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Multiple sources characteristics of root water uptake of crop under oasis farmlands in hyper-arid regions

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ABSTRACT

Understanding the water use strategy of crops is important for maintaining the stability of agricultural production and improving water use efficiency (WUE). Affected by a variety of water sources and hyper-arid climate, the characteristics of root water uptake (RWU) in seed maize are extremely complicated but underestimated in oasis farmlands with shallow groundwater. We hypothesized that isotope (δ^2H and δ^{18}O) measurements over three years coupled with a MixSIAR model would reveal the characteristics of RWU in maize. Stable water isotopes in oasis farmlands were continuously observed from 2019 to 2021. Over the growing season, the soil matrix potential increased with soil depth. The isotopes in stem water had high similarity to groundwater, irrigation water, and soil water. The contributions of soil water in 0–20 cm, 20–40 cm, 40–60 cm, and 60–100 cm soil layers to RWU in maize were 29.7%, 12.2%, 14.8%, and 43.3%, respectively. From the jointing stage to the dough stage, the depth of RWU in maize was from shallow to deep; but after the dough stage, the depth of RWU in maize was from deep to shallow. Crops might prefer to absorb more groundwater and irrigation water in oasis farmlands with shallow groundwater. This study provides insights into crop water uptake and agricultural water management in hyper-arid regions.

1. Introduction

About 70% of groundwater and surface water is used for agricultural irrigation worldwide (Penna et al., 2020). Unsustainable water resource management and low water use efficiency (WUE) in fields accelerate the shortages of water, which are more prominent in arid and semi-arid areas (Gomez-Alday et al., 2022). Artificial oasis farmland is a typical landscape in arid areas, whereas natural and environmental conditions, e.g. extreme drought, barren soil, and water shortage, impact the stability of agricultural production (Zhang et al., 2018). Water demand constantly increases with the continuous expansion of artificial oasis farmlands, which further increases water scarcity in hyper-arid regions (Zhang et al., 2016, 2019). Importantly, the mismatch between water supply schemes and the characteristics of root water uptake (RWU) leads to lower WUE of crops in these regions (Yang et al., 2015). Physiological characteristics of RWU for crops in artificial oasis farmlands remain largely unknown, especially the variation over crop growth stages.

Water use strategies of crops are an issue of wide concern in agroecosystems, which could mitigate the contradictions arising from water scarcity. The RWU in plants, the main process of water transfer in the soil-plant-atmosphere continuum (SPAC), is not only crucial to understanding the water cycle in ecosystems, but also for improving the production of crops (Bois et al., 2021). Exploring the mechanisms of RWU can regulate water use strategies of crops growth (Manzoni et al., 2013). However, RWU in crops are affected by the water supply. Understanding water use for crops from various water sources or different soil layers has become key to alleviating water stress of plant growth and ensuring high WUE in irrigated fields. The RWU patterns in crops are crucial to improving WUE for the stability of agricultural production and to making optimal irrigation schemes for better agricultural water management (Eriksson, 2017).

Isotope technology, a high accuracy, quick, and non-destructive method, can be used to explore water use in crops (Flanagan et al., 2019; Xiao et al., 2018). Through evaporation, transpiration, and infiltration, stable isotope fractionation occurs, which makes the isotopic composition of different water sources unique (Arellano et al., 2020).

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When using isotopes to study water use, the assumption is that isotopic fractionation does not occur during the process of water as it is absorbed by plant roots from the soil and transported to xylem (Ellsworth and Williams, 2007; Liu et al., 2020). The contribution of different water sources to plant growth can be determined by comparing isotopic composition between xylem and multiple sources. Moreover, some models, including binary or ternary hybrid models, Isosource models, and MixSIAR models, allow for the quantitative study RWU in plants (Yang et al., 2018). Importantly, MixSIAR models consider spatiotemporal variability and uncertainty of each source, whereby the results of RWU in plants are more representative and persuasive (Dudley et al., 2018). Thus, isotope measurements (δ^2H and δ^{18}O) combined with MixSIAR models can characterize crop water use from different soil depths or water sources (Schwendenmann et al., 2015; Ma and Song, 2016; Li et al., 2020). For example, in croplands, winter wheat throughout all growth stages obtained ~65% of its water derived from 0 to 60 cm depth, irrigation depth should be less than 60 cm (Liu et al., 2021). The main water uptake in maize was 50–80 cm depth (Zhao et al., 2018). Isotope has been employed to evaluate RWU in maize, cotton, rice, and wheat (Karakis et al., 2018; Yang et al., 2018). Isotope technology coupled with quantitative models is a powerful way to provide insight into optimal agricultural water management (Ehleringer and Dawson, 1992).

The artificial oasis in the middle reach of the Heihe River is the largest seed maize cultivation center in China (Yang et al., 2015). The production of maize in this area accounts for 40% of the seed maize produced throughout China (Zhang et al., 2016). Maize yield effectively determines agricultural productivity of this area. Due to heterogeneous conditions, the depth of RWU in maize varies during the growing season (Wu et al., 2016; Ma and Song, 2016; Liu et al., 2018). The roots of maize mainly consume shallow soil water during the early growth stage (Penna et al., 2020). The water use strategy of some plants was revealed using the isotope technology coupled with related models (Yang et al., 2018). However, these previous studies are limited to a single season and do not consider differences in seasonal variation in water supply (precipitation, irrigation, and groundwater) (Ma and Song, 2016). Also, the studies on RWU in plants were conducted over short-time scales, and the conclusions were drawn from a single year's data within high uncertainty caused by the external environmental and logistical errors. In our study area, maize was affected by various water sources (precipitation, irrigation water, soil water, and groundwater), and the patterns of RWU are extremely complex but undefined. Moreover, there are few observational studies on the characteristics of RWU in seed maize across consecutive years.

