Isotopic differences of soil-plant-atmosphere continuum composition and control factors of different vegetation zones in north slope of Qilian Mountains

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Abstract: Understanding the differences and control factors of stable water isotopes in the soil-plant-atmosphere continuum (SPAC) of different vegetation zones is of great significance to reveal hydrological processes and regional water cycle mechanisms. From April 2018 to October 2019, we collected 1281 samples to investigated the stable water isotopes changes in the SPAC of three different vegetation zones (alpine meadows, forests, and arid foothills) in the Shiyang River Basin. The results show that: (1) Precipitation plays a major control role in the SPAC. From alpine meadows to arid foothills, the temperature effect of precipitation isotopes increases as altitude decreases. (2) From the alpine meadow to the arid foothills, soil water isotopes are gradually enriched. (3) Alpine meadow plants are mainly supplied by precipitation in the rainy season, and forest plants mainly utilize soil water in the dry season and precipitation in the rainy season. The soil water in the arid foothills is primarily recharged by groundwater, and the evaporation of plant isotopes is strong. (4) Temperature and altitude are potential factors that control the isotopic composition of SPAC. This research will help understand the SPAC system's water cycle at different altitudes and climates in high mountains.

Keywords: Shiyang River Basin; Stable water isotope; Precipitation; Soil water; Plant water

1. Introduction

The relative abundance changes of hydrogen and oxygen isotopes in water can indicate the water cycle and the water use mechanism in plants, so isotope technology has become an increasingly important method to study the water cycle (Gao et al., 2009; Song et al., 2002; Coplen, 2013; Shou et al., 2013). The stable water isotopic composition is considered to be the "fingerprint" of water, which records a large amount of environmental information that comprehensively reflects the geochemical process of each system, and links the composition characteristics of each link (Darling et al., 2003; Raco et al., 2013; Nlend et al., 2020). As an effective tool, stable isotope technology is widely applied in studying the relationship between environmental factors and the water cycle (Araguás-Araguás et al., 1998; Christopher et al., 2009), water transportation, and distribution mechanisms (Gao et al., 2011), and ways of tracing water use by plants (Detjen et al., 2015). The understanding of the relationship between the influence of plant characteristics, water use efficiency and water sources (Ehleringer, 1991; Sun et al., 2005; Li et al., 2019) provides a new observation method for revealing the mechanism of the water cycle in the hydrological ecosystem (Nie et al., 2014; Yu et al., 2007; Wang et al., 2019).

Although the isotopic ratio in soil water varies with depth, it remains stable when transferred from plant roots to stems, leaves or young unbolted branches (Porporato, 2001; Meissne et al., 2014). Precipitation infiltration and runoff generation process (Bam and Ireso, 2018; Hou et al., 2008), groundwater recharge and regeneration capacity (Smith et al., 1992; Cortes and Farvolden, 1989) can be determined combined the isotopic composition changes of surface water, soil water and groundwater. Regional meteorological and hydrological conditions and the contribution of various environmental factors can be evaluated (Hua et al., 2019) by comparing different waterline equations and analyzing changes in various water bodies. Furthermore, it has laid a foundation for studying the deep mechanism of the water cycle (Gao et al., 2009). As an important component of the global water cycle, plants control 50-90% of transpiration (Jasechko et al., 2013; Coenders-Gerrits et al., 2014; Schlesinger and Jasechko, 2014). The plant's roots do not have isotope fractionation when absorbing water (White et al., 1985; Song et al., 2013), so the water isotopic composition of plant roots and stems reflects the isotope composition of water available for plants (Dawson et al., 1991).

The research of the water cycle based on SPAC plays a vital role in the study of water and the sources of plant water use in arid areas (Price et al., 2012; Shou et al., 2013). Hydrogen and oxygen isotopes have been used to study the water cycle at the interface of "soil-root", "soil-plant", and "soil-atmosphere", but only a few parameters play an important role in the complex interactions between the various surfaces (Durand et al., 2007; Li et al., 2006; West et al., 2010). Previous studies have shown that local factors, especially temperature, mainly control stable isotope precipitation changes in mid-latitudes (Dai et al., 2020). Through the research on the composition of hydrogen and oxygen isotopes in different water bodies, we can further understand the mechanism of water use by vegetation (Yang et al., 2015) and provide a scientific basis for vegetation restoration in arid and semi-arid areas. In the existing research, how to extend the results of the small-scale SPAC water cycle research to the large-scale area has become a hot and difficult spot. In inland arid areas, due to the lack of water resources, the exchange of energy and water with the outside world is small, and the water cycle is mainly the vertical circulation of groundwater-soil-atmospheric water. Therefore, studying the changes in SPAC isotopic composition in arid regions is significant for ecological restoration.

The Shiyang River Basin has the greatest ecological pressure and the most severe water shortage in China. The purpose of this study is to: (1) analyze the SPAC water cycle process in different vegetation zones and (2) identify the potential factors that control the SPAC water cycle. This research is helpful to clarify the water resource utilization mechanism and the local water cycle mechanism of different vegetation areas in high mountainous areas and provide the theoretical basis for the reasonable use of water resources in arid areas.

2. Materials and methods

2.1 Study area

The Shiyang River Basin is located at the northern foot of the Qilian Mountains, east of the Hexi Region, Gansu Province (Zhu et al., 2018) (Fig. 1). The Shiyang River originates from the snow-capped mountains on the north side of the Lenglongling in the eastern section of the Qilian Mountains. The river's total length is about 250 km, with a basin area of 4.16×104 km^2, and the annual average runoff is about 1.58×10^8 km^3. Rivers are supplied by precipitation from mountain and alpine ice and snow melt water. The runoff area is about 1.10×10^4 km^2, and the drought index is 1 to 4 (Zhou et al., 2020). The soil is classified as grey-brown desert soil, aeolian sandy soil, saline soil, and meadow soil. The Shiyang River Basin has a continental temperate arid climate with strong sunlight. The annual average sunshine hours are 2604.8-3081.8 hours, the annual average temperature is -8.2-10.5℃, the temperature difference between day and night is 25.2℃, the annual average precipitation is 222 mm, and the annual average evaporation is 700-2000 mm. The vegetation coverage in the upper and middle alpine regions is better than that of the lower reaches, with trees, shrubs, and grass-covered (Wan et al., 2019). The downstream vegetation coverage is poor under the strong influence of long-term human production, mainly desert vegetation.

Fig 1 about here

2.2 Sample collection

From April 2018 to October 2019, samples were collected at Lenglong (alpine meadow), Hulin (forest), and Xiying (arid foothills) in the Shiyang River Basin (Table 1). We collected 1281 samples in the Shiyang River Basin, including 472 precipitation samples, 570 soil samples, 119 plant samples, and 120 groundwater samples.

