We are deeply grateful for the valuable and encouraging feedback on the manuscript. Your thoughtful revisions and comments are sincerely appreciated.

We have revised the paper greatly, which is mainly reflected in the following aspects:We rearranged the logic of the manuscript and added data, especially for the xylem water of Qinghai spruce. The water vapor recirculation part is clearly expounded, and each parameter is described in detail. We haved carried out uncertainty analysis.We have re-landscaped all the images throughout the article and improved their clarity.We have changed the language to make it easier for native English speakers to make valuable suggestions.We have placed the revised manuscript PDF at the end of the document. **The red bolded words, sentences, and subsections in the manuscript represent our editing changes.**

We have taken your comments into careful consideration and responded to each one, demonstrating our attention and gratitude towards your input.

ABSTRACT

16 - Maybe need some clarifications.

Response: Based on your comments, **we have adjusted this sentence as follows**: We collected precipitation, soil water from 0 to 100cm, xylem water from Qinghai Spruce, temperature, relative humidity and rainfall in the eastern Qilian Mountains from 2018 to 2019. We simulated T/ET comprehensively, and quantified the contribution of recirculated water vapor in precipitation. The aim of this study was to clarify the evapotranspiration process and its effect on production and confluence in the forest belt of Qilian Mountain.

INTRODUCTION

The introduction explains quite clearly the general context and gives a reasonable overview of the relative state of the art. The cited literature may be increased in some sections and re-organization of some sentences is advisable (see comments by lines).

The last section of the introduction is a bit too much methods-referred and needs a correction (see comments by lines). The general objective should be better stated.

Response: These two parts of opinions are very important to the logic of our article, and we have carefully revised them.

34 to 41 - the text is discussing the importance of the spruce forests system referring to the Qinghai local one. Maybe, here a more general discussion about this ecosystem could be more appropriate.

Response: We have adjusted this sentence to a more appropriate content to fit the full text,**as follows:** As a natural reservoir and purifier, the Qinghai spruce ecosystem has the functions of storing, releasing and purifying water. The Qilian Mountains supply the water resources that human beings depend on for survival in the continental river basin in the arid region, regulate the water cycle in the arid region, and interact with the soil and atmosphere to form a vertical spatial continuum, which not only affects the ecological process of the local plant community, but also changes the regional microclimate by means of latent heat (Ault et al., 2020;Zhang et al.,2021;Eisenhauer et al., 2021).

39 to 41 - This can be better placed in the final part of the introduction. It seems a bit in the middle of the general knowledge section.

Response: Thank you for your suggestion, we have put it in the last paragraph of the introduction.

45 - May be good to add at least a sentence to clarify why ET, which is connected to climate change, is the right parameter to study in this context.

Response: Based on your comments, **we have adjusted this sentence as follows**: The interaction between soil and vegetation controls rainfall input and water transfer within ecosystem components. It is an important player in climate change mitigation in terms of climate benefits (Rohatyn et al., 2022). Evapotranspiration (ET) is an indispensable part of the terrestrial water and energy cycle. Therefore, exploring the spatio-temporal and component changes of soil evaporation and vegetation transpiration can help us increase the response of vegetation canopy to climate change (Liu et al., 2022). At the ecosystem scale, many studies have classified evapotranspiration (ET) as transpiration (T) and evapotranspiration (E) (Schlesinger et al.,2014).

79 - after "... in central Asia." can reasonable place to insert the previous sentence of lines 39 - 41.

Response: Based on your comments, we have placed it to the previous sentence of lines 39 - 41.

79 to 87 - is too much of a method. Shorter and more on the objectives.

Response: Based on your comments, **we have adjusted this sentence as follows**: In this study, we observed and analyzed the monthly xylem water, soil water, precipitation stable isotopes and soil water content of Spruce forest in the eastern Qilian Mountains from April to October 2018 and 2019, and used these data to solve the following problems: (1) Quantify the contribution rates of soil evaporation and vegetation transpiration to evapotranspiration of ecosystems; (2) Quantifying the ratio of recirculated water vapor in precipitation; (3) To investigate the evapotranspiration process and its influence on production and confluence in the forest belt of Qilian Mountain. This study provides an effective basis for local water resource use and ecological protection.

STUDY AREA

This section potentially needs quite some updates (see the comments by lines).

Response: We really appreciate your valuable comments. We have revised the description of the study area and created a new overview map of the study area.

Is the vegetation of the monitored basin only composed of the spruce forest? Can mentioning the vegetation types and distribution be useful (if feasible)?

Response: We think your suggestion is reasonable and have made some adjustments, **as follows:** The Qilian Mountains are located in the central part of the Eurasian continent, on the northeastern edge of the Qinghai-Tibet Plateau. The eastern region is dominated by water erosion, with large variations in mountainous terrain and an average elevation of over 4,000 meters. Permafrost is developed at elevations of 3,500 to 3,700 meters, and areas above 4,500 meters are characterized by modern glacier development. The region has a plateau continental climate, with hot summers and cold winters, strong solar radiation, and large temperature differences between day and night. The average annual temperature is below 4℃, with extreme highs of 37.6℃ and extreme lows of -35.8℃. The annual sunshine hours range from 2,500 to 3,300 hours, with a total solar radiation of 5,916 to 15,000 megajoules per square meter. The average annual precipitation is 400 millimeters, and the annual evaporation ranges from 1,137 to 2,581 millimeters. The average wind speed is around 2 meters per second, and the frost-free period lasts from 23.6 to 193 days. The Shiyang River originates from the Daxueshan on the northern side of the Lenglong Ridge in the eastern section of the Qilian Mountains, serving as a major water source for the city of Wuwei. The soil types in the eastern section are diverse, but with low organic matter content. The distribution of vegetation shows distinct zonal characteristics, with mountainous forest-grassland zones (2,600 to 3,400 meters), subalpine shrub-meadow zones (3,200 to 3,500 meters), and high mountain sub-ice-snow sparse vegetation zones (>3,500 meters) at elevations above 2,700 meters. The main types of natural forest vegetation include Qinghai spruce forest, Qilian juniper forest, and Chinese pine forest, with Qinghai spruce being the dominant tree species (Zhu et al., 2022).

89 to 100 - A reference to Fig. 1 is missing. There are many toponyms cited but these are not present in Fig. 1 which makes it quite difficult for readers not familiar with the area to understand the geographical setting of the study area.

Response: Thanks for your suggestion, we have revised Fig.1. We will display the image in the next question.

104 - Fig. 1 Label are too small. A legend of the color code is non-presented. Why are surface water sampling site if surface water is never addressed in the text?

Response: We re-made the map, and reasonably modified the legend and other labels.