We hypothesized that isotope measurements (δ^2H and δ^{18}O) across three years coupled with a MixSIAR model would reveal RWU strategies in seed maize. Soil matrix potential and stable isotopes were continuously observed under the oasis farmlands from 2019 to 2021. The aims of this study were to 1) investigate isotopic composition of hydrogen and oxygen for different water samples, 2) quantitatively assess the patterns of RWU in maize from different soil layers.

2. Materials and methods

2.1. Site description

Our observations were conducted in an oasis farmland in hyper-arid regions, located in the middle reach of the Heihe River, Northwestern China (39°19′N, 100°8′E, 1330 m above sea level; Fig. 1). The experimental fields belong to the National Field Science Research Station of Farmland Ecosystem in Linze, and China Flux Observation and Research Network, which has a hyper-arid, desert climate. The annual pan evaporation is 2388 mm, whereas the average annual precipitation is only 117 mm (1965–2012). The mean annual temperature is 7.6 °C, and the high temperature and precipitation are mainly concentrated from July to September. The study was performed from 2019 to 2021. The underground water depth in our study site is shallow within ~1 m (Yi, 2015). Soil physicochemical properties of the experimental site are shown in Table 1.

2.2. Experimental design

Monoculture of seed maize is the primary crop in the study area and has been planted there for more than 20 years. We established 48 m^2

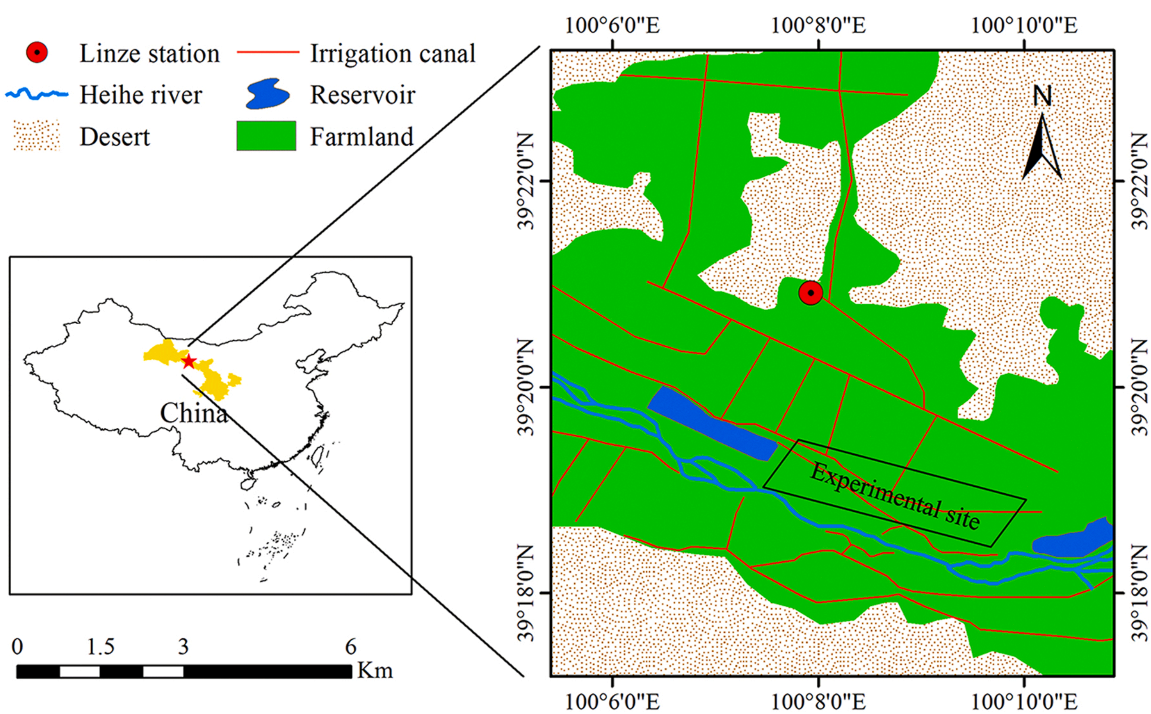

Fig. 1. Location of the experimental site.

Table 1
Soil properties of the experimental sites.