Table 1 about here

The precipitation samples were collected with a rain bucket. The rain measuring cylinder consists of a funnel and a storage part. After each precipitation event, we immediately transferred the liquid precipitation to a 100 ml high-density sample bottle. The sample bottle was sealed with a sealing film and stored at low temperature. Simultaneously, the polyethylene bottle sample was labeled with the date and type of precipitation (rain, snow, hail, and rain).

The soil samples were collected at intervals of 10 cm at a depth of 100 cm with a soil drill. Part of the soil sample was put into a 50 ml glass bottle. The bottle's mouth was sealed with parafilm and transported to the observation station for cryopreservation within 10 hours after sampling. The remaining soil sample was placed in a 50 ml aluminum box and used the drying method to measure the soil water content (swc).

The vegetation samples were collected with a sampling shear. First, we peel off the bark and put the stem into a 50 ml glass bottle. After that, we sealed the bottle mouth and kept it frozen before the experimental analysis.

The groundwater samples were collected with polyethylene bottles, and the samples were brought back to the refrigerator at the test station for cryogenic preservation within 10 hours.

2.3 Sample treatment

All water samples were tested using a liquid water analyzer (DLT-100, Los Gatos Research Center, USA) at the Northwest Normal University laboratory. Each sample and isotopic standard werer analyzed by six consecutive injections. To eliminate the memory effect of the analyzer, we discarded the values of the first two injections and used the average of the last four injections as the final result value. Isotopic measurements are given with the symbol "δ" and are expressed as a difference of thousandths relative to Vienna Standard Mean Ocean Water:

$$\delta\ (‰)= [(\delta/\delta_{v\text{-}smow})-1)]\times 1000 \qquad (1\text{-}1)$$

Where, δ is the ratio of $^{18}O/^{16}O$ or $D/^{1}H$ in the collected sample, $\delta_{v\text{-}smow}$ is the ratio of $^{18}O/^{16}O$ or $D/^{1}H$ in the Vienna standard sample.

Due to the existence of methanol and ethanol in plant water samples, it is necessary to calibrate the raw data of plant samples. To determine methanol (NB) and ethanol (BB) pollution degree, we used different concentrations of pure methanol and ethanol mixed deionized water, combined with Los Gatos' LWIA-spectral pollutant identification instrument V1.0 spectral analysis software, and then we established δD and $\delta^{18}O$ spectral pollutant correction method (Meng et al., 2012; Liu et al., 2015). For the broadband metric value NB metric of the methanol calibration result, its logarithm has a significant quadratic curve relationship with ΔδD and $\Delta\delta^{18}O$, and the formulas are respectively:

$$\Delta\delta D=0.018(\ln NB)^3+0.092(\ln NB)^2+0.388\ln NB+0.785\ (R^2=0.991,\ p<0.0001) \qquad (2\text{-}1)$$

$$\Delta\delta^{18}O=0.017\ (\ln NB)^3\ -0.017\ (\ln NB)^2+0.545\ \ln NB+1.358\ (R^2=0.998,\ p<0.0001) \qquad (2\text{-}2)$$

For ethanol calibration results , the broadband metric value BB metric has a quadratic curve and a linear relationship with ΔδD and $\Delta\delta^{18}O$, and the formulas are respectively:

$$\Delta\delta D=-85.67\ BB+93.664\ (R^2=0.747,\ p=0.026)\ (BB<1.2) \qquad (2\text{-}3)$$

$$\Delta\delta^{18}O=-21.421\ BB^2+39.9356\ (R^2=0.769,\ p<0.012) \qquad (2\text{-}4)$$

2.4 Data analysis

Since the isotopic data are generally normally distributed according to the Kolmogorov-Smirnov (KS) test, we used Pearson correlation to describe the various correlations between different water types (precipitation, soil water, plant water, and groundwater) and the control factors in different vegetation zones. The significance level for all statistical tests was set to the 95% confidence interval. All statistical analyses completed using the SPSS software.

3. Results

3.1 Changes in meteorological parameters over time

Figure 2 shows the changes in daily precipitation, relative humidity, temperature, and swc from April 2018 to October 2019. Meteorological data are obtained from the meteorological station in the Shiyang River Basin. During the summer monsoon (April to September), the accumulated precipitation accounts for 90.4% of the total precipitation, and the daily average precipitation is 3.98 mm. During the winter monsoon (October to March), the accumulated precipitation accounts for 9.60% of the total precipitation, with an average daily precipitation of 0.13 mm. During the summer monsoon, the relative humidity of the Shiyang River Basin is 43.78%, while during the winter monsoon it is 35.78%. During the observation period, the temperature is -16.2℃ and 32℃, and the average temperature of summer monsoon and winter monsoon are 20.20℃ and -0.69℃, respectively. The average SWC value of 0-100cm soil layer vary from 2.58% to 89.96 %, and the low SWC value usually appears in summer, which is related to the strong soil evaporation.

Fig 2 about here

3.2 The relationship between stable water stable isotopes in different vegetation zones

According to the definition of the global meteoric water line (GMWL) (Craig, 1961), the linear relationship of $\delta^{18}O$ and δD in local precipitation, soil water, plant water, and groundwater is defined as LMWL, SWL, PWL, and GWL, respectively.

As shown in Fig. 3, there are some differences in the local meteoric waterline equations of different vegetation zones. The slope of LMWL of alpine meadows (7.88), forests (7.82), and arid foothills (7.72) is all smaller than that of GMWL (8.00), this is because the study area is located in northwestern China's arid area, where the climate is dry, and the isotopes have undergone strong fractionation. The slope of the SWL in the alpine meadow is the largest (6.07), and the slope of the SWL in the forest (5.10) is greater than the slope of the SWL in the arid foothills (3.94), the intercept has the same characteristics, indicating that the arid foothills' soil evaporation is the largest. According to the Natural Resources Survey Report of the Shiyang River Basin in 2020, the vegetation coverage rate of the alpine meadow is 25.95%, and that of the arid foothills is 8.48%. The vegetation coverage rate of the alpine meadow is higher than that of the arid foothills, and it has better water retention ability and less evaporation of soil water (Wan et al., 2019; Wei et al., 2019). The slope of the PWL in the arid foothills is the largest (2.45), and the slope of the PWL in the alpine meadow (1.90) is greater than that of the forest (1.69).

According to the weighted average value of stable oxygen isotopes of various water bodies (Table 2), alpine meadows' soil water $\delta^{18}O$ is -9.16‰, which is the most depleted and the closest to the precipitation $\delta^{18}O$ (-9.44‰). The average $\delta^{18}O$ of groundwater is -8.84‰, which is between $\delta^{18}O$ of plant (-1.68‰) and $\delta^{18}O$ of precipitation (-9.44‰), indicating that precipitation is the primary source of alpine meadows replenishment. The average $\delta^{18}O$ of groundwater (-8.56‰) is between soil water $\delta^{18}O$ (-7.01‰) and precipitation $\delta^{18}O$ (-8.63‰), but it is close to precipitation $\delta^{18}O$, indicating that forest groundwater is replenished by soil water and precipitation. The mean $\delta^{18}O$ of soil water (-8.23‰) in the arid foothills are between precipitation $\delta^{18}O$ (-7.50‰) and groundwater $\delta^{18}O$ (-8.88‰) but closer to groundwater $\delta^{18}O$, indicating that the soil water in the arid foothills is mainly supplied by groundwater.

