



Seasonal reorganization of vertical soil-water partitioning among contrasting crops in an arid oasis agroecosystem

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Abstract

Soil-water availability in arid agroecosystems varies with depth, yet how contrasting crop functional types use water from different soil depths through the growing season remains poorly constrained. Here, we combined stable hydrogen and oxygen isotope measurements of precipitation, irrigation water, soil water, and crop xylem water with soil-water content observations and Bayesian source apportionment to examine seasonal soil-water partitioning among alfalfa, maize, and *Lycium chinensis* in an oasis agroecosystem of northwestern China. Soil-water isotopes showed the strongest variability in the upper profile, consistent with greater evaporative modification of near-surface water. Alfalfa exhibited comparatively stable reliance on shallow soil water, with estimated 0–20 cm contributions of 54.2–64.5 % across the growing season. *Lycium chinensis* relied more strongly on middle and deep soil-water stores, whereas maize showed the clearest seasonal shift, shifting from dominant shallow-water use early in the season towards increasing contributions from deeper layers as crop development progressed. These contrasting uptake-depth patterns were accompanied by differences in



28 soil-water availability and evaporative enrichment among crop fields. Although isotope-based
29 source fractions remain sensitive to end-member definition and temporal sampling, the results
30 indicate crop-specific differences in estimated contributions from soil-depth groups under the
31 sampled irrigated conditions.

32 **1 Introduction**

33 In arid and semi-arid climates, plant water uptake can depend on the vertical distribution
34 and seasonal variation of soil-water content within the root zone. Precipitation, irrigation,
35 infiltration, evaporation, and plant uptake can all influence the vertical distribution of soil
36 water. In irrigated drylands, these processes are superimposed on strong atmospheric demand
37 and episodic water inputs, creating steep vertical gradients in both soil-water availability and
38 isotopic composition (He and Rosa, 2023; Hou et al., 2021). The hydraulic retention behavior
39 of unsaturated soils influences how water is stored and released across wet and dry conditions,
40 and representing retention curves under dry conditions can be particularly challenging (de
41 Rooij et al., 2021; de Rooij, 2022).

42 Crops may draw different proportions of water from different soil depths when soil-water
43 content varies vertically within the root zone. Alfalfa, maize, and *Lycium chinensis* differ in
44 growth habit and seasonal development, which may be associated with different patterns of
45 water-source use (Huang et al., 2018; Hou et al., 2021; Wu et al., 2016). However, comparative
46 measurements of these crop-specific patterns under the same arid conditions remain limited.
47 Root depth and fine-root distribution can affect access to vertically structured soil water, as
48 shown for alfalfa and drought-affected woody vegetation (Luo et al., 1995; Ren and Huang,
49 2016; Yang et al., 2015; Zhao et al., 2020). Fertilizer and irrigation practices can also alter



alfalfa fine-root biomass (Li et al., 2018). Regional precipitation isotope signals are also influenced by atmospheric circulation, while irrigation infiltration and soil-water migration in oasis farmland respond to irrigation and mulching practices (Lu et al., 2024; Zhu et al., 2021a, 2021b). Stable-isotope studies have documented seasonal and depth-dependent shifts in plant water use during vegetation succession and across the soil–plant–atmosphere continuum, while water sources may also respond to altered precipitation regimes (Chang et al., 2019; Dai et al., 2020, 2023; Grossiord et al., 2017).

Stable isotopes of hydrogen and oxygen provide a means to link plant water uptake with soil-water storage and mixing because their signatures integrate infiltration history, evaporative modification, and source-water heterogeneity. When combined with vertical soil-water observations, isotope tracers and a mixing model can estimate contributions from sampled soil-depth groups to xylem water, provided that the sampled end members adequately represent the sources used by plants (Dawson et al., 2002; Rothfuss and Javaux, 2017; Wang et al., 2023). However, isotope-based source apportionment is sensitive to end-member separation, source grouping, temporal sampling resolution, and possible offsets between xylem and source water (Fu et al., 2024; Qiu et al., 2025). Process interpretation therefore requires explicit consideration of both vertical soil-water heterogeneity and model uncertainty. Stable isotopes have long been used to trace water movement through unsaturated soils and characterize spatial and temporal heterogeneity in soil-water isotope composition, with related applications to plant transpiration and hydrological water balances (Barnes and Allison, 1988; Mathieu and Bariac, 1996; Oerter and Bowen, 2019; Evaristo et al., 2015; Gibson and Reid, 2014). Recent studies further show that plant-water source estimates depend on source availability and root distribution, and that hydrogen-isotope offsets and model choice can affect inferred



73 contributions (Dai et al., 2023; Fu et al., 2024; Qiu et al., 2025; Li et al., 2026; Cai et al., 2024;
 74 Zhao et al., 2024).

75 Jingtai County in northwestern China provides a representative irrigated dryland setting in
 76 which alfalfa, maize, and *Lycium chinensis* are exposed to the same regional climatic
 77 constraints but differ strongly in life form and seasonal development. We used stable hydrogen
 78 and oxygen isotopes together with vertical soil-water observations to examine seasonal
 79 soil-water partitioning among these contrasting crops. The study objectives were to (1)
 80 characterize seasonal and vertical variation in soil-water content and isotope composition; (2)
 81 estimate the contributions of predefined soil-depth groups (0–20, 20–60, and 60–100 cm) to
 82 crop xylem water; and (3) compare the seasonal patterns among the three crops.