Soil depth (cm)	Clay content (%)	Silt content (%)	Sand content (%)	Bulk density (g cm^{-3})	Soil organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	Total potassium (g kg^{-1})
0–20	21.89	23.35	54.76	1.48	18.1	1.3	1.3	10
20–40	29.01	31.48	39.50	1.63	14.1	0.9	1.2	10
40–60	13.38	21.70	64.92	1.49	7.1	0.4	1.1	9
60–80	3.13	4.34	92.53	1.56	4.9	0.2	0.7	9
80–100	2.46	5.10	92.44	1.58	2.7	0.2	0.8	9

(6 m × 8 m) sampling plot with three replicates. Maize (Seed maize 1256) was grown using ridge-furrow cultivation. Ridges were constructed by elevating the soil on both sides of the plot and then mulching with black plastic film. The planting density was 72,000 seeds hm^{-2}. Maize was sown along the midline of each ridge on April 10 and harvested on September 15. To ensure growth, fertilizer consisting of 360 kg N hm^2 in the form of urea (N 46%) and triamine (N 18%), 180 kg P hm^2 in the form of triamine (P_2O_5 18%), and 180 kg K hm^2 in the form of triamine (K_2O 18%) was applied to each plot every year. Fertilizer was applied evenly in the seedling, jointing, and filling stages. We used furrow irrigation three times in 2019 (June 9, July 20, and August 24), three times in 2020 (June 7, July 15, and August 15), and three times in 2021 (June 6, July 16, and August 14) during maize growth. The amount of water used was 80–90 mm on each time. The growth season of maize is generally divided into six growth stages: the seedling, jointing, tasseling, filling, dough, and mature stages (Ding et al., 2010). We sampled from April 2019 to September 2021. The proportion of dry root weight density at different growth stages were referred from the same study sites as in Yi (2015).

2.3. Isotope sampling and measurement methods

The sampled plants and soil samples were sealed with parafilm (PM-996) and immediately put into the refrigerator and then sent to the laboratory for cold storage (below −4 ℃) until δ^2H and δ^{18}O were measured. The same, established sampling and measurement methods were used across the three consecutive years, as described below:

2.3.1. Stem water samples

Two maize plants with three replicates were randomly sampled in each growth stage. The stem each plant was cut about 5 cm from the ground, and the bract was removed. To prevent isotope fractionation caused by transpiration, the 2–3 cm stem base samples were put quickly into brown glass bottles.

2.3.2. Soil water and groundwater samples

In order to investigate the contributions of soil water from different layers to RWU in maize, the soil profile was divided into five layers based on soil layer classification and soil water sources: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm. On the same day when sampling plants in each growth stage, soil samples at the five soil layers were taken near the sampled maize using a soil auger each month. Soil samples (with three replicates) were put quickly into 50 ml centrifuge tubes. Groundwater samples were collected in an observation well with 20 ml centrifuge tubes with three replicates.

2.3.3. Irrigation and precipitation samples

Rainwater samples were collected during each precipitation event via rainwater collector and stored in 20 ml centrifuge tube with three replicates. Irrigation water samples were collected from each irrigation event with 20 ml centrifugal tubes from irrigation outlets with three replicates. After each collecting samples, irrigation and precipitation samples were measured every time.

2.3.4. Measurement methods

The samples were analyzed in the Isotope Hydrology Laboratory of the Key Laboratory of Inland River Basin, Chinese Academy of Sciences. The collected samples was independently measured each time. Stem water and soil water were extracted by low temperature vacuum distillation extraction apparatus. The δ^2H and δ^{18}O was measured by LGR liquid water isotope analyzer (lwia, 912-0008-1001, Los Gatos Research Inc., Mountain View, CA, USA). In order to reduce the error caused by instrumentation, each sample was measured 6 times, and the average value of the last 4 measurements was taken. To better reflect the difference in isotopic composition for different samples, the following equation was used.

$$\delta(‰) = (R_{sample} - R_{standard})/R_{standard} \times 1000 \quad (1)$$

where $\delta(‰)$ denotes the isotopic composition of samples, R_{sample} and $R_{standard}$ represent the hydrogen or oxygen stable isotope ratio (^{2}H/^{1}H or ^{18}O/^{16}O) of the samples and Vienna Standard Mean Ocean Water (VSMOW), respectively. The measurement accuracies of δ^2H and δ^{18}O are ± 0.2‰ and ± 0.03‰, respectively.

2.4. Auxiliary measurements

Meteorological data (e.g., atmospheric pressure and precipitation) were monitored from the National Field Science Research Station of Farmland Ecosystem in Linze. Underground water depth in our study sites was obtained from the Linze station, which was manually observed. Soil matrix potential was monitored with the TEROS 21 sensor (METER Company, USA) at depths of 10, 30, 50, 70, and 90 cm at each sampling plot. Sensors were installed in the center of each plot, with one monitoring profile of soil matrix potential at each plot due to logistical difficulties. Soil matrix potential was monitored every 30 min.

2.5. Data analysis

The MixSIAR model, a new Bayesian hybrid model, was developed based on the following equations (Stock et al., 2018):

$$Y_i = \sum_{k=1}^{n} f_k W_{ik} \quad (2)$$

where Y_i represents the mixed source data, n is the number of sources, W_{ik} is each source data, f_k is the contribution of each source to mixed source.

The R package MixSIAR (https://github.com/brianstock/MixSIAR) was used to calculate the contribution of different soil layers to RWU in maize. The "mixed source data" was input as the isotope ratio of stem water, and the "source data" was input as the isotope ratio of different soil layers. Since it was assumed that isotope fractionation did not occur, the "discrimination data" was set to zero. The error structure consisted of "resid" and "process" errors, and the parameter running step was set to "very long".