Fig 3 about here

Table 2 about here

3.3 Relationship between soil water and plant water isotope in different vegetation zones

By analyzing the isotopic composition of soil and plant xylem, it is possible to preliminarily determine whether there is an overlap between soil moisture and plant moisture at different depths (Javaux et al., 2016; Dawson et al., 1993; Rothfuss et al., 2017; Tetzlaff et al., 2017; McCole et al., 2007; Zhou et al., 2015; Schwendenmann et al., 2015). Soil water may evaporate before being absorbed by plants, which leads to the increase of δD and $\delta^{18}O$ values of soil water (Chen et al., 2014). Therefore, it can be well explained that the surface soil water isotope in Fig. 4 is more enriched than the deep soil water isotope.

According to the study area's precipitation, the current experiment is divided into the dry season (October-April of the following year) and the rainy season (May-September) for analysis (Fig. 4). In the dry season, alpine meadow plants have the highest value of $\delta^{18}O$ (-2.84‰), and there is no overlap between soil and plant water. In the rainy season, the plant water $\delta^{18}O$ (-6.04‰) and precipitation $\delta^{18}O$

(-6.40‰) are close, the groundwater and soil water's surface and deep layers intersect, indicating that plant water is mainly supplied by precipitation in the rainy season, while the groundwater is supplied by soil water. In the dry season, due to the low temperature (average temperature 0.30°C), there is a lot of ice and snow in alpine meadows, and plants do not directly use soil water. As the increase of temperature (average temperature 8.72°C), precipitation and surface runoff increases, and water infiltrate groundwater from soil. Forest plant water intersects with deep soil during the dry season and intersects with the soil surface during the rainy season, indicating that forest plants mainly use deep soil water during the dry season and shallow soil water during the rainy season. In the rainy season, the surface layer of soil water intersects with plant water, the groundwater and soil water's surface and deep layers intersect, showing that the plant water preferentially uses the surface layer water of the soil in the arid foothills. In the dry season, plant water oxygen is the most enriched, and the isotopic values of groundwater and soil water are close, indicating that the soil water is mainly recharged by the groundwater. According to the Natural Resources Survey Report of the Shiyang River Basin, the buried groundwater level in the arid foothills is 2.5-15 m, and the groundwater table is relatively shallow, making the soil water in the arid foothills mainly recharged by groundwater in the dry season.

Fig 4 about here

4. Discussion

4.1 Variation of soil water isotope and SWC between different vegetation zones

In Fig. 5, along the three vegetation zones of alpine meadow-forest-arid foothills, soil water isotope is gradually enriched. The coefficient of variation of the arid foothills is the largest (-0.15), while that of the forest is the smallest (-0.25), indicating that from forest to arid foothills, the closer to arid regions, the greater the coefficient of variation and that the greater the instability of soil water isotope. The soil water isotopes of different vegetation zones showed the same characteristics as the soil depth changed, that is, they were all depleted in May and August and enriched in October.

The swc of alpine meadows (average θ of 42.21%) is higher than that of forests (average θ of 26.98%) and arid foothills (average θ of 17.05%), and the swc of alpine meadows increases with the increase of soil depth (from 43.78% to 49.27%), while that of forests the swc decreases with the soil depth (from 26.10% to 25.41%). Compared with forests, plants in alpine meadows have shallower root systems and smaller canopies, so transpiration and water consumption are lower, and swc is higher (Csilla et al., 2014; Li et al., 2009; Western et al., 1998). On the one hand, with the improvement of vegetation restoration, the ability of alpine meadows to retain soil water has enhanced, and the soil water evaporation has reduced On the other hand, Lenglong, a representative of alpine meadows, has an average annual precipitation of 595.10 mm, and a low temperature (average annual temperature of -0.20°C), makes the soil water evaporation intensity weak. The swc of the alpine meadows (86.95%) and forests (53.45%) is the largest in August, while the arid foothills' swc (11.13%) is the smallest in August, this is because the northern slope of the Qilian Mountains is a windward slope. In August, a lot of precipitation falls on the high-altitude alpine meadows and forests, the arid foothills have little precipitation and low swc.

Fig 5 about here

4.2 Control factors of SPAC in different vegetation zones

4.2.1 The influence of temperature on SPAC

As shown in Fig. 6, with the changes in the water cycle of precipitation-soil water-plant water, the $\delta^{18}O$ of forests gradually enriched, while the soil water $\delta^{18}O$ of arid foothills and alpine meadows are the most depleted in summer. In other seasons, $\delta^{18}O$ is gradually enriched along with precipitation-soil water-plant water. In summer, there is much precipitation and large swc in alpine meadows, but due to the low temperature (average temperature in summer is 9.80°C), the soil water $\delta^{18}O$ of alpine meadows is relatively depleted. In the arid foothills, in summer, especially in August, although the temperature is relatively high (the average temperature is 23.92°C), the swc is low, evaporation is weak, and $\delta^{18}O$ are relatively depleted. This phenomenon shows that precipitation plays a major control role in the water cycle of precipitation-soil-plants. When the temperature is below 0°C, the air will expand adiabatically, and the water vapor will change adiabatic cooling (Rozanski, 1992). When the temperature is between 0°C and 8°C, the influence of local water vapor circulation is greater. When the temperature is below 8°C, the below-cloud evaporation is very strong (Zhu et al., 2021). Therefore, we divided the temperature into three gradients (below 0°C, between 0°C and 8°C and above 8°C) for analysis. From the alpine meadow to arid foothills, the correlations between temperature and soil $\delta^{18}O$ are 0.41, 0.30, and 0.19, respectively, and the correlations with plant $\delta^{18}O$ are 0.24, 0.27, and 0.25, respectively, and the temperature effect is not significant compared with precipitation. As shown in Table 3, from the alpine meadow to the arid foothills, the temperature effect of the precipitation isotope increased, and there is a significant positive correlation with temperature and all of which have passed the significance test. With the increase of temperature, the linear relationship between temperature and precipitation isotope in each vegetation zone became weaker. When the temperature is lower than 0°C, the correlation between precipitation $\delta^{18}O$ and the temperature in the arid foothills fails to pass the significance test. The relationship between $\delta^{18}O$ and temperature in alpine meadows, forests, and arid foothills are $\delta^{18}O$=0.62T-10.84, $\delta^{18}O$=1.58T-12.14, and $\delta^{18}O$=1.29T-11.78, respectively. When the temperature is between 0°C and 8°C, the temperature effect of precipitation weakens with the temperature increases, which may be related to the weakening of the local water cycle and the enrichment of precipitation isotopes. The relationship between $\delta^{18}O$ and temperature in alpine meadows, forests, and arid foothills are $\delta^{18}O$=0.51T-11.41, $\delta^{18}O$=2.46T-22.84, and $\delta^{18}O$=2.27T-22.78, respectively. When the temperature is above 8°C, there is no correlation between the precipitation $\delta^{18}O$ and the temperature, but the precipitation $\delta^{18}O$ is the most enriched, which may be related to the $\delta^{18}O$ enrichment caused by the below-cloud evaporation. The relationship between $\delta^{18}O$ and temperature in alpine meadows, forests, and arid foothills are $\delta^{18}O$=0.48T-10.82, $\delta^{18}O$=0.13T-7.76, and $\delta^{18}O$=0.27T-10.13, respectively.