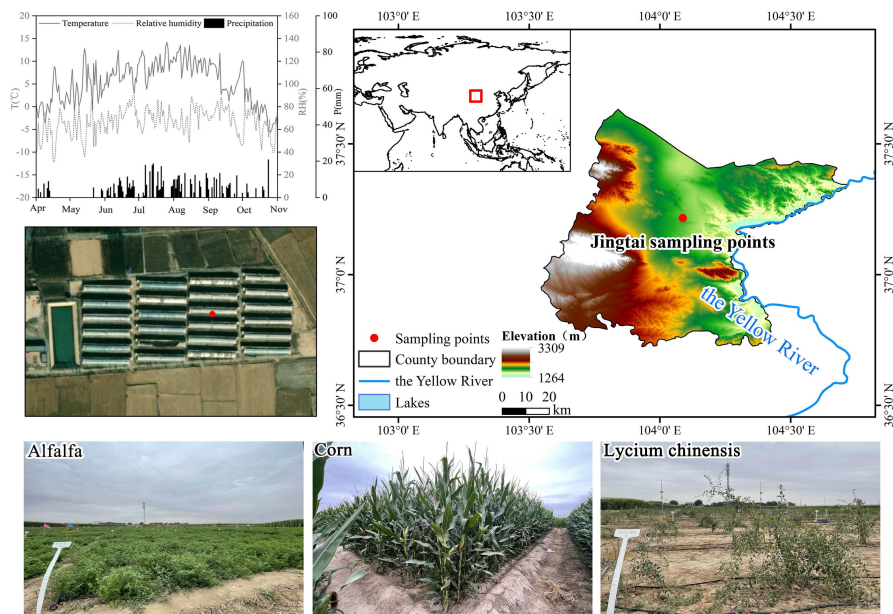
83 **2 Materials and methods**

84 **2.1 Study area**

85 Jingtai County is located in central Gansu Province (103°33′–104°43′ E, 36°43′–37°38′
 86 N), at the eastern end of the Hexi Corridor and the transition between the Loess Plateau and the
 87 Tengger Desert. The county covers 5483 km² and ranges from 1276 to 3321 m above sea level.
 88 The terrain is inclined from southwest to northeast, and the study fields occur on a gently
 89 inclined plain (Fig. 1). The area has a temperate arid continental climate with cold winters, hot
 90 summers, abundant sunshine, and scarce precipitation. Mean annual precipitation is
 91 approximately 185 mm, reported annual evaporation is approximately 3038 mm, annual
 92 sunshine duration is 2652 h, and mean annual temperature is 8.2 °C. Cultivated soils are
 93 primarily irrigated light chernozems with soluble salts, relatively low topsoil organic matter,
 94 and loose structure. Surface-water resources are limited, making irrigation an important control



95 on soil-water storage during the growing season.



96

97 **Fig. 1** Overview of the study area and location of sampling points

98 **2.2 Sample collection and measurement**

99 **2.2.1 Sample collection**

100 Precipitation, irrigation water, plant xylem and soil samples from 0–100 cm depth were
101 collected for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analysis. Precipitation samples covered August 2020–September
102 2024, and irrigation water samples covered May 2023–June 2024. Plant and soil sampling was
103 conducted during the 2023 and 2024 crop-growing seasons, with eight sampling campaigns
104 available for isotope analysis. Plant and soil samples were collected during the same
105 campaigns, allowing isotope values to be compared by sampling date. Sampling was
106 conducted between 08:00 and 11:00 whenever possible to limit short-term thermal and
107 evaporative effects.



Table 1 Summary of water sample collection and isotope analyses used in this study

Sample type	Sampling location/source	Sampling period	Sampling frequency and details	Number of samples
Precipitation water	Jingtai meteorological observation site	August 2020–September 2024	Individual rainfall events; one sample was collected after each event (one sample per day during multi-day events).	144
Irrigation water	Common irrigation inlet shared by three experimental fields	May 2023–June 2024	Monthly during the irrigation period; sampled at the common inlet supplying all three fields.	18
Xylem water	Alfalfa, maize, and <i>Lycium chinensis</i> fields	May–September 2023; May–August 2024	During the crop-growing seasons; one xylem sample was collected from each selected plant individual per campaign.	24
Soil water	Alfalfa, maize, and <i>Lycium chinensis</i> fields	May–September 2023; May–August 2024	At 10 cm intervals from 0–100 cm (10 soil layers per sampling event).	240

(1) Precipitation sample collection

A standard rain gauge was installed in an open area near the study fields. A funnel fitted with a ping-pong ball was used to reduce post-collection evaporation. Immediately after each event, rainwater was transferred to a 50 mL high-density polyethylene bottle, sealed with Parafilm, and refrigerated until analysis. During multi-day precipitation events, one sample was collected per day. A total of 144 precipitation samples were collected during the sampling period.

(2) Irrigation water sample collection

Irrigation water was sampled at the common inlet supplying all three experimental fields; 18 samples were retained for isotope analysis during May 2023–June 2024.

(3) Plant sample collection

Representative and healthy individuals were selected from each crop plot. The sampled



121 crops were alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.) and *Lycium chinensis*. For each
 122 sampling event, one individual per crop field was selected for xylem-water extraction. For
 123 maize, stem segments were cut directly. For *Lycium chinensis*, 3–5 cm stem segments were
 124 collected; the bark and phloem were removed promptly, and the xylem was retained. For
 125 alfalfa, non-green tissue at the root–stem junction was sampled. Plant samples were
 126 immediately placed in 50 mL glass bottles, sealed and frozen until laboratory analysis.
 127 Sampling time and field conditions were kept as consistent as practicable among crop plots.
 128 Xylem sampling followed the available crop-season campaigns; crop phenological stage was
 129 not used as a separate sampling criterion.