All data were represented as means ± standard deviation (SD). Statistical analyses were implemented using SPSS, ver. 20.0 (SPSS Inc., Chicago, IL). The Spatial Kriging interpolation tool in ArcGIS 10.2 (ESRI, Redlands, CA, USA) was used to estimate variation in soil matrix potential in the soil profile. Univariate linear regression analysis was performed using SPSS, version 20.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Variation in soil matrix potential and underground water depth

Soil matrix potential increased from shallow to deep soil layers (Fig. 2), and soil matrix potential near groundwater was higher than in the topsoil layer, indicating that the lower soil layers might often replenish soil water in the upper layer. Furthermore, the variation of soil matrix potential was responded markedly to drought events. Soil matrix potential in the topsoil layer was lower in May 2020 than those in other two years resulting from low winter irrigation amount in 2019. Surface soil matrix potential gradually decreased before irrigation and rose sharply after irrigation. Soil matrix potential at 0–30 cm varied considerably during maize growth, whereas the variation in soil matrix potential below 70 cm was more stable (Fig. 2). In our study sites, underground water depths over crop growth stages were 0.75–1.12 m in 2019, 0.78–1.09 m in 2020, and 0.67–1.01 in 2021, respectively. Moreover, there were no differences in underground water depth among the observation periods in 2019, 2020, and 2021.

3.2. Isotopic composition of hydrogen and oxygen for different water samples

The linear fitting equation of the Local Meteoric Water Line (LMWL) in all three years was $\delta^2H = 7.51\delta^{18}O + 7.14$ (R^2=0.97, $P < 0.01$). The slope of the Local Meteoric Water Line (LMWL) was smaller than the Global Meteoric Water Line (GMWL: $\delta^2H = 8\delta^{18}O+10$), but the slope of the LMWL equation was larger than that of the soil water fitting equation (Fig. 3). The isotopes of stem water were distributed among different water samples, whereby stem water was a mixture of multiple water sources. According to the isotopic distribution of different water sources, stem water had high similarity to groundwater, irrigation water, and soil water, while differing from precipitation (Fig. 3).

The variation in $\delta^{18}O$ was roughly the same as that of δ^2H in each water sample (Fig. 4). The range of $\delta^{18}O$ in precipitation was the highest, ranging from − 11.21 to − 1.14‰, with a mean value of − 5.58‰. The average values for $\delta^{18}O$ of irrigation water (−8.70‰) and groundwater (−8.26‰) were similar to that of stem water (−8.25‰), but precipitation and stem water differed. The $\delta^{18}O$ in soil water ranged from − 11.23 to − 5.11‰, with a mean value of − 8.57‰. The $\delta^{18}O$ of 0–40 cm soil layer fluctuated each year but remained below 40 cm (Fig. 4d-f). The $\delta^{18}O$ of 20–40 cm soil layer was the lowest throughout the soil profile, and, overall, the $\delta^{18}O$ first decreased and then increased with soil depth (Fig. 4d-f).

3.3. Contribution of different soil layers to the root water uptake of maize

We compared the $\delta^{18}O$ of stem water to soil water. The depth of RWU for maize was concentrated at 0–20 cm during the jointing stage (Fig. 5). During the growth stage, the depth of RWU was from the shallow to deep layers. From the tasseling to dough stage, the depth of RWU was concentrated in the 50–90 cm layer (Fig. 5). During the mature stage, the depth of RWU reduced to 0–20 cm in 2019 and 2020 (Fig. 5). In 2021, the depth of RWU was concentrated at 60–80 cm resulting from high soil water content in deeper soil layers and lower underground water depth during the observation period.

The contribution from soil water at 0–20 cm to RWU was 45.8%, 32.7%, 22.8%, 13.2%, and 33.7% at the jointing, tasseling, filling, dough, and mature stages, respectively (Fig. 6). Over the growing season, the annual average contributions of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm layers to RWU were 29.7%, 12.1%, 14.9%, 20.6%, and 22.7%, respectively. Maize preferred to use 0–20 cm and below 60 cm during the growing season, whereas the contribution of the 20–60 cm layers to RWU was lower (Fig. 6).

4. Discussion

The isotopic composition of various water sources differ due to isotopic fractionation (Dudley et al., 2018). The evaporation in our study area was higher than the global average resulting in the slope of the LMWL to be lower than the GMWL, and there were pronounced differences in isotopic composition between precipitation and other water sources. The slope of in soil water isotopes fitting equation was lower than the LMWL, suggesting that evaporation occurs when precipitation infiltrates soils. Our results coincide with previous findings in arid regions (Liu et al., 2020; Wu et al., 2016), indicating groundwater recharge might rarely come from local low precipitation events.

The composition of isotopes varied among different soil layers. Stable isotopes at 40–100 cm depth were more stable than 0–40 cm depth. The seasonal variation of soil matrix potential at 0–40 cm was high and likely caused by irrigation, precipitation, and strong evaporation. Thus, stable isotopes were either depleted or enriched in topsoil layers (Leroux et al., 1995). Moreover, the stable isotopes in topsoil fluctuated seasonally as in Corneo et al. (2018). However, the stable isotopes for soil water in our study area first decreased and then slightly increased with depth, wherein the inflection point of the soil profile was at about 30 cm (Fig. 5), where evaporation weakened (Schwendenmann et al., 2015). Stable isotopes at 20–40 cm soil layer were the lowest, which explains isotope enrichment being weakest. Stable isotopes for soil water then slightly increased with depth, which was similar to groundwater (Fig. 4), likely because below 40 cm is affected by groundwater replenishment. Thus, the isotope composition among different soil layers differed in the oasis farmlands, which are comprehensively affected by irrigation, groundwater, and soil evaporation.