Fig 6 about here

Table 3 about here

4.2.2 The influence of altitude on SPAC

In Fig.7, the altitude effect of precipitation $\delta^{18}O$ is the strongest, and the relationship between plant water $\delta^{18}O$ and altitude is weakest, showing that in SPAC, precipitation isotope is most affected by altitude, and plant water isotope is least affected by altitude. From the arid foothills to alpine meadows, the elevation increases from 2097 m to 3647 m, and the change rate of $\delta^{18}O$ and δD was -0.11‰ $(100\ m)^{-1}$ and -0.41‰ $(100\ m)^{-1}$. As the water vapor quality increases along the hillside, the temperature continues to decrease, and the isotopic values of precipitation continue to consume. In the rainy season, the squares of the correlation coefficients between precipitation $\delta^{18}O$ and altitude, precipitation δD and altitude are 0.79 and 0.98, the change rate of $\delta^{18}O$ and δD are -0.12‰ $(100\ m)^{-1}$ and -1.05‰ $(100\ m)^{-1}$, respectively. In the dry season, the correlation coefficient squares between precipitation $\delta^{18}O$ and altitude, precipitation δD and altitude are 0.88 and 0.90, respectively, and the rate of $\delta^{18}O$ and δD change is -0.18‰ $(100\ m)^{-1}$ and -0.79‰ $(100\ m)^{-1}$, respectively. We can see that the altitude effect of precipitation $\delta^{18}O$ is stronger in the dry season (R^2=0.88) than in the rainy season (R^2=0.79). The results showed that as the temperature increase, the temperature effect of precipitation $\delta^{18}O$ masks the altitude effect, which leads to the weakening of the altitude effect of precipitation $\delta^{18}O$. The relationship between soil water $\delta^{18}O$ and altitude is stronger in the dry season (R^2=0.26) than in the rain season (R^2=0.28). The relationship between plant water $\delta^{18}O$ and altitude is stronger in the dry season (R^2=0.11) than in the rainy season (R^2=0.10), this is consistent with the changes in the altitude effect of precipitation isotope .

Fig 7 about here

4.2.3 The influence of relative humidity and precipitation on SPAC

To find out the potential factors that control the isotope composition of SPAC in different vegetation zones, we also analyzed the influence of relative humidity and precipitation on $\delta^{18}O$ of SPAC. It can be seen from Fig. 8 and Table 4 that the greatest impact of relative humidity on the isotope composition of SPAC appears in the arid foothills in the dry season, with a correlation coefficient of 0.38. Although in the dry season, the square of the correlation coefficient between forest precipitation isotope and relative humidity is 0.78, there is an inverse humidity relationship between the two, which may be related to the lack of precipitation samples in the dry season. The largest impact of precipitation on the isotopic composition of SPAC occurs in the arid foothills in the rainy season, and the square of the correlation coefficient is 0.14. It can also be seen from Fig. 8 that the influence of relative humidity and precipitation on precipitation isotope is greater than that on plant water isotope and soil water isotope. The influence of relative humidity and precipitation on the isotopic composition of SPAC in alpine meadows is greater than that in arid foothills and greater than that in forests. The influence of relative humidity and precipitation on the isotopic composition of SPAC in alpine meadows is greater than that of arid foothills and greater than that of forests. In general, the SPAC isotopic composition of alpine meadows, forests, and arid foothills has a weak precipitation effect, and the correlation with relative humidity is also weak.

By comparing the correlation of temperature, altitude, relative humidity and precipitation with SPAC isotope composition in different vegetation zones, we can see that the correlation between temperature and altitude and SPAC isotope composition is stronger than relative humidity and precipitation. Temperature and altitude are potential factors that control the isotope composition of SPAC. However, in the dry season, there is a phenomenon that the temperature effect conceals the altitude effect.

Fig 8 about here

Table 4 about here

5. Conclusion

This paper uses the hydrogen and oxygen isotope method to study the differences and control factors of SPAC in different vegetation zones. Temperature and altitude are the main control factors for the isotopic composition of SPAC. From alpine meadows to forests to arid foothills, as the decreases of altitude, the temperature effect of precipitation isotope increases, and the influence of temperature also increases. When the temperature is lower than 0℃, the temperature effect of the vegetation zone is the strongest. In the dry season, there is a phenomenon that the temperature effect masks the altitude effect. With the increase of the soil depth, the soil water isotopes are gradually depleted. The soil water content of alpine meadows is the largest and increases with the soil depth, while the soil water content in forest decreases with the soil depth, and the soil water content of the arid foothills is the least in August. In the rainy season, plants mainly use precipitation, while forest plants mainly use soil water in the dry season. Alpine meadow plants do not directly use soil water because of the abundant precipitation and melt water in the growing season. The groundwater table exposed in the arid foothills can provide water for plants in the dry season. Forests and grasslands affect intercepting rainfall, they delay or hinder the formation of surface runoff and convert part of the surface runoff into soil flow and groundwater, which can provide part of water resources for plants. To better understand the water cycle of SPAC at different temperatures and altitudes in high mountain areas, long-term observations of different plants are needed to provide a theoretical basis for the rational and practical use of water resources in arid mountainous areas.

Data Availability

The data that support the findings of this study are openly available at https://data.mendeley.com/datasets/d5kzm92nn3/1.

Author contributions

Guofeng Zhu and Yuwei Liu conceived the idea of the study; Zhuanxia Zhang analyzed the data; Zhigang Sun and Leilei Yong were responsible for field sampling; Liyuan Sang participated in the experiment; Kailiang Zhao participated in the drawing; Yuwei Liu wrote the paper; Liyuan Sang and Lei Wang checked and edited language. All authors discussed the results and revised the manuscript.