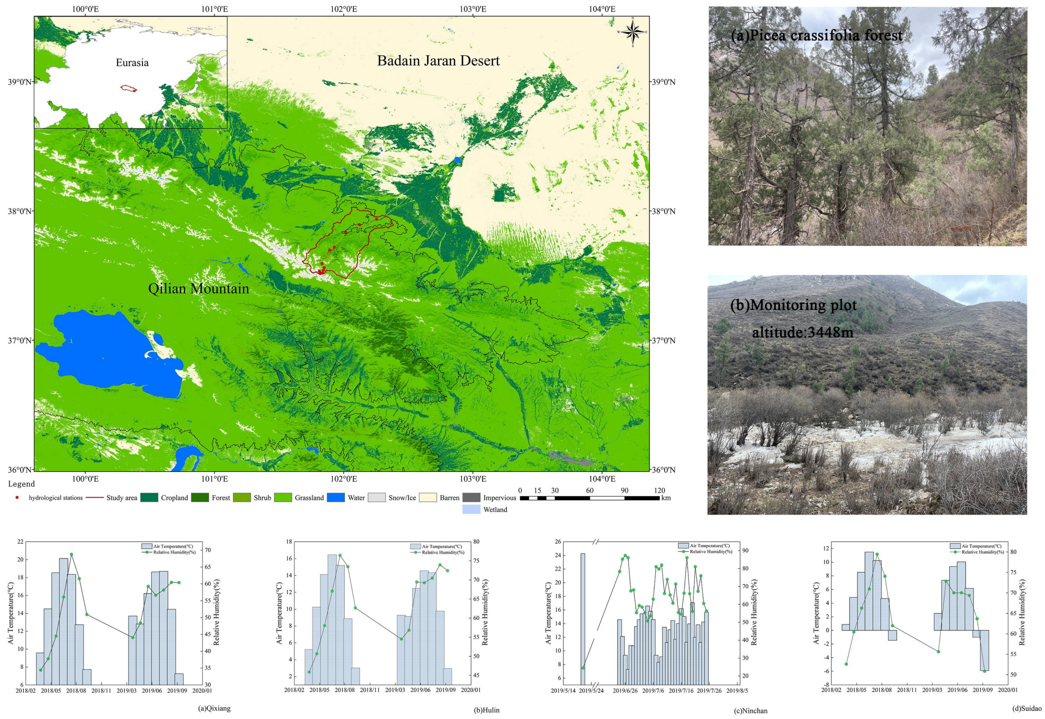

Figure 1 Location of the study area and changes in meteorological elements

MATERIALS AND METHODS

The description of the analytical procedures used for isotope determination is completely missing. Please insert it with accurate specifications of the methodology and the associated analytical errors.

Response: In response to your comments, **we have inserted the following**:

3.2 Experimental Analysis

The isotopic data used in this study mainly include stable isotopes of precipitation, soil water, and xylem water. All isotopic samples were analyzed at the Stable Isotope Laboratory of Northwest Normal University. The precipitation samples were analyzed for hydrogen and oxygen stable isotopes using a liquid water isotope analyzer (DLT-100, Los Gatos Research, USA). After thawing the soil and vegetation samples, they were extracted using a low-temperature vacuum condensation device (LI-2100, LICA United Technology Limited, China), and the extracted water was subjected to isotopic analysis. Each water sample was tested six times to ensure accuracy, with the first two tests considered as interference and only the results of the subsequent four tests were averaged. In order to ensure the accuracy of the measurement results, a parallel sample was collected for each sample, and the average value of the two determination results was taken as the final value(Zhu et al., 2022). The isotopic measurements are represented by δ, which represents the deviation in parts per thousand of the ratio of two stable isotopes in the sample relative to the ratio in a standard sample. The International Atomic Energy Agency (IAEA) defined the Vienna Standard Mean Ocean Water (VSMOW) in 1968 as the standard for isotopic composition, which is derived from distilled seawater and has a similar isotopic composition to Standard Mean Ocean Water (SMOW).

$$\delta = (\frac{\delta_{Sampling}}{\delta_{Standard}} - 1) \times 1000‰ \quad (1)$$

107 to 110 **-** It seems that the sampling was done only at one point, but multiple points are reported in Fig. 1. Important, isotopic values are not observed but determined in samples, and samples are collected at certain locations, unless the case of "portable" analyzer (like some CRDLS). The sampling strategies need a clearer explanation.

Response: Based on the reviewer's comments, we rearranged the sampling points needed for the whole paper to avoid the lack of xylem water data. **3.1 Materials Sources** has been greatly adjusted to make it more reasonable and clear.

3.1 Materials Sources

3.1.1 Sampling network

Parameter \ Station		Qixiang	Hulin	Ninchan	Suidao
Altitude(m)		2543	2721	3068	3448
Local climate	Temperature(℃/a)	3	3.2	3.3	-0.9
	Precipitation(mm/a)	510	469.44	394	475
	Relative humidity（%/a）	52.9	56.1	66.6	69.2
Samplings number	Precipitation	53	108	91	135
	Soil water	220	560	560	560
	Xylem water	236	56	56	56

3.1.2 Sample collection

We use an automatic weather station in 2018 and 2019 to record meteorological data, in which a rain gauge is used to collect precipitation and transfer samples to 100ml containers after each rain. Drill holes 0 ~ 5 cm, 5 ~ 10 cm, 10 ~ 20 cm, 20 ~ 30 cm, 30 ~ 40 cm, 30 ~ 50 cm, 50 ~ 60 cm, 60 ~ 70 cm, 70 ~ 80 cm, 80 ~ 90 cm, 90 in the sample plot by using soil drill ~ 100 cm. The soil samples were divided into two parts, one of which was placed in a 50 ml glass bottle. The bottle was sealed with a subfilm and transported to the observation station within 10 hours after the sampling date was marked for cryopreservation to detect stable isotope data. The other part of the sample was placed in a 50ml aluminum box and the soil moisture content was determined by drying method. When collecting plant samples, we used scissors to collect vegetation xylem stems, peeled off the bark, and put them in 50ml glass bottles sealed and frozen for experimental analysis.

117 to 141 - Sections 3.3.1, 3.3.2 and 3.3.3 miss citations. The sources of the reported equations need to be cited.