130 (4) Soil sample collection

131 Near each plant-sampling location, soil was collected with a hand auger at 10 cm intervals
 132 to a maximum depth of 100 cm, where field conditions permitted. Where augering was not
 133 feasible, a soil profile was excavated manually. Soil samples were collected from ten soil
 134 layers (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm) to
 135 resolve vertical changes in soil-water content and isotope composition across the sampled
 136 profile. Each soil sample was divided into two subsamples. One subsample was sealed in a 50
 137 mL glass bottle with Parafilm, labelled with the sampling date, and refrigerated until isotope
 138 analysis. The other subsample was placed in a pre-weighed aluminium container and weighed
 139 before and after oven-drying at 105 °C for 24 h to determine gravimetric soil-water content
 140 (SWC). SWC was calculated as the difference between the wet and oven-dried soil masses
 141 divided by the oven-dried soil mass and expressed as a percentage. Undisturbed cores were
 142 also collected from the same soil layers, sealed immediately, and oven-dried in the laboratory
 143 to determine soil bulk density.



(5) Meteorological data

During the sampling period, air temperature, relative humidity, dew-point temperature, and other meteorological variables were recorded by a WatchDog 2000 Series automatic weather station deployed near the sampling site.

2.2.2 Experimental analysis

The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of all water samples were measured at the Stable Isotope Laboratory of Northwest Normal University using a DLT-100 liquid-water isotope analyzer (Los Gatos Research, USA). Water was extracted from plant xylem and soil samples by low-temperature vacuum distillation using an LI-2100 system (LICA United Technology Limited, China). Soil and plant samples were extracted at 190 °C for 150 and 180 min, respectively, under a vacuum pressure below 800 Pa. The extracted water was collected using a liquid nitrogen cold trap, and the extraction recovery was approximately 98%.

The isotope compositions were expressed relative to Vienna Standard Mean Ocean Water (VSMOW) using the following equation:

$$\delta_{\text{sample}}(\text{‰}) = \left[\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 1000 \quad (1)$$

where R_{sample} is the $^{18}\text{O}/^{16}\text{O}$ or $2\text{H}/1\text{H}$ ratio of the sample and R_{standard} is the corresponding ratio in Vienna Standard Mean Ocean Water. Analytical precision was $\pm 0.6\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$. Each sample was measured six times, with the first two injections discarded to minimize memory effects, and the mean value of the remaining four injections was used for isotope analysis. Spectral contamination correction was performed using the LWIA-Spectral Contamination Identifier v1.0 software to evaluate and correct potential methanol and ethanol interference.



166 **2.3 Analytical methods**

167 **2.3.1 LC-excess**

168 Line-conditioned excess (LC-excess) quantifies the deviation of a sample from the local
 169 meteoric water line (LMWL) and is commonly used as an indicator of evaporation-related
 170 nonequilibrium fractionation relative to local precipitation (Landwehr and Coplen, 2006).

$$171 \quad \text{Lc-excess} = \delta^2\text{H} - a \times \delta^{18}\text{O} - b \quad (2)$$

172 where a and b are the slope and intercept of the LMWL, respectively, and $\delta^2\text{H}$ and $\delta^{18}\text{O}$
 173 are the isotope values of the sample. Samples that plot on the fitted LMWL have LC-excess
 174 values near zero, whereas evaporation-enriched soil water generally has negative LC-excess
 175 values relative to that line (Landwehr and Coplen, 2006).

176 **2.3.2 MixSIAR model**

177 The Bayesian MixSIAR model was used to estimate posterior contributions of soil-water
 178 source groups to crop xylem water (Stock and Semmens, 2016; Stock et al., 2018). Soil water
 179 was grouped into shallow (0–20 cm), middle (20–60 cm), and deep (60–100 cm) sources based
 180 on vertical patterns in soil-water content and isotope composition. Both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ were
 181 used as tracers. No fixed, random, nested, or continuous effects were included, and a
 182 non-informative Dirichlet prior ($\alpha = 1$) was assigned to source proportions. Process error was
 183 included whereas residual error was not. The model was run using the predefined “very long”
 184 MCMC setting. Convergence was assessed using Gelman–Rubin and Geweke diagnostics
 185 following MixSIAR guidance (Stock and Semmens, 2016). Posterior source proportions are
 186 quantitative estimates conditional on the three defined source groups and measured isotope
 187 signatures. They represent contributions within the sampled end-member set rather than direct
 188 measurements of volumetric water flux; the potential for incomplete end-member coverage is



189 considered for alfalfa in the Discussion.

190 **2.3.3 Hydrological context from estimated crop water demand**

191 Reference evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith
 192 method; crop evapotranspiration (ET_c) and gross irrigation requirements were then estimated
 193 using crop coefficients, growth-period duration, and assumed irrigation efficiency (Allen et al.,
 194 1998). These estimates were used only as complementary hydrological context and were not
 195 treated as measurements of field water balance, plant water uptake, or water-use efficiency.
 196 Stable-isotope approaches have also been used to quantify soil-water fluxes and field water
 197 balances under contrasting tillage and irrigation systems (Alba Canet-Martí et al., 2023).

$$198 \quad CWR = ET_0 \times K_c \quad (3)$$

199 ET_0 is the reference evapotranspiration, K_c is the crop coefficient, and their product gives
 200 crop evapotranspiration for the corresponding growth stage.

$$201 \quad I = \frac{CWR}{E} \quad (4)$$

202 where I is the gross irrigation requirement and E is irrigation efficiency expressed as a
 203 fraction.

$$204 \quad G = I \times C \quad (5)$$

205 where G is the stage-total gross irrigation requirement (mm) and C is the duration of the
 206 growth stage (days).