Competing interests

The authors declare no competing interests

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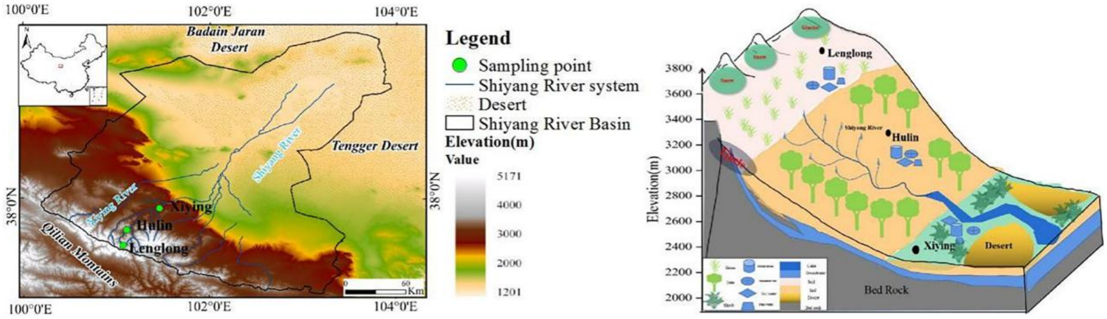

Fig. 1 Study area and observation system

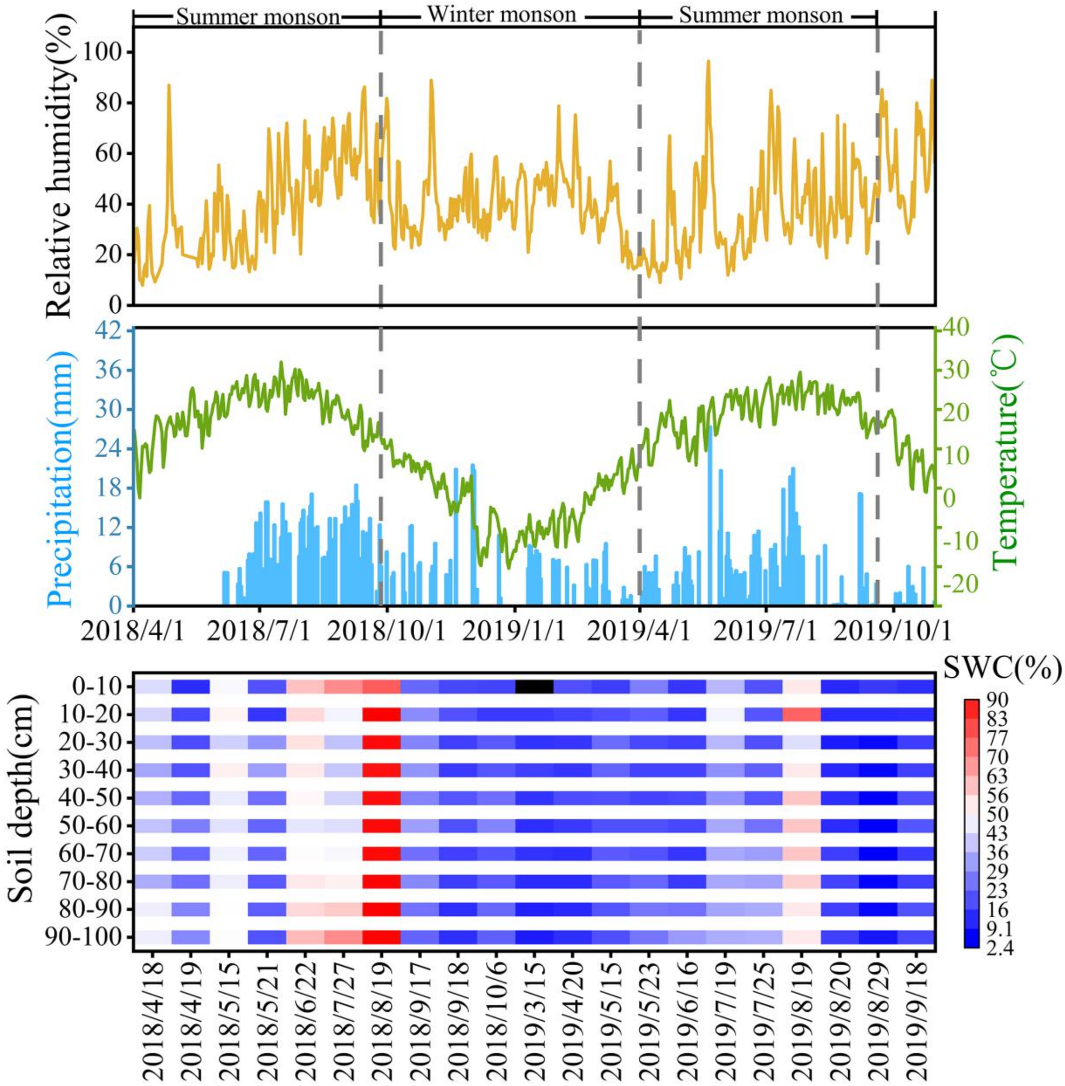

Fig. 2 Diurnal variation of relative humidity, precipitation, temperature, and swc (%) from April 2018 to October 2019

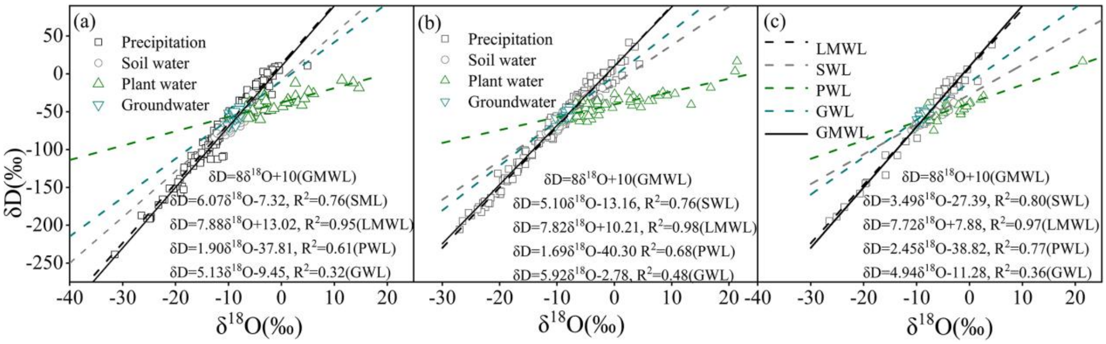

Fig.3 Relationship of stable isotopes in different water bodies in alpine meadow (a), forest (b) and arid foothills (c)