Response: Based on your comments, we have inserted citations for each formula in the manuscript, and supplement the formula and meaning. **as follows:**

3.3.1 Isotopic composition of atmospheric water vapour

The stable isotope composition of moisture in ambient air is calculated as follows(Gibson and Reid, 2014;Skrzypek et al., 2015):

$$\delta_A = \frac{\delta_{rain} - k\varepsilon^+}{1 + k\alpha^+ \times 10^{-3}} \qquad (2)$$

where k=1, or by fitting k to some fraction of 1 as the best fit to the local evaporation line, is the isotopic fractionation factor. Defined by $\varepsilon^+ = (\alpha^+ - 1) \times 1000$. α^+about ^2H and ^{18}O are calculated as follows(Horita and Wesolowski, 1994):

$$10^3 \ln^2 \alpha^+ = 1158.8T^3/10^9 - 1620.1T^2/10^6 + 794.84T/10^3 - 161.04 + 2.9992 \times 10^9/T^3 \qquad (3)$$

$$10^3 \ln^{18} \alpha^+ = -7.685 + 6.7123 \times 10^3/T - 1.6664 \times 10^6/T^2 + 0.35041 \times 10^9/T^3 \qquad (4)$$

3.3.2 Isotopic composition of soil evaporation

The Craig-Gordon model was used to calculate the stable isotopic composition of soil evaporation water vapour, δ_E, using the following equation(Craig and Gordon, 1965;Yepez et al., 2005).

$$\delta_E = \frac{\alpha_e^{-1}\delta_s - \hbar^*\delta_A - \varepsilon_{eq} - (1-\hbar^*)\varepsilon_k}{(1-\hbar\ ) + 10^{-3}(1-\hbar\ )\varepsilon_k} \tag{5}$$

where α_e(>1) is the equilibrium factor calculated as a function of water surface temperature, δs is the stable isotopic composition of liquid water at the evaporating surface of the soil (0 ~ 10 cm average stable isotopic composition of soil water), δ_A is the stable isotopic composition of atmospheric water vapour near the surface, ε_{eq} represents the equilibrium fractionation corresponding to $\varepsilon_{eq} = (1-1/\alpha e) \times 1000$, ε k is the kinetic fractionation factor of O^2 is approximately 18.9‰ and h*is the atmospheric relative humidity(Gibson and Reid, 2010). For $\delta^{18}O$, α_e is calculated as follows(Raz-Yaseef et al., 2010):

$$\alpha_e = \frac{1.137\times10^6/T^2 - 0.4156\times10^3/T - 2.0667}{1000} + 1 \tag{6}$$

Where T is the soil Kelvin temperature (K) at a depth of 5 cm.

3.3.3 Isotopic composition of plant transpiration

When transpiration is strong, leaf water is in "isotopic stable state", that is, the isotopic composition of leaf transpiration water is equivalent to that of water absorbed by the roots of rain plants at noon. Therefore, the stable isotopic composition of water in plant xylem can be used to represent the stable isotopic composition of water vapor in plant transpiration. The expression is as follows(Aron et al., 2020):

$$\delta_T = \delta_X \tag{7}$$

where δx is the isotopic ratio of xylem water and δ_T is the isotopic ratio of transpiration.

3.3.4 Evapotranspiration isotope assessment

The Keeling Plot model describes the linear relationship between the oxygen isotope composition of atmospheric water vapour and its reciprocal concentration . The intercept of the curve on the Y-axis represents the oxygen isotopic composition of evapotranspiration (δ_{ET}) and is expressed as(Keeling, 1958;Wang et al., 2015):

$$\delta_a = \frac{C_b(\delta_b - \delta_{ET})}{C_a} + \delta_{ET} \tag{8}$$

Where δ_a and C_a represent the atmospheric water vapour oxygen isotopic composition (‰) and water vapour concentration in the ecosystem boundary layer, δ_b and C_b represent the background atmospheric water vapour oxygen isotopic composition and background atmospheric water vapour concentration, and δ_{ET} is the ecosystem evapotranspiration oxygen isotopic composition.

3.3.5 Ecosystem evapotranspiration partitioning

The determination of evapotranspiration by means of biotic and abiotic isotopic water fluxes can be used to improve the understanding of community structure and ecosystem function in Qinghai spruce forests in the Qilian Mountains. Based on the isotope mass balance approach to consider the distribution of major and minor isotopes, the partitioning of evapotranspiration can be achieved using two end-member mixing models (E and T) with the following expression(Kool et al.,2014;Wei et al., 2018):

$$\frac{T}{ET} = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \quad (9)$$

where δ_{ET}, δ_E and δ_T are the isotopic compositions of evapotranspiration (ET), soil evapotranspiration (E) and plant evapotranspiration (T), respectively, and the isotopic values of the three can be obtained by both direct observation and model estimation.

3.3.6 Three-component mixing model

Assuming that precipitation vapor is a mixture of advective water vapour and recirculating water vapour, it is understood that the proportion of both precipitation and precipitation water vapour has the same nature. The proportion of precipitation occupied by advective vapour is calculated as follow(Kong et al., 2013; Wang et al., 2022):

$$f_{re} = \frac{P_{tr} + P_{ev}}{P_{tr} + P_{ev} + P_{adv}} \quad (10)$$

where P_{tr}, P_{ev} and P_{adv} are precipitation produced by transpiration, surface evaporation and advection, respectively.

This can be calculated using the following formula(Brubaker et al., 1993; Sang et al., 2023):

$$\delta_{pv} = \delta_{tr} f_{tr} + \delta_{ev} f_{ev} + \delta_{adv} f_{adv} \quad (11)$$

$$f_{ev} + f_{tv} + f_{adv} = 1 \quad (12)$$

where f_{tr}, f_{ev} and f_{adv} are the proportional contributions of transpiration, surface evaporation and advection to precipitation, respectively, and δ_{pv}, δ_{tr}, δ_{ev} and δ_{adv} values are the stable isotopes in precipitating transpiration, transpiration, surface evaporation and advective vapour, respectively. f_{tr},f_{ev} and f_{adv} are calculated by Isoerror software, based on dual isotopes and three sources(Ver. 1.3.1, https://www.epa.gov/)(Phillips and Gregg, 2001). δ_{pv} is calculated using the following formula:

$$\delta_{pv} = \frac{\delta_p - k\varepsilon^+}{1 + k\varepsilon^+} \quad (13)$$

Using the C-G model to calculate δev, the formula is as follows:

$$\delta_e = \frac{\delta_s/\alpha^+ - h\delta_{adv} - \varepsilon}{1 - h + \varepsilon_k} \quad (14)$$

Including the δs is the isotopic composition of liquid water evaporation front, δ_{adv} is advection steam, h is relative humidity, α^+ is equilibrium fractionation factor, $\mathcal{E}_k$ is kinetic fractionation factor, Ɛ is total fractionation factor.

$$\varepsilon = \varepsilon^+/\alpha^+ + \varepsilon_k \quad (15)$$

$$\varepsilon_k = (1-h)\theta_n C_k \quad (16)$$

h is the relative humidity, Ck is the kinetic fractionation constant, δ^2H is 25.1‰, $\delta^{18}O$ is 28.5‰.The weight coefficient θ of small water body is 1, and θ of large water body is 0.5. n ranges from 0.5 (fully turbulent transport, with reduced kinetic fractionation, suitable for lake or saturated soil conditions) to 1 (fully diffused transport, suitable for very dry soil conditions), with a kinetic fractionation coefficient of about 12.2-24.5‰ for Ɛk (^2H) in a dry atmosphere (h=0). The kinetic separation coefficient of Ɛk (^{18}O) is about 13.8-27.7‰.