The depth of RWU in plants varied with growth stage. Crop root

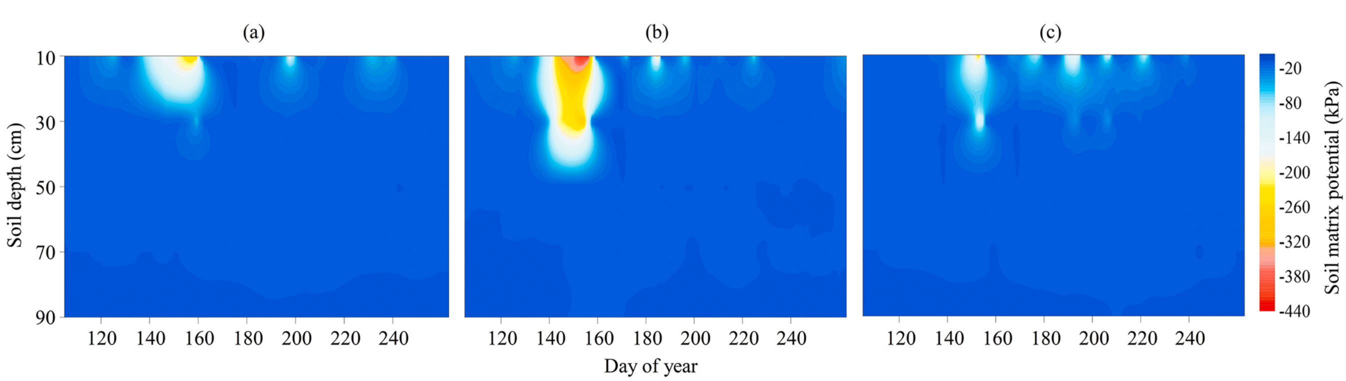

Fig. 2. Variation of and soil matrix potential during the maize growing season in 2019 (a), 2020 (b), and 2021 (c).

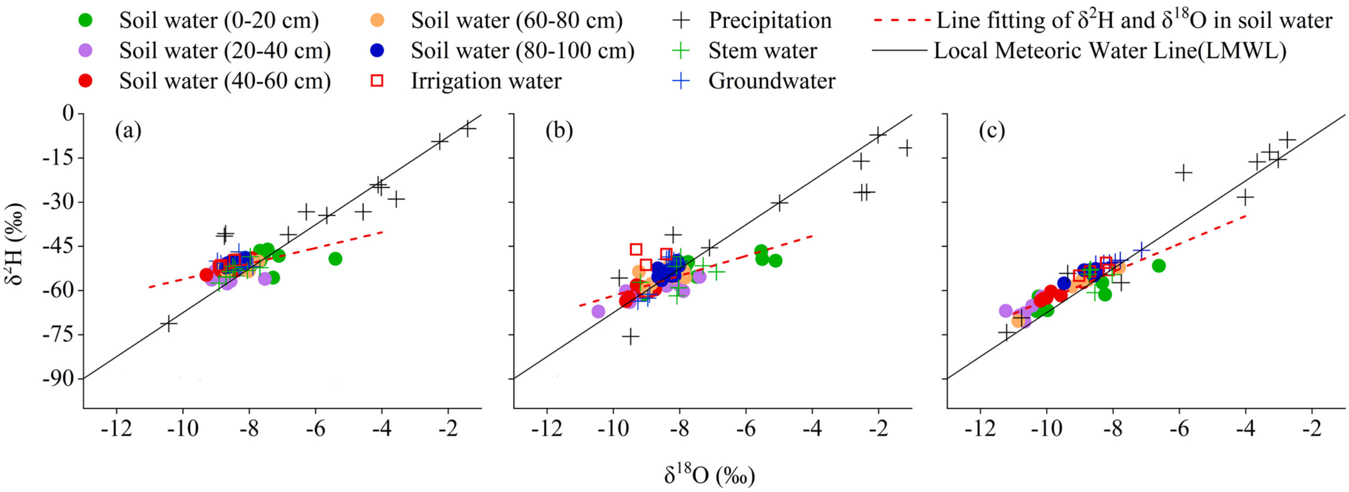

Fig. 3. Relationship between $\delta^{18}O$ and $\delta^{2}H$ in different water samples in 2019 (a), 2020 (b), and 2021 (c).