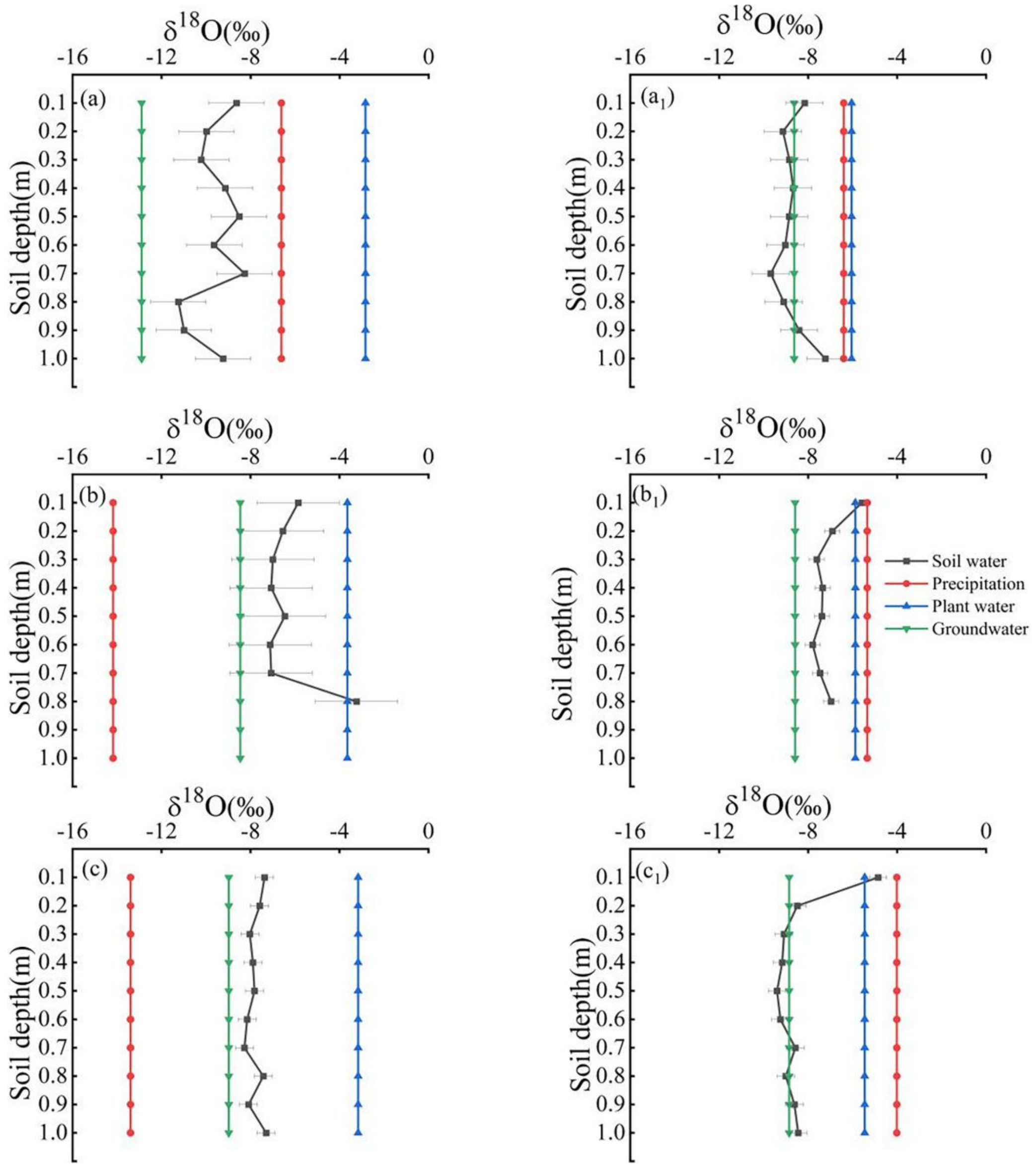

Fig. 4 (a)-(c) represents the variation of $\delta^{18}O$ of soil, plant, precipitation and groundwater with soil depth in the alpine meadow, forests and arid foothills in the dry season, and (a_1)-(d_1) represents the variation of δ18O of soil, plant, precipitation and groundwater in the alpine meadow, forests and arid foothills in the rainy season

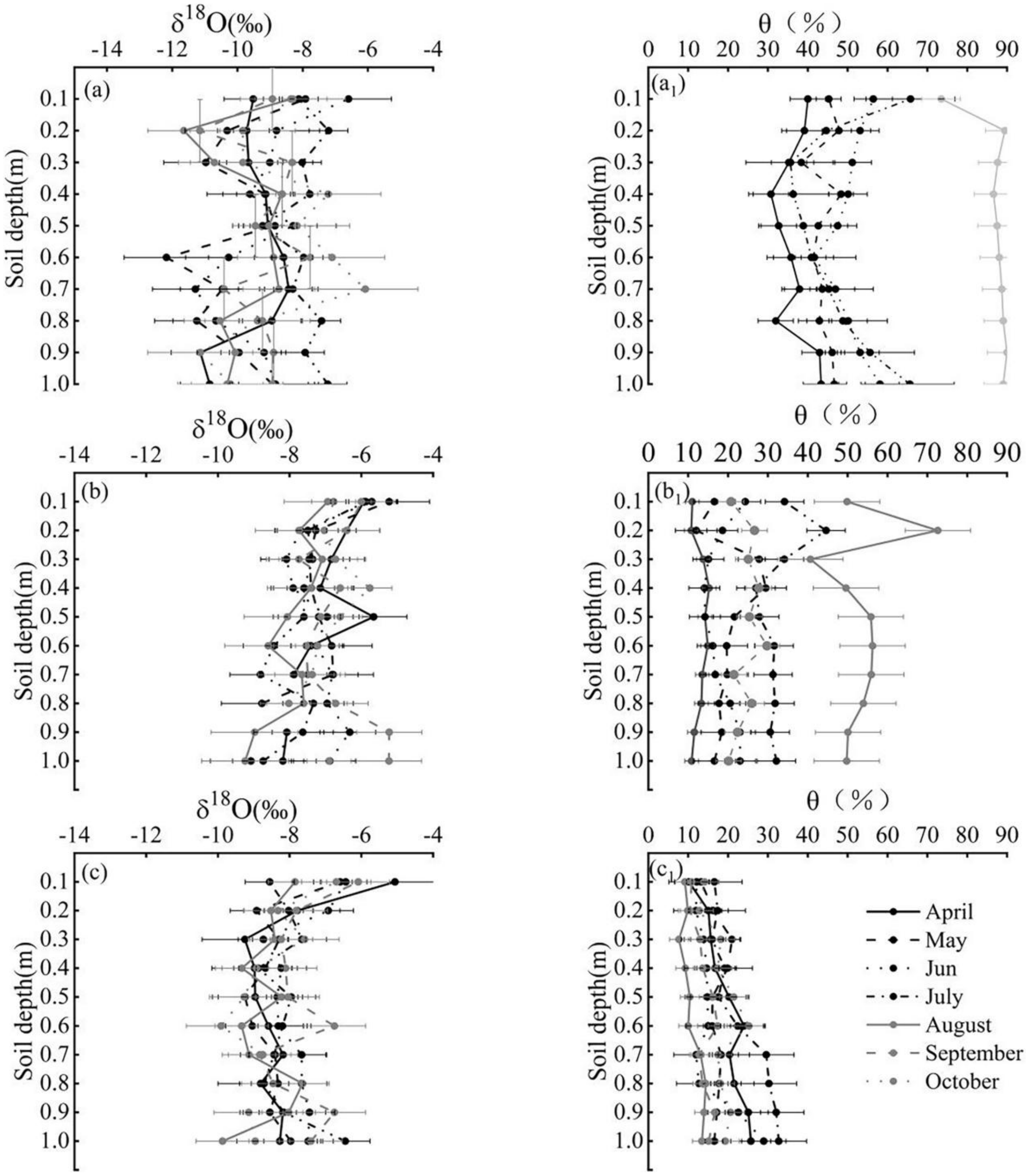

Fig.5 The variation of $\delta^{18}O$ and soil water content (θ, %) with soil depth. (a)-(c) represent alpine meadow, forests and arid foothills, respectively