The advection water vapor isotope δadv in the three-component mixing model needs to be determined by the water vapor isotopic composition at the upwind position. Based on the HYSPLIT model, we found that the eastern Qilian Mountains was controlled by westerly winds, southeast monsoon and plateau monsoon in June, July and August, and by prevailing westerly winds in September and October. The clustering analysis of air masses in different months shows that air masses accumulate at the northern foot of Qilian Mountains and move from low altitude to high altitude along the valley. Xiying, at 2097 m above sea level, is therefore used as a headwind station from April to October. When steam isotopes show a depletion trend along the transport path, isotopic fractionation is assumed to be due to Rayleigh distillation, and the expression is as follow:

$$\delta_{adv} = \delta_{pv-adv} + (\alpha^+ - 1)lnF \quad (17)$$

Where $\delta_{pv\text{-}adv}$ is the isotopic composition in the vapor of the winds tation, and F is the ratio between the final vapor and the initial vapor. Since rainfall is positively correlated with the surface vapor pressure of the whole study area (c=1.657e, where c is the water vapor content in mm, e is the surface vapor pressure in hPa,R^2=0.94), we used the surface vapor pressure of each site to calculate the value of F. The recirculated water entering the air mass is not considered here, because the contribution of recirculated water to the total air column is very limited, and most of the available precipitation does not result in rainfall but escapes to other areas. If there is no depletion of isotope ratios along the transmission track, the vapor isotope ratio from the upwind station is applied directly, and the Rayleigh distillation equation is not applied.

The δp is corrected by the local evaporation line (LEL), and the LEL slope (SLEL) can be calculated as（Skrzypek et al.，2015):

$$S_{LEL} = \frac{(h-10^{-3}{}^{18}\varepsilon)[h({}^{2}\delta_{pv} - {}^{2}\delta_{p}) + {}^{2}\varepsilon(1+10^{-3}\,{}^{2}\delta_{pv})}{(h-10^{-3}\,{}^{2}\varepsilon)[h({}^{18}\delta_{pv} - {}^{18}\delta_{p}) + {}^{18}\varepsilon(1+10^{-3}\,{}^{18}\delta_{p})]} \quad （18）$$

Where h is the relative humidity, Ɛ is the total fractionation factor, and δ_{PV} and δ_{P} are the stable isotopic components of water vapor and precipitation.According to our research results, the LEL equation for the study area is $\delta^2H=3.86\delta^{18}O-19.88$ ($R^2=0.994$, $P < 0.0001$, n=19).

RESULTS AND ANALYSIS

Comment to Tab. 1. The number of analyzed xylem water samples seems quite low with respect to other water matrices. This can pose a serious problem with the statistical significance of the results. How can the work deal with this?

Response: We recognized this serious problem and expanded the sampling points into four sampling strips at different altitudes(Table 1). Furthermore, we have made revisions to Table 2 in Section 4.1 as follows:

Table 1 Sampling Point Locations and Sample Quantity Information

Parameter \ Station		Qixiang	Hulin	Ninchan	Suidao
	Altitude(m)	2543	2721	3068	3448
Local climate	Temperature(℃/a)	3	3.2	3.3	-0.9
	Precipitation(mm/a)	510	469.44	394	475
	Relative humidity（%/a）	52.9	56.1	66.6	69.2
Samplings number	Precipitation	53	108	91	135
	Soil water	220	560	560	560
	Xylem water	236	56	56	56

Table 2 Stable isotopes of different water bodies during the growing season

Average / Period	δ^2H/‰			$\delta^{18}O$/‰		
	Precipitation	Xylem water	Soil water (0~10cm)	Precipitation	Xylem water	Soil water (0~10cm)
4	-69.15	-39.02	-53.10	-10.25	2.56	-7.10
5	-39.09	-29.78	-45.38	-7.61	4.44	-6.42
6	-31.29	-45.83	-46.08	-5.74	-2.83	-6.12
7	-32.39	-47.63	-47.71	-5.33	-0.97	-7.06
8	-48.88	-44.55	-68.85	-7.79	-2.06	-9.07
9	-29.38	-42.62	-49.20	-6.46	-1.83	-6.79
10	-68.43	-44.57	-54.88	-11.06	-2.25	-7.96

Comment to Figure 4b, is it not clear why δb is represented instead of δET. Does the x-axis represent humidity?

Response:We would be happy to explain the meaning of the x-axis to you. We have provided a clearer explanation of this aspect in our revised section. The fundamental principle of the Keeling plot method is to perform a linear regression of water vapor concentrations (1/[H^2O]) at different heights within the ecosystem's boundary layer against stable isotopic compositions ($\delta^{18}O$ and δ^2H). The resulting Keeling plot is used to estimate δ_{ET}, with the x-axis representing water vapor concentration. After incorporating additional sampling points and expanding the study timeframe, **we have reorganized this section as follows**:

The Keeling plot method was used to analyze the stable isotope composition of ecosystem evapotranspiration (Figure 4). Its principle involves linearly fitting the water vapor concentration in the ecosystem boundary layer against the oxygen isotope composition, with the intercept on the y-axis representing the stable isotope value of δ_{ET}. The results indicate that at different heights within the distribution of deciduous trees, the average δ_{ET} value is -22.59‰. Throughout the entire growing season, δ_{ET} does not consistently decrease with increasing elevation. Specifically, near the treeline, there are higher stable isotope values, but in the middle and upper layers of the forest, there is a minimal value, indicating lower and less stable isotopic fractionation in that layer. At an elevation of 3448m, as the number of deciduous trees decreases and shrubs become dominant, the δ_{ET} value is -21.81‰(Table 3). We found that the stable isotope δ_E of soil evaporation at depths of 0-10cm is more enriched at lower elevations, particularly in April and May when the isotopic enrichment is more pronounced. From June to August, due to a significant increase in vegetation coverage, soil evaporation intensity decreases. In the early stage of the growing season, when leaves have not fully developed, the stable isotope composition of the xylem exhibits a relatively depleted characteristic. In July and August, when leaves are fully expanded, temperatures rise, and the rainy season in mountainous areas commences, transpiration becomes more intense.