207 ET_0 is calculated using the FAO Penman–Monteith equation.

$$208 \quad ET_0 = \frac{0.408 \times K \times (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{K + \gamma (1 + 0.34 u_2)} \quad (6)$$

209 where ET_0 is the reference crop evapotranspiration (mm day⁻¹); R_n is the net radiation
 210 (MJ m⁻² day⁻¹); G is the soil heat flux density (MJ m⁻² day⁻¹), which was set to zero for the



211 daily calculations; T is the mean daily air temperature ($^{\circ}\text{C}$); u_2 is the wind speed at 2 m height
 212 (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); K is
 213 the slope of the saturation vapor pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$); and γ is the psychrometric
 214 constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

$$215 \quad e_s = 0.6108 \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right) \quad (7)$$

$$216 \quad e_a = e_s \times \frac{RH}{100} \quad (8)$$

$$217 \quad K = \frac{4098 \times e_s}{(25 + 237.3)^2} \quad (9)$$

218 **2.3.4 Estimation of isotopic evaporative modification of soil water**

219 The Craig–Gordon isotope framework was used to estimate an isotope-derived
 220 evaporative-loss fraction for soil water. This is an isotope-mass-balance estimate of the fraction
 221 of water loss attributable to evaporation, not a direct ratio of evaporation flux to total
 222 soil-water content. Under the stated isotopic mass-balance assumptions, the isotope-derived
 223 evaporative loss fraction was calculated following Gonfiantini (1986) and subsequent
 224 applications to soil water (Mahindawansa et al., 2020):

$$225 \quad f = 1 - \left[\frac{(\delta_s - \delta^*)}{(\delta_p - \delta^*)} \right]^m \quad (10)$$

226 In Eq. (10), f is dimensionless; δ_s is the measured soil-water isotope composition (‰), δ_p
 227 is the reference isotope composition of the initial water input (‰; represented here by
 228 precipitation isotope composition), δ^* is the limiting isotope-enrichment value (‰), and m is
 229 dimensionless. The limiting isotopic enrichment term and associated atmospheric-vapour
 230 composition were calculated from ambient relative humidity, precipitation isotope composition,
 231 kinetic separation and liquid–vapour equilibrium fractionation following Gonfiantini (1986)
 232 and Gibson et al. (2008). Kinetic fractionation followed Merlivat (1978), with $n = 0.75$ used as



an intermediate value between wet- and dry-surface conditions. Temperature-dependent equilibrium fractionation factors were calculated from the expressions of Horita and Wesolowski (1994).

3 Results

3.1 Vertical patterns of soil-water storage

During the study period, soil-water content (SWC) varied among months and soil depths in the three fields (Fig. 2). Across the three fields, SWC was generally lower in the surface soil than in deeper layers. Across the three depth groups, mean SWC was generally lower in the *Lycium chinensis* field than in the alfalfa and maize fields. SWC in the *Lycium chinensis* field varied among months and was lower in June, July, and August than in the other sampled months. The maize field showed pronounced vertical differences: shallow-layer SWC varied more among months, whereas middle and deep layers were comparatively stable. The alfalfa field also showed temporal and vertical variation. Mean SWC across the three depth groups was lower in May, June, and September than in July and August, and the 40–80 cm interval generally retained more water than the shallowest and deepest intervals.

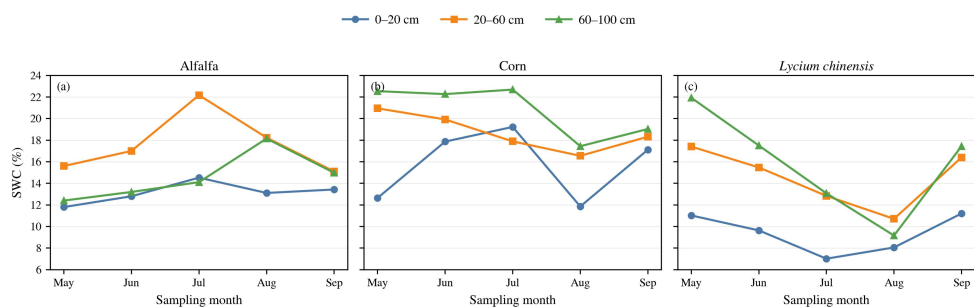


Fig. 2 Seasonal variations in gravimetric soil-water content (SWC) across three soil-depth groups (0–20, 20–60, and 60–100 cm) in (a) alfalfa, (b) maize, and (c) *Lycium chinensis* fields during the 2023-2024 growing season.



3.2 Depth-dependent soil-water isotope dynamics

Fig. 3 shows the vertical distributions of soil-water isotopic composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and LC-excess in the three crop fields. Isotope profiles varied among fields, soil depths, and sampling months. Mean soil-water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and their observed ranges are summarized in Table 2. Across the full 0–100 cm profile, mean $\delta^{18}\text{O}$ was 0.79‰ less negative in maize and 0.72‰ less negative in *Lycium chinensis* than in alfalfa. Mean $\delta^2\text{H}$ was 2.40‰ less negative in alfalfa and 4.17‰ less negative in *Lycium chinensis* than in maize (Table 2). In all fields, the 0–10 cm layer was generally isotopically enriched relative to deeper soil, consistent with surface evaporation.