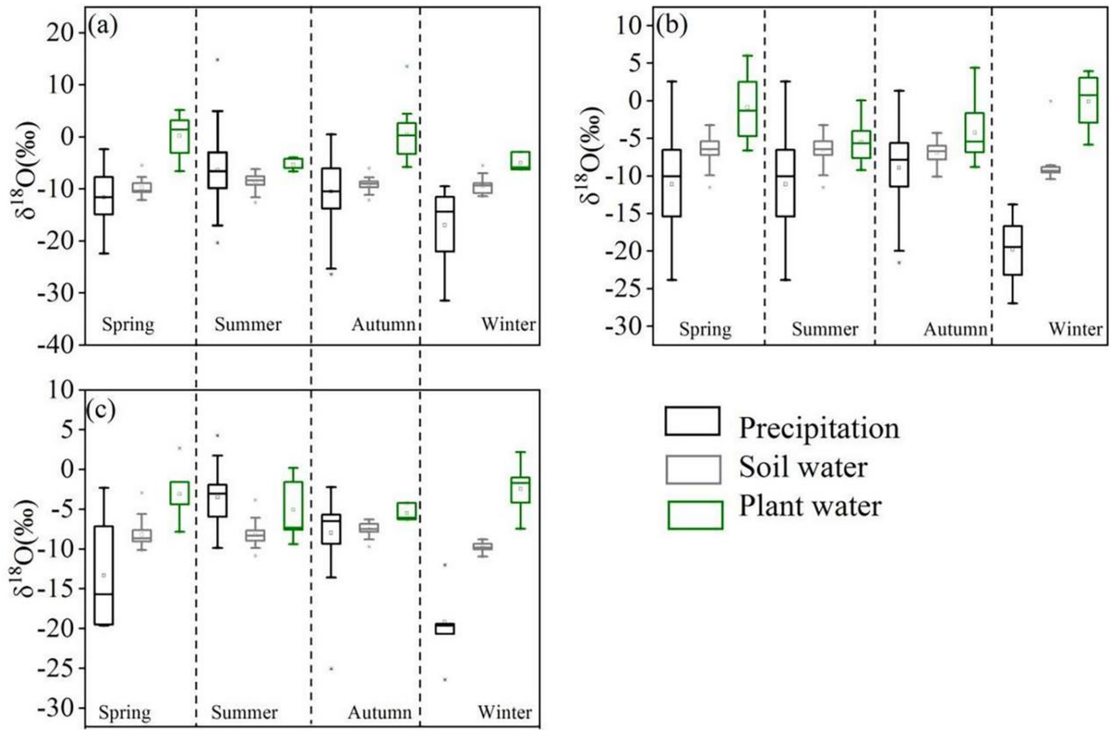

Fig. 6 Seasonal variations of different water isotopes in alpine meadow (a), forests (b) and arid foothills (c)

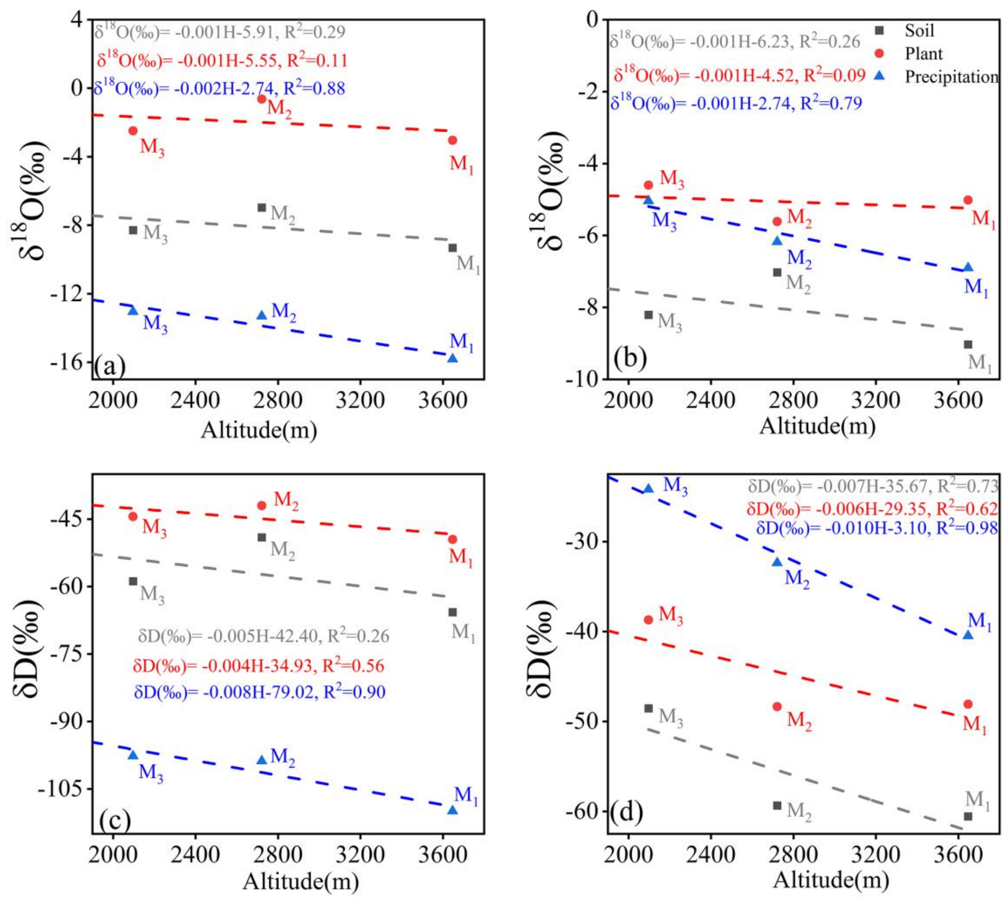

Fig. 7 Relationship between different isotope and altitude in the dry season (a, c) and in the rain season

(b, d), M_1 stands for alpine meadows, M_2 stands for forests, and M_3 stands for arid foothills