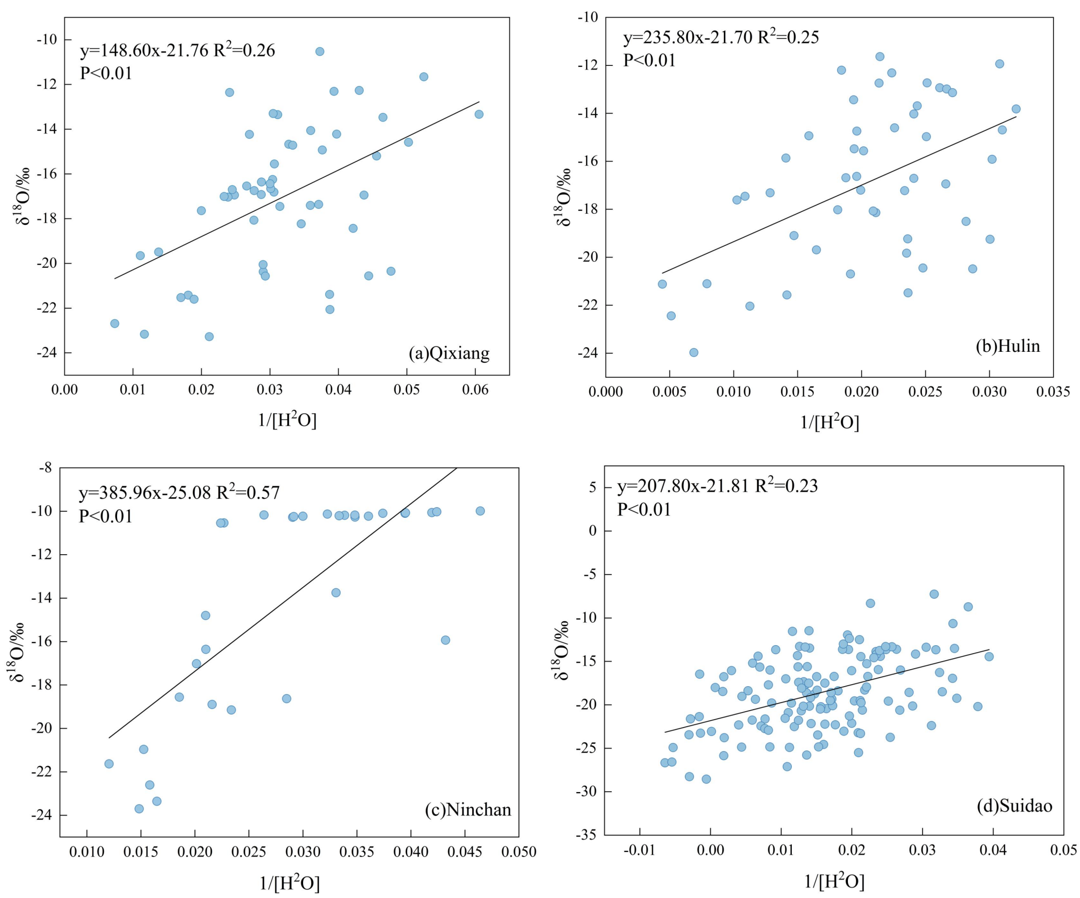

Figure 4 Each sampling point is fitted with a trend line based on the Keeling plot method

Comments to Figure 5a, how can the two data points for which δ^{18}Os is lower than δOE be justified? Which may seem counterintuitive. What is the y-axis representing?

Response: After adding additional sampling points, we have restructured Section 4.3 and incorporated clearer chart types to effectively convey the information we wish to present. **As follows:**

4.3 T/ET assessment of Qinghai spruce forest ecosystem in different months

We found that the canopy closure of deciduous trees significantly influences the evapotranspiration of the entire ecosystem (Figure 5). In April and May, as temperatures rise, surface vegetation exhibits weaker growth, resulting in a higher proportion of soil evaporation within the ecosystem, while transpiration by vegetation remains relatively low. During the rainy season in June to August, vegetation experiences vigorous growth, and transpiration reaches its peak in July. In September and October, soil evaporation becomes more dominant as temperatures, relative humidity, and rainfall gradually decrease, and deciduous tree leaves become wilted. At lower elevations, the T/ET ratio fluctuates between 0.20 and 0.70 in a distinct pattern, while above the treeline, transpiration ratios fluctuate between 0.20 and 0.80 in a similar pattern. Overall, summer is characterized as the peak season for transpiration, with a minimal contribution from soil evaporation.

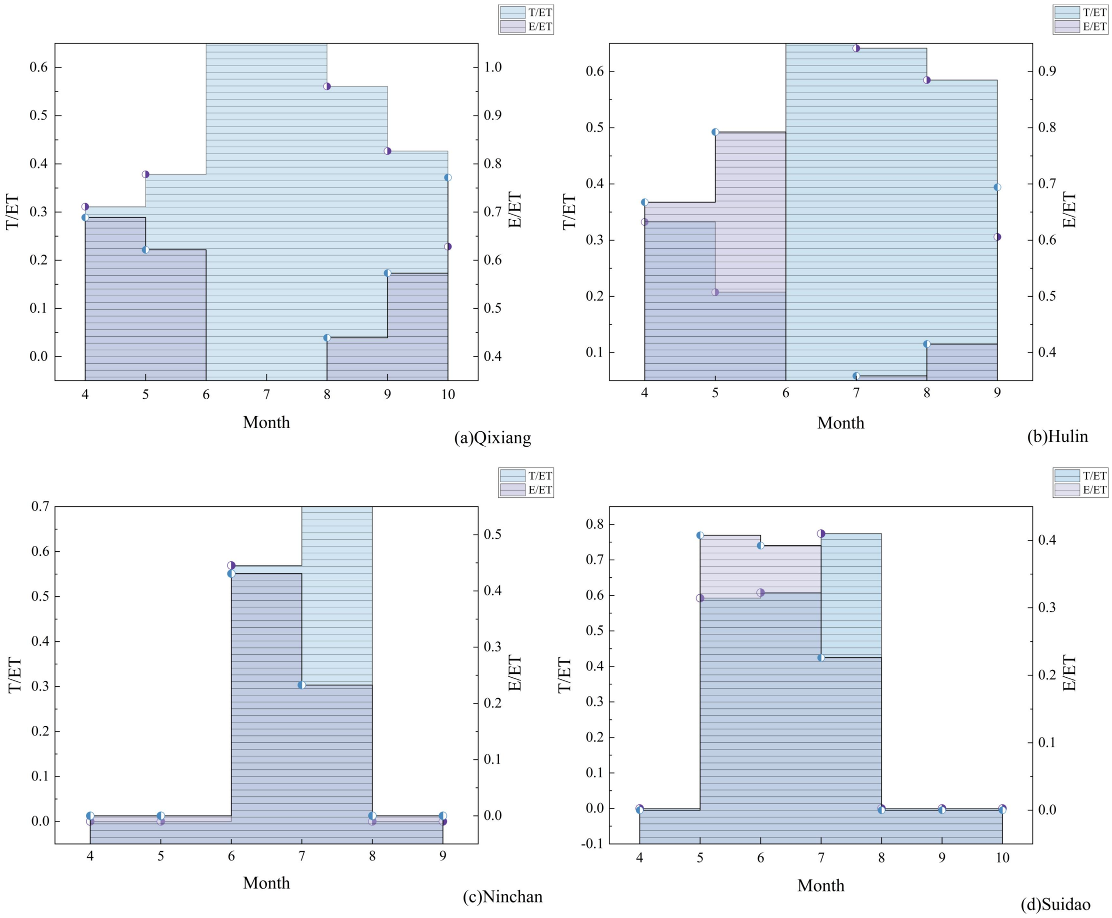

Figure 5 The proportion of soil evaporation and vegetation transpiration in evapotranspiration of ecosystem(0 represents missing data)

Comment to Figures 5a and 5b. In both figures, δ18Os is represented. Are these the same data? If yes, why are the values different?