Overall, soil-water isotope values overlapped among the three fields. In the alfalfa and maize fields, vertical isotope profiles were broadly similar across most months, whereas *Lycium chinensis* showed comparatively enriched soil water in August and September. Across the three fields, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ varied more in the upper 0–30 cm than below 30 cm (Fig. 3).

Table 2 Mean and observed range of soil-water $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in the three crop fields

Crop	$\delta^{18}\text{O}$ (‰), mean (range)	$\delta^2\text{H}$ (‰), mean (range)
Alfalfa	−10.03 (−13.98 to +5.94)	−74.50 (−105.56 to −53.55)
Maize	−9.24 (−11.15 to −4.58)	−76.90 (−89.56 to −46.21)
<i>Lycium chinensis</i>	−9.31 (−11.87 to −3.51)	−72.73 (−82.36 to −50.67)

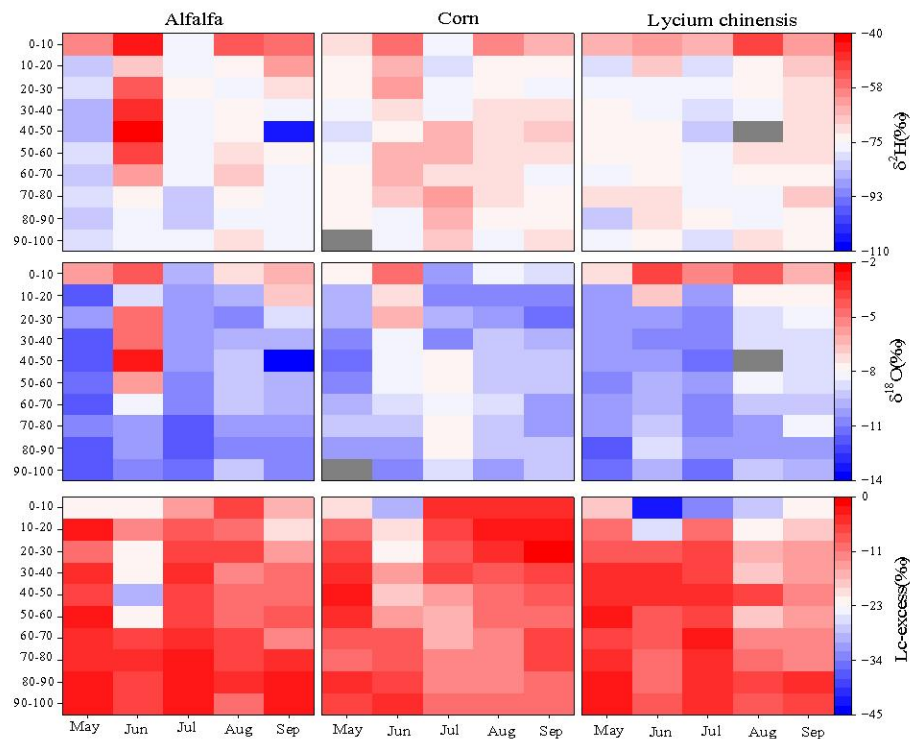


Fig. 3 Vertical distributions of soil-water $\delta^2\text{H}$ (a), $\delta^{18}\text{O}$ (b), LC-excess (c), at 0–100 cm depth during the growing season in the three crop fields

3.3 Isotope-space relationships and source constraints

Dual-isotope relationships differed among precipitation, irrigation water, soil water, and crop xylem water (Table 3; Fig. 4). The local meteoric water line was $\delta^2\text{H} = 7.36\delta^{18}\text{O} + 7.03$ ($R^2 = 0.95$, $n = 144$), whereas the irrigation water line was $\delta^2\text{H} = 3.89\delta^{18}\text{O} - 30.91$ ($R^2 = 0.79$, $n = 18$). Soil-water lines had lower slopes than the local meteoric water line, consistent with evaporative modification after infiltration. Lower slopes indicate greater enrichment of $\delta^{18}\text{O}$ relative to $\delta^2\text{H}$ during evaporation, but line slopes alone do not quantify the amount of water lost. Xylem-water isotope values broadly overlapped the soil-water domain, although the mean alfalfa xylem-water $\delta^{18}\text{O}$ (+7.35 ‰) exceeded the maximum measured soil-water $\delta^{18}\text{O}$ (+5.94 ‰), indicating incomplete end-member coverage for that crop.



Table 3 Meteoric, irrigation, soil-water, and xylem-water lines in the study area

Water type	Crop	Isotope line (R^2)
Local meteoric water line	—	$\delta^2\text{H} = 7.36\delta^{18}\text{O} + 7.03$ ($R^2 = 0.95$)
Irrigation-water line	—	$\delta^2\text{H} = 3.89\delta^{18}\text{O} - 30.91$ ($R^2 = 0.79$)
Soil-water line	Alfalfa	$\delta^2\text{H} = 4.945\delta^{18}\text{O} - 35.056$ ($R^2 = 0.94$)
Soil-water line	Maize	$\delta^2\text{H} = 3.567\delta^{18}\text{O} - 37.926$ ($R^2 = 0.79$)
Soil-water line	<i>Lycium chinensis</i>	$\delta^2\text{H} = 2.90\delta^{18}\text{O} - 45.7$ ($R^2 = 0.81$)
Xylem-water line	Alfalfa	$\delta^2\text{H} = 1.62\delta^{18}\text{O} - 54.67$ ($R^2 = 0.84$)
Xylem-water line	Maize	$\delta^2\text{H} = 2.02\delta^{18}\text{O} - 56.12$ ($R^2 = 0.63$)
Xylem-water line	<i>Lycium chinensis</i>	$\delta^2\text{H} = 1.189\delta^{18}\text{O} - 55.016$ ($R^2 = 0.33$)