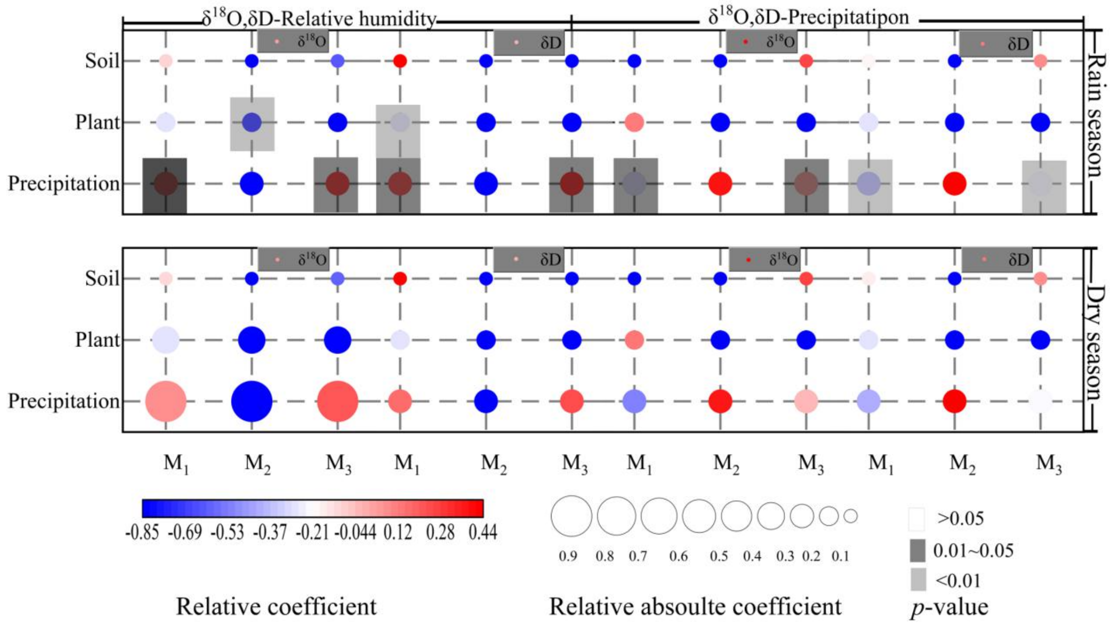

Fig. 8 Relationship between different isotopes and relative humidity and precipitation, M_1 stands for alpine meadows, M_2 stands for forests, and M_3 stands for arid foothills

Table 1 Basic information table of sampling points

Sampling Station		Geographical Parameters			Meteorological Parameters	
		Longitude (E)	Latitude (N)	Altitude (m)	Average annual temperature (°C)	Average annual precipitation (mm)
M1	Lenglong	101°50'	37°33'	3647	-0.20	595.10
M2	Hulin	101°53'	37°41'	2721	3.24	469.44
M3	Xiying	102°18'	38°29'	2097	7.99	194.67

Table 2 Comparison of stable isotope of water in different vegetation zones

Vegetation zone types	Water types	$\delta^{18}O$(‰)				δD(‰)			
		Min	Max	Average	Coefficient of Variation	Min	Max	Average	Coefficient of Variation
Alpine meadow	Precipitation	-31.49	14.79	-9.44	-0.70	-238.62	63.43	-59.43	-0.84
	Soil water	-12.62	-5.46	-9.16	-0.16	-83.86	-26.13	-62.92	-0.16
	Plant water	-6.68	5.12	-1.68	-2.18	-60.22	-12.14	-41.14	-0.28
	Groundwater	-10.07	-7.71	-8.84	-0.07	-68.55	43.72	-54.85	-0.10
Forest	Precipitation	-26.96	4.38	-8.63	-0.74	-205.40	41.35	-60.24	-0.87
	Soil water	-11.96	-0.07	-7.01	-0.25	-78.43	-18.48	-48.68	-0.21
	Plant water	-9.24	5.98	-5.44	-1.31	-63.29	-23.77	-45.12	-0.24
	Groundwater	-10.25	-7.43	-8.56	-0.09	-68.80	-43.75	-53.46	-0.12
Arid foothills	Precipitation	-26.47	4.24	-7.50	-0.87	-194.34	38.62	-48.62	-1.04
	Soil water	-10.98	-2.96	-8.23	-0.15	-74.22	-8.79	-59.17	-0.12
	Plant water	-9.41	2.67	-3.61	-0.88	-74.90	-29.39	-48.79	-0.23
	Groundwater	-10.34	-7.43	-8.88	-0.07	-71.67	-44.26	-55.12	-0.09

Table 3 Correlation between precipitation isotopes and different temperatures in different vegetation zones

Vegetation zone type	Correlation below 0°C ($\delta^{18}O$ /δD)	Correlation between 0°C-8°C ($\delta^{18}O$ /δD)	Correlation above 8°C ($\delta^{18}O$ /δD)	Correlation during the study period
Alpine meadow	0.51*/0.59*	0.30*/0.24*	0.15/0.12	0.59*/0.61*
Forest	0.95*/0.94*	0.66*/0.69*	0.14/0.10	0.69*/0.65*
Arid foothills	0.47/0.51	0.79*/0.71*	0.31/0.14	0.83*/0.81*

Note: ** indicates a significant correlation (two-tailed) at a confidence level of 0.01, * indicates a significant correlation (two-tailed) at a confidence level of 0.05

Table 4 Correlation between different isotopes' $\delta^{18}O$ and relative humidity and precipitation in different vegetation zones

Meteorological parameters	Isotope types	Rain season			Dry season		
		Alpine meadow	Forest	Arid foothills	Alpine meadow	Forest	Arid foothills
Relative Humidity	Soil	y= -0.001x-8.89, R^2=0.001	y= -0.03x-5.21, R^2=0.13	y= -0.002x-8.01, R^2=0.002	y= -0.01x-8.39, R^2=0.03	y= 0.01x-7.21, R^2=0.07	y= -0.04x-6.38. R^2=0.38
	Plant	y= -0.11x+6.11, R^2=0.11	y= 0.08x-10.53, R^2=0.13	y= 0.05x-7.68, R^2=0.04	y= -0.09x+3.78, R^2=0.10	y= -0.02x-0.28, R^2=0.004	-
	Precipitation	y= -0.22x+9.45, R^2=0.28	y= 0.02x-9.50, R^2=0.002	y= 0.13x+3.57, R^2=0.29	y= 0.02x-16.47, R^2=0.002	y= 0.16x+4.33, R^2=0.72	y=0.08x-20.23, R^2=0.02
precipitation	Soil	y= 0.04x-9.55, R^2=0.15	y= 0.02x-7.36, R^2=0.01	-	y= -0.13x-8.94, R^2=0.18	-	y= 0.06x-8.73, R^2=0.06
	Plant	y -0.07x-1.09, R^2=0.002	y= -0.06x-5.01, R^2=0.01	y= 0.18x-6.00, R^2=0.05	y= 0.07x-2.75, R^2=0.03	y= -0.41x-0.32, R^2=0.06	-
	Precipitation	y= -0.30x-5.21, R^2=0.09	y= -0.17x-6.17, R^2=0.05	y= -0.28x-2.84, R^2=0.14	y= -0.14x-14.24, R^2=0.002	y= 0.17x-9.41 R^2=0.11	y=0.14x-16.49, R^2=0.02