Response: That's a great suggestion. We have removed unnecessary charts and streamlined the content accordingly. What we need to explain here is that through reading literature, we found that $\delta^{18}O$ is more reliable than $\delta^{2}H$ in calculating soil evaporative isotope and evapotranspiration partitioning. Therefore, only oxygen isotope was calculated in the manuscript. However, in order to make the diagram more clearly reflect the evaluation of T/ET in the spruce forest ecosystem in Qinghai, we remade the them. **The modified results have been presented in the previous question for your reference.**

Comments to Figure 5c. Some remarkable mistakes are present in this figure. The y-axis is reporting a fraction(0 to 1) value, but the label has the percentage symbol. The y-axis does not have the same interval magnitude. Moreover, see the comment in the pdf on lines 286 to 288

Response: Thank you very much for your feedback. We greatly appreciate your input, and we took particular note of the issue you raised when recreating the charts. We have made the necessary corrections accordingly. **Please refer to the revised content in section 4.3 for further details.**

252 - Te following is stated " δ 18OX> δ 18OET> δ 18OE" but from the graph in fig. 4a, it seems that except for the first data point δ 18OX and δ 18OE are more or less equal. A statistical test (like t-test) would probably tell that no significant difference is present between the two sample-populations.

Response: Your point is valid, and we believe that the lack of sufficient sample size has contributed to the observed uncertainty, resulting in the insignificant differences among them. In this latest manuscript, we have presented the isotopic composition of soil evaporation, vegetation transpiration, and ecosystem evapotranspiration in a tabular format **(Table 3)** for a more straightforward and explicit representation of their interrelationships. As follows:

Table 3 Evaporation and transpiration at different altitudes during the growing season

Site	Type	April	May	June	July	August	September	October
Qixiang	δ_T	2.22	-5.87	-4.59	-0.72	-1.72	-1.78	-2.26
	δ_E	-30.32	-28.68	-27.33	-29.12	-28.68	-26.32	-27.27
	δ_{ET}	-20.19	-20.05	-11.63	-9.87	-13.56	-15.85	-21.56
Hulin	δ_T	-5.34	-3.58	-4.13	-0.34	-2.35	-4.25	-1.97
	δ_E	-29.68	-27.28	-25.8	-27.75	-24.56	-25.21	-27.88
	δ_{ET}	-21.59	-22.36	-8.93	-10.17	-11.57	-18.8	/
Ninchan	δ_T	/	-3.45	-1.98	-1.05	-6.68	/	/
	δ_E	/	-20.57	-26.31	-29.08	-18.22	-18.15	-18.22
	δ_{ET}	/	/	-12.46	-7.57	/	/	/

	δ_T	/	-8.45	-6.98	-6.05	-6.68	/	/
Suidao	δ_E	-29.79	-27.32	-27.91	-23.83	-28.78	-25.8	-28.06
	δ_{ET}	-24.31	-16.14	-15.19	-10.07	-18.05	-23.02	-18.65

DISCUSSION

Comments to section 5.1.2, figure 7, and lines 190 to 192. The results expressed in the referred section and figure are based on the following parameters reported in lines 190 to 192 "δpv, δtr, δev and δadv values are the stable isotopes in precipitating transpiration, transpiration, surface evaporation, and advective vapour, respectively". Of these four parameters is never explained how these two δpv and δadv are derived or measured. All this section and elaboration is not understandable.

Response: We fully understand your comments and concerns.We have presented the calculation steps for δpv and δadv in the methodology section, formula (11) to (17) . In order to make Section 5.1.2 clearer and more logical, we have made detailed revisions and explanations in terms of methods, logic, content, and figures. As follows:

5.1.2 Contribution to recirculating water vapour in precipitation

Our previous study in the eastern section of the Qilian Mountains (Zhang et al., 2021) indicated that above an altitude of 2100m, air masses gather from the northern foothills and move along the valley from low to high elevations. From June to August, the atmospheric circulation is influenced by westerlies, southeast monsoons, and plateau monsoons, while from September to October, the westerlies are the dominant factor. Therefore, we selected the Xiying station at an altitude of 2097m as our upwind site. The δ_{pv} values showed depletion in April and October, gradually enriching from June to August. The maximum δ^2H value was -76.02‰ (Table 5), and the minimum was -184.93‰, while the maximum $\delta^{18}O$ value was -11.89‰, and the minimum was -26.38‰. Above 2700 meters, there is a gradual decrease in precipitation vapor with increasing altitude. The δ_{ev} values exhibited significant fluctuations throughout each month, with different patterns at different locations. At 2721m, the δ_{ev} range varied between -172.3‰ and 96.39‰. From the forest's lower layer to the upper layer, the isotopic composition of the advected moisture from the valley gradually diminished, resulting in decreasing values of δ_{adv}.

Table 5 Isotopic Composition of Precipitation Vapor, Surface Evaporation Vapor, and Vegetation Transpiration Vapor at Different Months and Altitudes