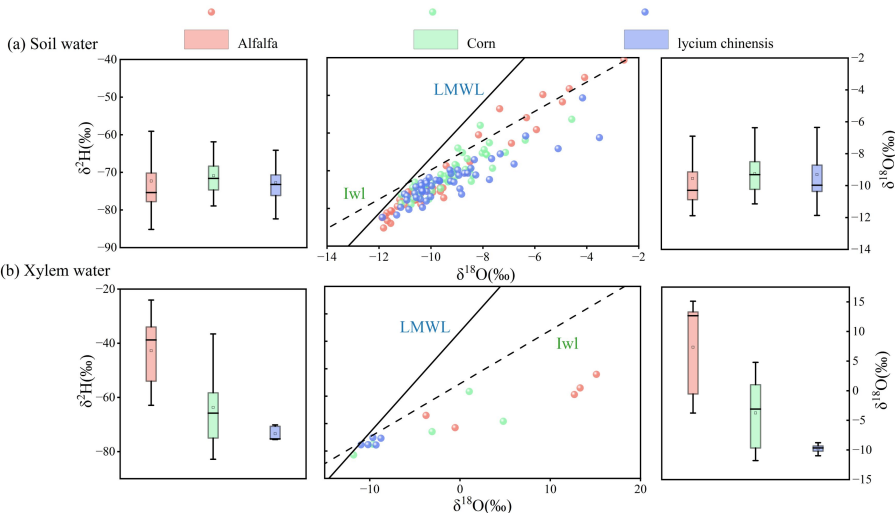


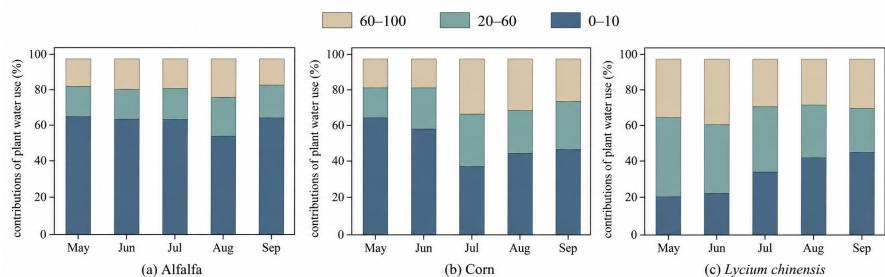
Fig. 4 Dual-isotope relationships for soil water and crop xylem water. LMWL denotes the local meteoric water line ($\delta^2\text{H} = 7.36\delta^{18}\text{O} + 7.03$, $R^2 = 0.95$, $n = 144$), and IWL denotes the irrigation water line ($\delta^2\text{H} = 3.89\delta^{18}\text{O} - 30.91$, $R^2 = 0.79$, $n = 18$).

3.4 Seasonal water-source partitioning among crops

MixSIAR indicated contrasting depth-use patterns among the three crops (Fig. 5). Alfalfa consistently received the largest estimated contribution from shallow (0–20 cm) soil water, with monthly contributions of 64.4 %, 64.5 %, 64.1 %, 54.2 %, and 63.2 % from May to September. *Lycium chinensis* relied more strongly on middle (20–60 cm) and deep (60–100 cm) sources; estimated middle-layer contributions ranged from 32.2 % to 46.3 %, and deep-layer



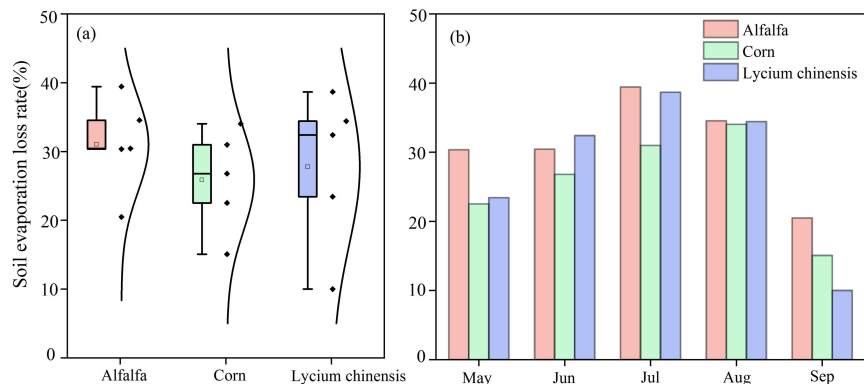
293 contributions from 33.9 % to 45.0 %. Maize showed the strongest seasonal shift: shallow-layer
294 contributions declined from 65.2 % in May and 58.6 % in June to 36.1 % in July, while
295 contributions from middle and deeper layers increased later in the growing season.



296
297 **Fig. 5** Seasonal posterior contributions of shallow (0–20 cm), middle (20–60 cm), and deep (60–100 cm)
298 soil-water groups to crop xylem water estimated with MixSIAR for alfalfa, maize, and *Lycium chinensis*.

