes top-down piston flow infiltration in the soil. The 0–40 cm layer soil water content stabilized on the first day after irrigation, and the soil water isotope distribution slope also returned to pre-irrigation values on the fifth day, indicating that irrigation water infiltration time in the 0–40 cm soil layer is about five days.

3.3 Effects of Soil Temperature and Volumetric Water Content on Maize Root Water Uptake

Changes in maize water uptake strategies are influenced by root growth and distribution, temperature, soil moisture, and soil texture. Maize root systems consist of primary roots, secondary roots, and aerial roots. Previous studies have shown that maize roots are mainly distributed in the 0–30 cm layer, with root dry weight and length increasing rapidly from jointing to tasseling stage and reaching maximum around tasseling. This study's results using direct comparison and MixSIAR models show that shallow (0–30 cm) soil water provides the main water source for maize growth. Changes in air temperature and soil temperature during the growth period and the contribution proportions of different soil layers to maize growth are shown in Fig. 12. The 0–20 cm soil temperature changes consistently with air temperature.

This study found that changes in water uptake proportions from different soil layers during different maize growth stages and after irrigation respond to soil temperature. From seedling to jointing stage, the combined effects of drought stress caused by increasing shallow soil temperature and downward root growth prompted maize to increase water uptake from middle and deep soil layers, with the absorption proportion increasing by 6.33%. From jointing to tasseling stage, the effects of root growth and drought stress further increased, with the proportion of water uptake from middle and deep soil layers continuing to increase by 8.47% until tasseling. After tasseling, maize roots almost stopped growing, decreasing air temperature led to lower shallow soil temperature, and the proportion of water uptake from shallow soil layers increased. The proportion of water uptake from shallow soil layers at maturity increased by 9.05% compared to tasseling stage. Overall, the proportion of water uptake from shallow soil layers during the maize growth period showed a pattern of first decreasing then increasing, while the proportions from middle and deep soil layers showed the opposite pattern.

Soil moisture has a profound impact on crop water uptake. Within the 0–100 cm soil profile, the volumetric water content of middle and deep layers (40–100 cm) is generally higher than that of shallow layers (0–30 cm). Correlation analysis between the contribution proportions of different soil layers to maize water uptake and the volumetric water content of those layers (Fig. 13) shows that the contribution proportion of shallow soil water is negatively correlated with soil volumetric water content, while the contribution proportions of middle and deep soil water are positively correlated with soil volumetric water content. Shallow soil moisture fluctuates greatly due to evaporation and root water uptake. When shallow soil water content is too low, maize experiences water stress, requiring timely irrigation to replenish soil moisture in this layer to ensure normal maize growth and development. There is a complementary effect between shallow and middle-deep root water uptake, consistent with findings from Yang et al.

Conclusion

In the Qingtongxia Yellow River irrigation district located in an arid climate zone, precipitation undergoes strong secondary evaporation under clouds during falling, resulting in the local meteoric water line having smaller slope and intercept than the global meteoric water line. Both precipitation and irrigation water undergo intense surface evaporation after entering the field, and hydrogen and oxygen isotopes are significantly enriched in shallow (0–30 cm) soil. Groundwater in the irrigation district is mainly recharged by precipitation and irrigation water.

Irrigation water rapidly infiltrates within five days after entering the field, with piston flow as the main infiltration form. Maize in the irrigation district primarily utilizes shallow soil water (0–30 cm), with the utilization proportion showing a pattern of first decreasing then increasing during the growth period. The utilization proportions of middle and deep soil water show the opposite pattern. After irrigation, maize increases its absorption proportion from shallow soil layers, but the main water absorption layer remains unchanged.

The stratified water uptake patterns of maize are related to soil temperature and volumetric water content. Increased air temperature leads to higher shallow soil temperature, and decreased soil volumetric water content due to transpiration and evaporation promote increased utilization of middle and deep soil water by maize. The contribution proportion of shallow soil water is negatively correlated with soil volumetric water content, while those of middle and deep soil water are positively correlated, highlighting the importance of shallow soil moisture for maize growth.

In summary, in the arid Qingtongxia Yellow River irrigation district, soil evaporation is intense, and soil temperature and moisture are two key factors affecting maize water uptake. Therefore, under arid conditions, timely irrigation is needed to replenish water in the main soil layer to ensure normal maize growth and development.

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