Month	Type	isotope	April	May	June	July	August	September	October
Qixiang	δpv	δ^2H/‰	-141.95	-123.83	-99.87	-115.99	-128.34	-120.9	-152.43
		$\delta^{18}O$/‰	-19.27	-16.58	-14.04	-15.91	-18.6	-17.22	-22.34
	δev	δ^2H/‰	-	-125.69	-123.69	-117.98	-134.57	-	-
		$\delta^{18}O$/‰	-	-30.21	-29.56	-28.62	-31.19	-	-
	δtr	δ^2H/‰	-39.9	-29.32	-46.19	-49.58	-45.15	-42.66	-44.64
		$\delta^{18}O$/‰	2.22	-5.87	-4.59	-0.72	-1.72	-1.78	-2.26
	δadv	δ^2H/‰	-145.57	-83.25	-81.12	-92	-109.62	-100.53	-122.62
		$\delta^{18}O$/‰	-20.24	-11.93	-10.73	-12.06	-15.31	-13.46	-18.16
Hulin	δpv	δ^2H/‰	-129.93	-123.29	-98.68	-113.98	-124.16	-118.52	-164.82
		$\delta^{18}O$/‰	-17.54	-16.62	-13.18	-15.48	-17.33	-17.88	-22.46
	δev	δ^2H/‰	-114.24	-117.01	-107.75	-123.44	-106.92	-96.39	-172.3
		$\delta^{18}O$/‰	-14.77	-16.35	-15.03	-16.7	-14.53	-12.78	-24.82
	δtr	δ^2H/‰	-24.12	-39.62	-35.97	-26.44	-35.85	-38.39	-40.53
		$\delta^{18}O$/‰	-5.34	-3.58	-4.13	-0.34	-2.35	-4.25	-1.97
	δadv	δ^2H/‰	-112.79	-115.67	-106.61	-122.19	-106.49	-95.7	-170.54
		$\delta^{18}O$/‰	-14.59	-16.15	-14.88	-16.54	-14.46	-12.69	-24.57
Ninchan	δpv	δ^2H/‰	-	-76.02	-139.21	-135.74	-129.96	-113.71	-184.93
		$\delta^{18}O$/‰	-	-11.89	-19.87	-18.7	-17.91	-16.77	-26.38
	δev	δ^2H/‰	-	-83.76	-81.42	-92.42	-110.24	-101.11	-123.42
		$\delta^{18}O$/‰	-	-12.01	-10.76	-12.09	-15.37	-13.49	-18.27
	δtr	δ^2H/‰	-	-25.58	-46.77	-37.77	-43.66	-	-
		$\delta^{18}O$/‰	-	-3.45	-1.98	-1.05	-6.68	-	-
	δadv	δ^2H/‰	-162.36	-113.49	-111.45	-106.16	-122.12	-114.67	-141.33
		$\delta^{18}O$/‰	-22.73	-15.94	-15.28	-14.46	-16.96	-16.58	-20.42
Suidao	δpv	δ^2H/‰	-167.86	-128.08	-124.95	-117.32	-137.73	-130.44	-155.52
		$\delta^{18}O$/‰	-22.9	-18.02	-17.28	-16.04	-19.09	-18.64	-21.59
	δev	δ^2H/‰	-164.16	-114.52	-112.37	-106.9	-122.96	-115.47	-142.85
		$\delta^{18}O$/‰	-22.98	-16.07	-15.41	-14.56	-17.08	-16.69	-20.64
	δtr	δ^2H/‰	-	-25.58	-46.77	-37.77	-43.66	-	-
		$\delta^{18}O$/‰	-	-8.45	-6.98	-6.05	-6.68	-	-
	δadv	δ^2H/‰	-162.38	-113.51	-111.47	-106.18	-122.14	-114.69	-141.36
		$\delta^{18}O$/‰	-22.73	-15.94	-15.28	-14.47	-16.97	-16.58	-20.42

In July, the ratio of vegetation transpiration to precipitation vapor is significantly higher compared to other months. The temperatures in the lower layers of the forest are relatively high, and the middle to upper layers are densely populated with spruce, resulting in a higher f_{tr} (transpiration ratio) throughout the entire growing season. Both the early and late stages of the growing season exhibit noticeably higher f_{ev} (evaporation ratio) compared to other months, with the middle and upper parts of the forest having a higher proportion of evaporated vapor. The average f_{adv} (advected vapor ratio) is 72%, with contributions exceeding 70% for all months except June and July (Figure 7).

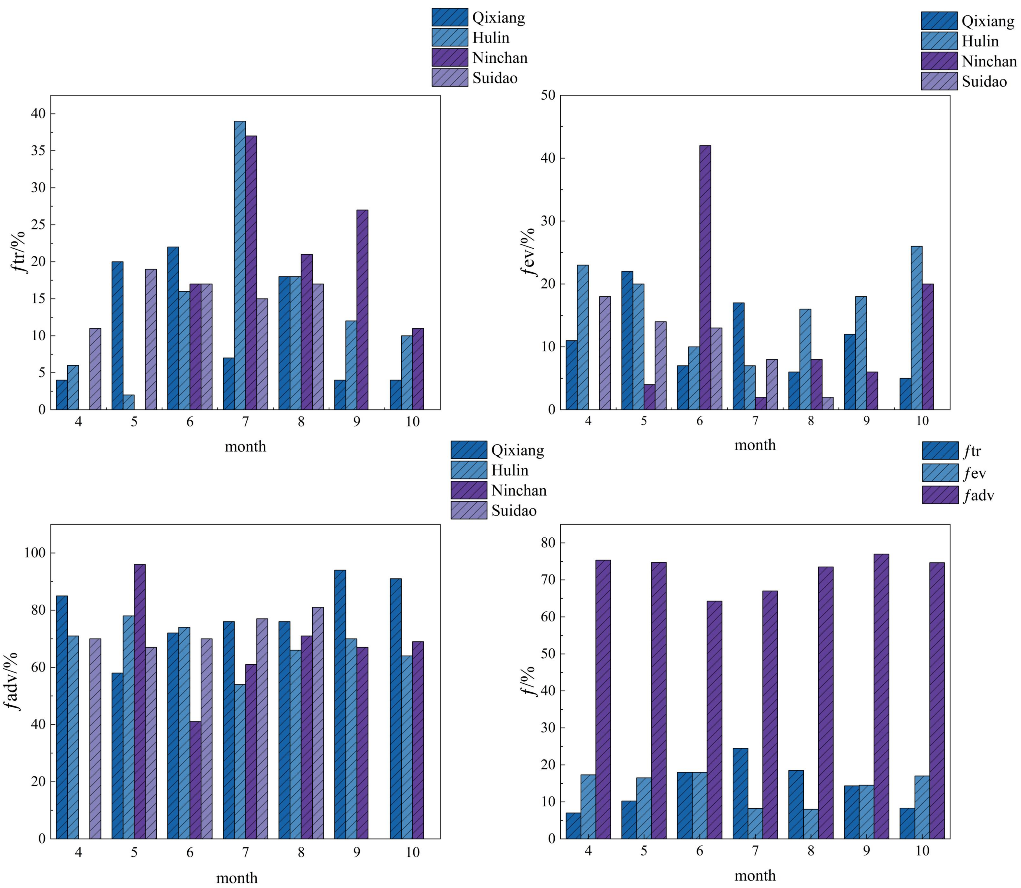

Figure 7 Comparison of f_{adv} (advective water vapour contribution), f_{ev} (surface evaporation water vapour contribution) and f_{tr} (plant transpiration water vapour contribution) for each of period

Hydrological effects of evapotranspiration in the Qilian Mountains forest belt

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Abstract: Mountainous regions play a crucial role as primary water sources and origins of rivers. The changing climate patterns worldwide are altering the distribution of vegetation and water utilization methods. Hence, gaining a comprehensive understanding of evapotranspiration in mountainous forest zones is essential for comprehending the ecohydrological impact of vegetation and its influence on the water cycle within the watershed. We collected precipitation, soil water from 0 to 100cm, xylem water from Qinghai Spruce, temperature, relative humidity and rainfall in the eastern Qilian Mountains from 2018 to 2019. We simulated T/ET comprehensively, and quantified the contribution of recirculated water vapor in precipitation. The aim of this study was to clarify the evapotranspiration process and its effect on production and confluence in the forest belt of Qilian Mountain. The study revealed that transpiration from Qinghai spruce trees constituted the largest portion of evapotranspiration within the entire Qinghai spruce forest ecosystem, averaging 57%. This indicates that transpiration surpasses evaporation during the growing season. Soil water content and air humidity emerged as the primary factors influencing evapotranspiration within the Qinghai spruce forest zones. Throughout each month of the growing season, evapotranspiration from Qinghai spruce was found to exceed precipitation. Water loss through evapotranspiration is much greater than

water inputs from precipitation and surface water replenishment. Consequently, the forest zone does not yield flows in the eastern part of the Qilian Mountains. The warming of global temperatures and human activities are likely to trigger shifts in the distribution areas and evapotranspiration regimes of Qinghai spruce, which in turn will lead to a change in water resource patterns in the basin.