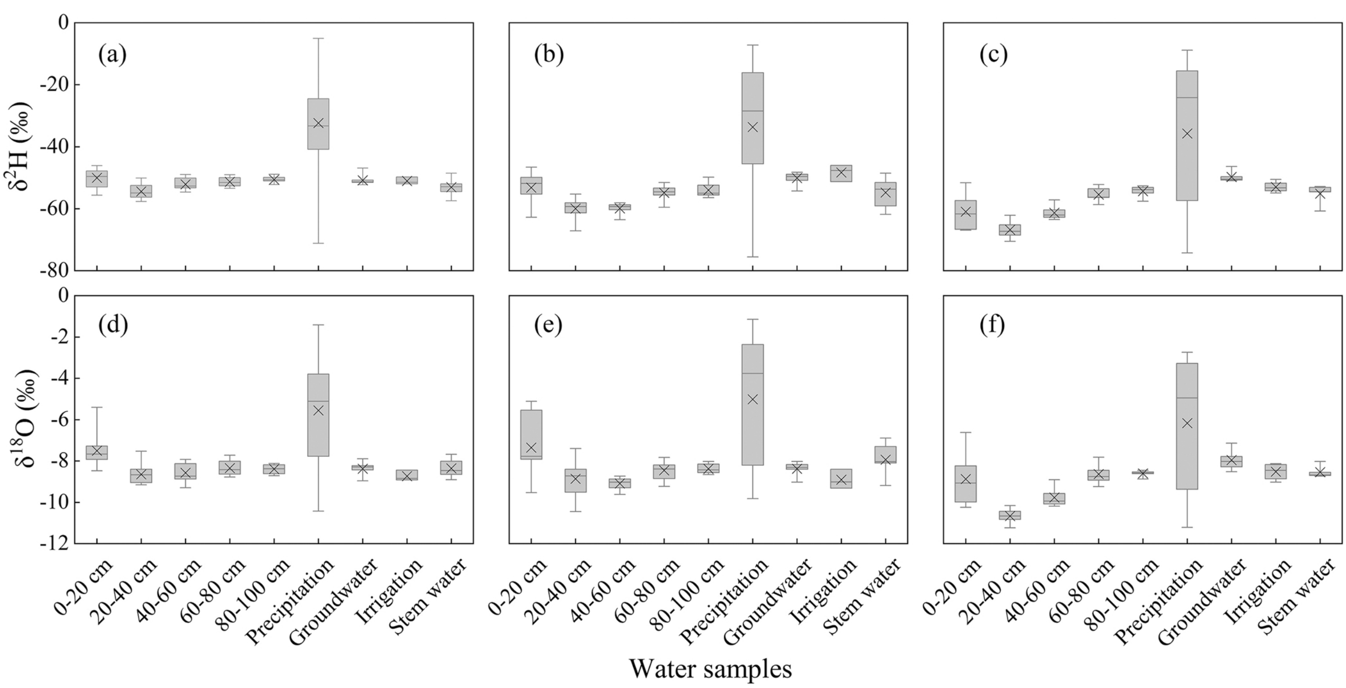

Fig. 4. $\delta^{2}H$ in different water samples in 2019 (a), 2020 (b), and 2021 (c), and $\delta^{18}O$ in different water samples in 2019 (d), 2020 (e), and 2021 (f).

distribution is thought to trace the depth of RWU in plants, but it may not reflect actual water uptake temporally and spatially (Ehleringer and Dawson, 1992), which mainly depends on root activity and soil moisture (Wu et al., 2014; Zhao et al., 2018). Generally, root-length is considered when determining sampling depth. For most crops, scarcely any roots are found below 120 cm (Zhao et al., 2018). Thus, the sampling soil depth in our study was 100 cm with shallow groundwater. The contribution of the 0–20 cm layer to RWU in maize was 45.8% in the jointing stage, indicating that the topsoil layer was the dominant depth of RWU at this growth stage. Similarly, Liu et al. (2018) showed that the 0–20 cm layer provided 59.7% of water for maize growth at early stages. Aboveground aerial roots in maize support crop growth and account for a large percentage of the shallow root weight (Ma and Song, 2016). In our plots, maize roots were short and distributed in the upper soil layer at the vegetative stages (Yi, 2015). From the jointing to dough stage, the water requirements of maize and its evapotranspiration increased. The depth of RWU became deeper because roots were long and SWC at the top layers could not meet the water requirements (Wu et al., 2016). Maize roots extend to deeper soils, and these roots may be more efficient at absorbing water in deep layers. Also, soil matrix potential at deeper layers was higher than the topsoil layer, and SWC at deeper soil layers met the water demand of maize. However, from the dough to mature stage, the depth of RWU became shallower. As the crops enter the mature stage, the water demand of maize decreases due to shrinking roots (Zhao et al., 2018). Zhao et al. (2018) found that 52.4% of water was from 0 to 20 cm at the harvest stage. The depth of RWU in our study area was complex and mainly depended on root activity and SWC, but it was roughly consistent with the findings that the depth of RWU was characterized by "shallow-deep-shallow" according to growth stage (Wang et al., 2010).

The contributions of soil water at 0–20 cm and 60–100 cm to RWU in maize were 29.7% and 43.3%, respectively, during the three years. The contribution of soil water at 20–60 cm to RWU for maize was less (Fig. 7), suggesting maize absorbed soil water from the upper soil layer,