299 3.5 Isotope-derived evaporative modification of soil water

300 The mean isotope-derived evaporative-loss estimates were 31.05 % for alfalfa, 25.88 %
301 for maize, and 27.79 % for *Lycium chinensis* (Fig. 6). Estimates peaked in July for alfalfa and
302 *Lycium chinensis* and in August for maize; all three crops had their lowest estimated values in
303 September.



304
305 **Fig. 6** Isotope-derived evaporative loss fractions for 0–100 cm soil water in alfalfa, maize, and *Lycium*
306 *chinensis* fields: (a) distributions by crop (outer curves show density, boxes show the interquartile range and
307 median, and points show individual observations) and (b) monthly estimates.



3.6 Hydrological context from estimated crop water demand

Under the adopted FAO-56 crop-coefficient, growth-period, and irrigation-efficiency assumptions, the estimated gross irrigation requirement for maize was about 16 % higher than that for *Lycium chinensis* and 86 % higher than that for alfalfa (Table 4). These are model-based estimates of potential demand, not measured irrigation deliveries or a closed field water balance.

Table 4 Growth-period characteristics and estimated gross irrigation requirements of the three crops

crop	Irrigation Method	Growth period (days)	ET ₀ (mm d ⁻¹)	Irrigation efficiency (%)	Gross irrigation, G (mm)
alfalfa	Sprinkler Irrigation	100	3.85	75	462
maize	Flood Irrigation	120	3.58	60	859.2
<i>Lycium chinensis</i>	Sprinkler Irrigation	180	3.67	75	741.6

4 Discussion

4.1 Vertical soil-water storage and isotope stratification

Precipitation and irrigation water were the identified water inputs to the soil profile. After entering the soil, infiltration, mixing, and evaporation modified the isotope composition of precipitation-derived and irrigation-derived water. The strongest isotope variability occurred in the upper 0–30 cm, and surface soil water was consistently more enriched than deeper water. This pattern is consistent with greater evaporative modification and more variable replenishment of shallow soil water, whereas deeper layers showed smaller short-term isotope changes (Gibson et al., 2008; Sprenger et al., 2018). Experimental comparisons also indicate that isotope-line slopes and LC-excess can respond differently to evaporation, supporting cautious interpretation of isotope-derived evaporative modification (Hu et al., 2025). Stable-isotope methods have also been used to estimate soil evaporation and non-productive



327 water losses in agricultural fields under different cover and irrigation conditions
 328 (Mahindawansha et al., 2020; Zhang et al., 2022; Jiao et al., 2023; Kader et al., 2025).

329 Xylem-water isotope composition is not, by itself, evidence of water uptake from a given
 330 depth; isotope overlap indicates compatibility between xylem water and the sampled soil-water
 331 domain, while interpretation of uptake also depends on soil-water availability and atmospheric
 332 demand. The alfalfa xylem-water $\delta^{18}\text{O}$ mismatch indicates that the sampled soil profile did not
 333 fully represent all water accessible to that crop. Temporal or microsite heterogeneity, together
 334 with possible extraction-related offsets, may contribute to this discrepancy. Alfalfa has a deep
 335 taproot and may access water below 100 cm, but this remains a plausible explanation rather
 336 than a demonstrated source. MixSIAR estimates are quantitative posterior source proportions
 337 conditional on the defined depth groups; for alfalfa, the proportions may be incomplete
 338 because the sampled 0–100 cm soil-water domain did not span the xylem-water isotope value.

339 **4.2 Functional controls on vertical water partitioning**

340 The three crops displayed distinct patterns in estimated contributions from soil-water
 341 depth groups. Alfalfa consistently obtained the largest estimated contribution from shallow soil
 342 water, whereas *Lycium chinensis* relied more strongly on middle and deep stores; maize
 343 showed a seasonal shift from dominant shallow-source contributions early in the season toward
 344 greater contributions from middle and deep groups later in the season. These differences are
 345 consistent with crop-specific patterns of water-source use under the same regional climatic
 346 forcing. Because root distributions were not measured directly, the results do not establish root
 347 architecture or imply that uptake at a given depth is proportional to local root density.
 348 Comparable isotope-based analyses combining root observations with Bayesian mixing models
 349 have likewise shown that inferred source contributions depend on root distribution and



soil-water availability (Zhang et al., 2025).

4.3 Seasonal shifts in estimated crop water-source contributions

Maize showed the clearest seasonal shift in estimated water-source contributions. Shallow-source contributions declined from 65.2 % in May and 58.6 % in June to 36.1 % in July, while contributions from middle and deeper groups increased later in the growing season. This pattern coincided with changes in the vertical soil-water profile and may reflect both crop development and changing water availability; root extension was not measured, so this mechanism cannot be tested directly (Hou et al., 2021; Wu et al., 2016).

Soil-water availability and evaporative modification provide additional hydrological context for these seasonal shifts. Across the sampled dates, soil-water content was generally higher in the maize field than in the alfalfa and *Lycium chinensis* fields, while the surface layers tended to be drier than deeper layers. The isotope-derived evaporative loss fractions followed broadly similar seasonal trajectories but differed in magnitude among fields. These field-level contrasts likely reflect interacting effects of vegetation cover, crop development, irrigation, and soil properties, which cannot be separated with the present observational design.