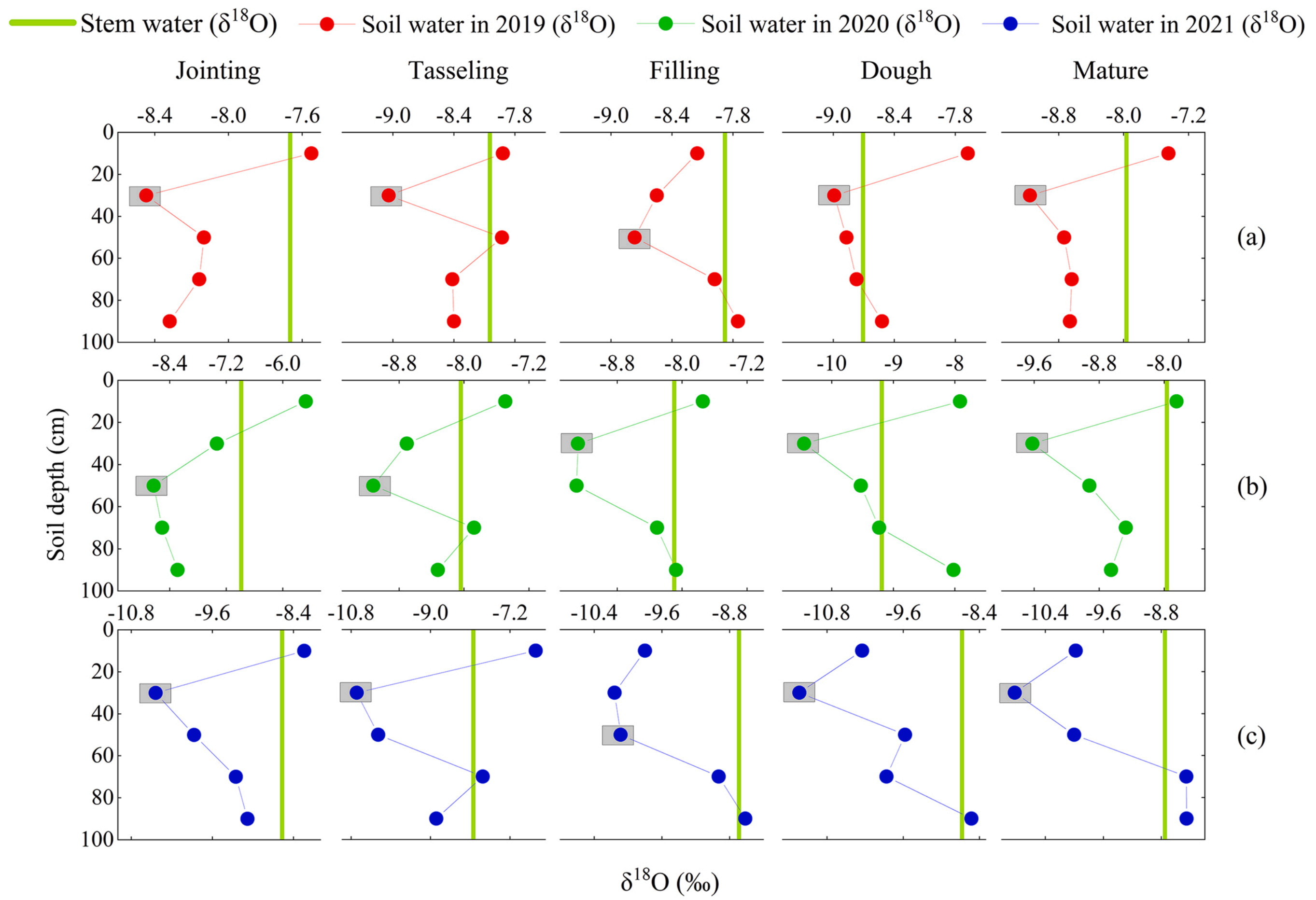

Fig. 5. Relationship between $\delta^{18}O$ of stem water and $\delta^{18}O$ in different soil layers during growth stages in 2019 (a), 2020 (b), and 2021 (c).

which is affected by irrigation events, and from the deeper soil layer, which is regulated by groundwater. As Zhang et al. (1999) reported, plants preferred to absorb "fresh" water such as irrigation water or precipitation rather than soil water. Vegetation depends on groundwater in arid areas without irrigation (Cui et al., 2015). The shallow groundwater may replenish the deeper soil layers in our study area. Maize was inclined to absorb soil water at higher SWC layers (Drake and Franks, 2003). The contribution of soil water to RWU was positively correlated with SWC (Rose et al., 2003). SWC consequently should be taken into consideration when determining crop water uptake (Wang et al., 2010; Yang et al., 2015). Thus, crops prefer to absorb soil water at 0–20 cm and 60–100 cm, which may be a survival strategy for maize with shallow groundwater in hyper-arid regions.

Due to affecting by various water sources, RWU patterns in maize became complicated in our study area. In our study area, annual pan evaporation averaged twenty times greater than annual precipitation (Zhang et al., 2022). Generally, SWC in the oasis regions was replenished by irrigation and groundwater during the growing season (Ding et al., 2010). The isotopic values of soil water at 0–20 cm and 60–100 cm might represent the isotopic values of irrigation water and groundwater (Fig. 4). Thus, crops more prefer to absorb irrigation water and groundwater in oasis farmlands with shallow groundwater. Our results are different than those from humid areas and semi-arid regions (Wu et al., 2021; Aguzzoni et al., 2022) but consistent with RWU in plants in arid areas (Maihemuti et al., 2021). The contribution of different soil layers to RWU in maize as estimated by the MixSIAR model will guide water use strategy for crops. Using isotope data presents a quantitative interpretation of water use of crops from various soil depths. This evaluation explicitly contributes to the field water cycle and provides an important scientific basis for improving WUE for maize. Moreover, RWU in crops and variation in the underground water table, soil properties, and irrigation methods should be considered in future studies. These studies provide new insights into exploring optimal agricultural water management practices in hyper-arid regions.