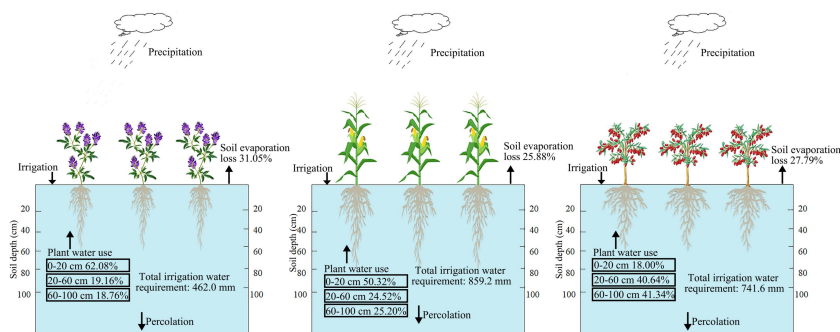


Fig. 7 Conceptual representation of precipitation and irrigation inputs, evaporative modification of shallow soil water, vertically structured soil-water storage, and contrasting seasonal contributions from these soil-depth groups by alfalfa, maize, and *Lycium chinensis*.



370 **4.4 Uncertainty and hydrological implications**

371 The contrasting uptake-depth patterns indicate that crop functional type and phenological
372 development are associated with differences in the vertical distribution of soil-water content
373 and plant water uptake in irrigated drylands. This depth partitioning may affect the persistence
374 of shallow and deep soil-water stores and the sensitivity of crop water use to short-term drying.
375 However, the separate monoculture fields do not allow these patterns to be translated directly
376 into claims about competition or complementarity under mixed cropping. The hydrological
377 significance of the observed differences therefore lies in their demonstration of crop-specific
378 relationships between vertical soil-water distribution and estimated plant water uptake rather
379 than a prescriptive crop-management recommendation.

380 Several limitations define the scope of inference. Plant and soil sampling was discrete
381 rather than continuous, root distributions were not measured, and actual irrigation schedules
382 and evapotranspiration were not resolved at a frequency suitable for closing the field water
383 balance. MixSIAR source proportions remain sensitive to source grouping and end-member
384 variability, and the sampled 0–100 cm soil-water domain did not fully cover the alfalfa
385 xylem-water isotope composition. Further monitoring across additional growing seasons, with
386 deeper soil-water sampling, direct root observations, and measured irrigation and
387 evapotranspiration, would test the temporal robustness of the estimated source contributions
388 and better constrain the field water balance. Soil-water isotope results can also depend on
389 extraction procedures and sample characteristics, so method-specific uncertainty should be
390 considered when comparing studies (Kocum et al., 2025).

391 **5 Conclusions**

392 The isotope mixing analysis quantified distinct seasonal contributions from the predefined



393 soil-depth groups. Alfalfa obtained 54.2–64.5 % of its estimated xylem-water contribution
394 from the 0–20 cm group across May–September; *Lycium chinensis* relied more strongly on the
395 20–100 cm groups; and maize showed a decline in shallow-source contribution from 65.2 % in
396 May and 58.6 % in June to 36.1 % in July. These differences demonstrate crop-specific
397 patterns in the use of sampled soil-depth groups under the observed field conditions. The
398 alfalfa isotope mismatch indicates that the sampled 0–100 cm source domain may not cover all
399 sources accessible to that crop, so the estimated proportions for alfalfa may be incomplete. The
400 results therefore provide quantitative source-partitioning estimates within the sampled
401 end-member domain, rather than a closed field water balance.

402 **Code availability**

403 No custom hydrological model code was developed for this study. Bayesian source
404 apportionment was performed with the publicly available MixSIAR package; analysis scripts
405 used to prepare the reported results are available from the corresponding author upon
406 reasonable request.

407 **Data availability**

408 The stable water isotope data available from the monitoring network are openly accessible
409 from Zhu (2022), “Stable water isotope monitoring network of different water bodies in
410 Shiyang River Basin, a typical arid river in China”, Mendeley Data, V1,
411 <https://doi.org/10.17632/vhm44t74sy.1>. The additional data generated and analysed in this
412 study are available from the corresponding author upon reasonable request.

413 **Author contribution**

414 Dongfei Yang: conceptualization, methodology, investigation, writing – review and editing,



415 supervision, and project administration. Siyu Lu: methodology, investigation, data curation,
416 formal analysis, visualization, and writing – original draft. Guofeng Zhu: conceptualization,
417 methodology, formal analysis, writing – review and editing, supervision, project administration,
418 and funding acquisition. Rui Li: data curation and formal analysis. Wenzhang Sun, Xinyue
419 Wang, Wanting Li, Wenmin Li, Ziwen Liu, and Ru Ma: investigation and data curation. All
420 authors reviewed and approved the manuscript.

421 **Competing interests**

422 The authors declare that they have no conflict of interest.

423 **Acknowledgements**

424 The authors acknowledge the Shiyang River Ecological Environment Observation Station and
425 the Stable Isotope Laboratory of Northwest Normal University for supporting field
426 observations and isotope analyses. During manuscript preparation, ChatGPT (OpenAI) was
427 used for language editing and structural refinement. All scientific interpretations, numerical
428 values, and final wording were reviewed and approved by the authors, who take full
429 responsibility for the content.

430 **Financial support**

431 This research was financially supported by the National Natural Science Foundation of China
432 (42371040), the Western Light Young Scholars Program of the Chinese Academy of Sciences
433 (25JR6KA001), the Cultivation Program of Major Key Projects of Northwest Normal
434 University (NWNLU-LKZD-202302), the Oasis Scientific Research Achievements
435 Breakthrough Action Plan Project of Northwest Normal University (NWNLU-LZKX-202303),
436 and the Special Project on Rural Revitalization and Food Security of the Ministry of



437 Agriculture and Rural Affairs.

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