5. Conclusions

The patterns of RWU in maize were quantitatively estimated in oasis farmlands from 2019 to 2021. Soil matrix potential increased with depth, and the variation of soil stable isotopes first decreased and then increased with depth. The isotopic composition between precipitation and soil water, groundwater, and irrigation water were different. The depth of RWU in maize was characterized by "shallow-deep-shallow" in coordination with the growing periods. Maize may prefer to absorb irrigation water and groundwater in oasis farmlands. This study provides a guide for optimizing water use strategies in oasis farmlands with shallow groundwater in hyper-arid regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors declare that the majority of the data supporting the findings of this study are available from Y.Y. Zhang

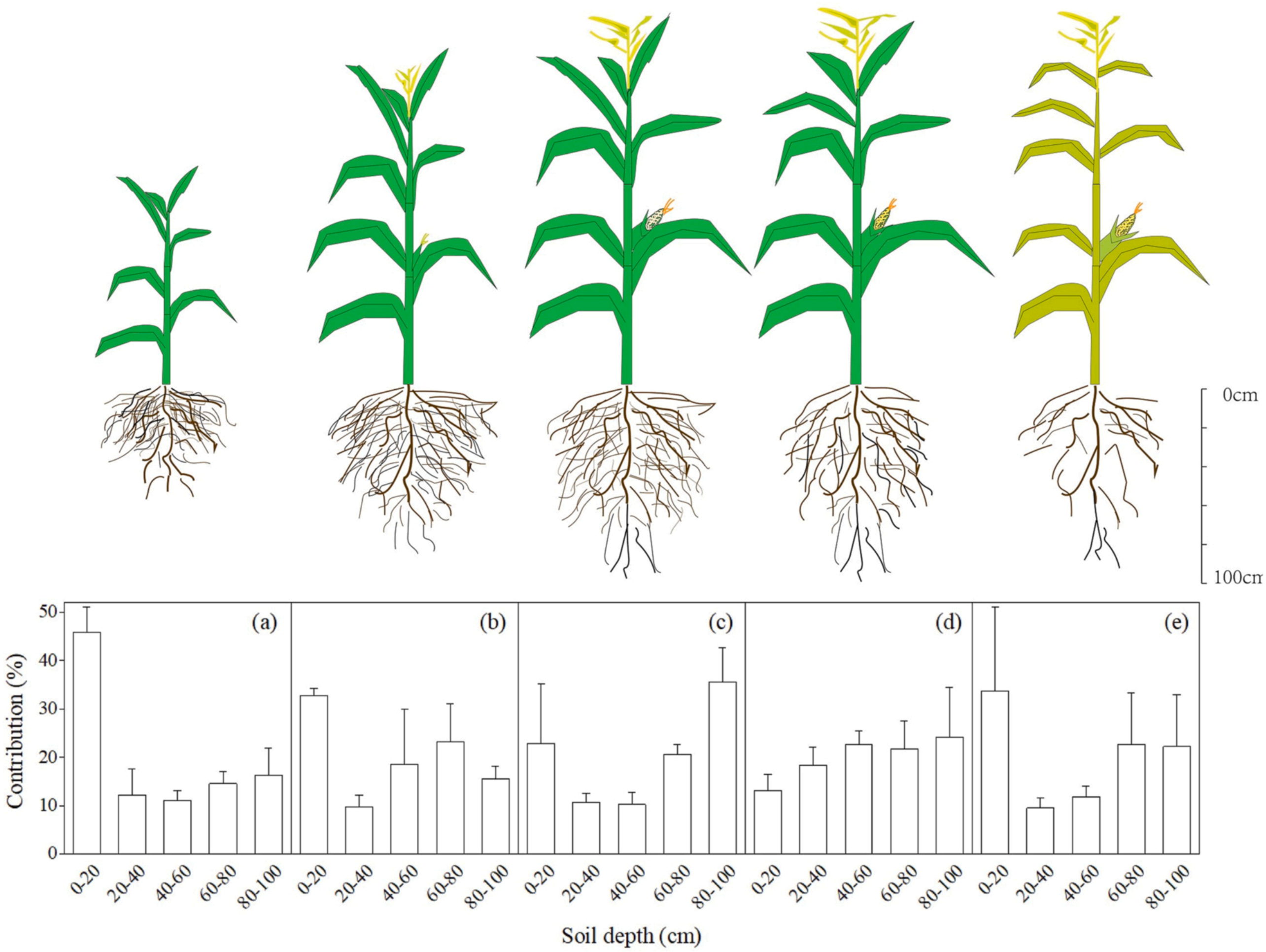

Fig. 6. Contribution of soil water at different soil layers to root water uptake in maize in the jointing (a), tasseling (b), filling (c), dough (d), and mature (e) stages.

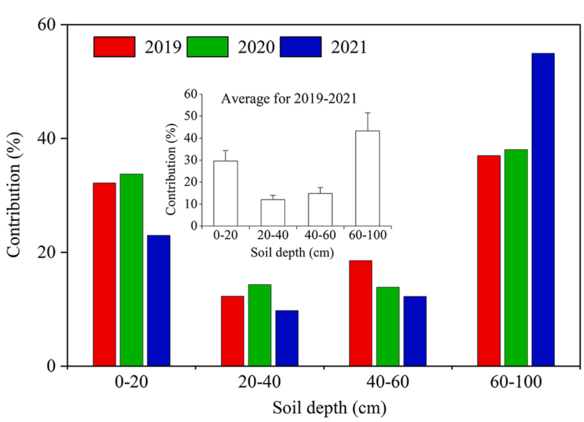

Fig. 7. Contribution of soil water at different layers to root water uptake in maize from 2019 to 2021.

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