Keywords: Qinghai spruce; stable isotopes; end-member mixing model; evapotranspiration partitioning

1. Introduction

Future droughts are likely to be more frequent, more severe, and longer-lasting than in recent decades.Under the influence of climate change, in ecologically fragile areas, particularly in arid and semi-arid regions, these changes will be the most rapid and extreme (Ault et al., 2020). As a natural reservoir and purifier, the Qinghai spruce ecosystem has the functions of storing, releasing and purifying water. The Qilian Mountains supply the water resources that human beings depend on for survival in the continental river basin in the arid region, regulate the water cycle in the arid region, and interact with the soil and atmosphere to form a vertical spatial continuum, which not only affects the ecological process of the local plant community, but also changes the regional microclimate by means of latent heat (Zhang et al.,2021). As a water source for several inland rivers, the Qilian Mountains are an important ecological security barrier and a priority area for biodiversity conservation in central Asia. The spruce forest ecosystem provides various ecological, climatic, and social benefits to the Qilian Mountains but is highly vulnerable to drought and temperature extremes. More to the point, climate drivers put spruce forests at risk from drought and heat stress. As the magnitude of climate change increases, the disturbance to its ecosystem is also expected to be higher. The interaction between soil and vegetation controls rainfall input and water transfer within ecosystem components. It is an important player in climate change mitigation in terms of climate benefits (Rohatyn et al., 2022). In the face of complex climate changes, unpredictable weather variations, and continual alterations in surface coverage, the subsystems comprising the atmospheric, soil, and vegetation components in ecohydrological systems undergo corresponding changes in resilience, fragility, and sensitivity. Water moves from the soil through plant roots and stems, eventually reaching the leaves. During photosynthesis, water vapor is released into the atmosphere through open stomata. Stable isotopes of hydrogen and oxygen serve as natural tracers, enabling monitoring of the vertical migration and transformation of water in the ecosystem(Goodwell et al., 2018).

Evapotranspiration (ET) is an indispensable part of the terrestrial water and energy cycle. Therefore, exploring the spatio-temporal and component changes of soil evaporation and vegetation transpiration can help us increase the response of vegetation canopy to climatechange (Liu et al., 2022). At the ecosystem scale, many studies have classified evapotranspiration (ET) as transpiration (T) and evapotranspiration (E) (Schlesinger et al.,2014). The measurement of evapotranspiration (ET) in field research is often based on physical evaporation from the soil surface and biological transpiration, which involves the uptake of soil water by roots and the loss of water vapor through plant stomata during photosynthesis. Some studies have classified evaporation (E) and transpiration (T) by analyzing the isotopic composition of oxygen in soil and runoff, finding that $\delta^{18}O$ enrichment is primarily associated with evaporation rather than transpiration (Wershaw et al., 1966). Differentiating between soil evaporation and stomatal plant evapotranspiration is a challenging yet crucial task for assessing biomass production and allocating scarce water resources effectively. Generally, plant evapotranspiration (T) is the desired component of water that enhances plant productivity, while soil evaporation (E) is considered a source of water loss or inefficiency. The magnitude of soil evaporation can be significant in sparsely vegetated systems, especially in arid regions or very wet systems such as surface irrigated crops and wetlands (Liu et al., 2015; Zhang et al., 2018). Zoning evapotranspiration is essential for accurately monitoring system hydrology and implementing improved water management practices in these specific scenarios (Kool et al., 2014). Quantifying the role of regional evapotranspiration in the terrestrial water balance and the global water cycle is therefore critical.

On regional and global scales, there are various methods employed to partition evapotranspiration. Firstly, in river basins, researchers investigate the role of lateral groundwater flow in distributing evapotranspiration by utilizing comprehensive continental-scale hydrological models. These models couple vegetation and land energy processes with surface and underground hydrology to study the distribution of evapotranspiration at the continental scale (Maxwell et al., 2016). Secondly, remote sensing-based approaches are employed to identify differences in evapotranspiration partitioning among different models (Talsma et al., 2018; Chen et al., 2022). Thirdly, eddy covariance methods are utilized to assess multi-year energy fluxes and evapotranspiration in typical alpine meadows, exploring the environmental and biophysical controls on evapotranspiration (Chang et al., 2022). Additionally, studies synthesize available literature data to establish quantitative relationships between evapotranspiration allocation and vegetation cover indices (such as leaf area index, or LAI) in agricultural and natural systems. These studies aim to explain observed changes in T/ET at global scales (Wang et al., 2014; Wei et al., 2018; Cui et al., 2021). The semi-arid natural environment influences the hydrological processes in the soil-plant-atmosphere continuum. However, the contribution of vegetation transpiration (T) to water fluxes in these mountainous regions, which rely on rainfall and snowmelt as water sources, remains unclear. Furthermore, most studies have focused solely on partitioning evapotranspiration within the ecosystem, which obscures the fate of water vapor. In our research, we analyze the water vapor fluxes from soil evaporation and vegetation transpiration into the atmosphere, which is crucial for understanding water loss dynamics and ensuring appropriate allocation of water resources in the upstream and downstream regions of mountainous areas.

As a vascular plant species, Qinghai spruce forests are one of the important entry points for energy and materials in the environment into terrestrial ecosystems. Their growth, survival, and reproduction affect other species' ecological functions and forms within and outside their habitats. There is a high degree of responsiveness between the vegetation, drought resilience, and microclimatic conditions of forests and their ecosystems (Eisenhauer et al., 2021). In this study, we observed and analyzed the monthly xylem water, soil water, precipitation stable isotopes and soil water content of Spruce forest in the eastern Qilian Mountains from April to October 2018 and 2019, and used these data to solve the following problems: (1) Quantify the contribution rates of soil evaporation and vegetation transpiration to evapotranspiration of ecosystems; (2) Quantifying the ratio of recirculated water vapor in precipitation; (3) To investigate the evapotranspiration process and its influence on production and confluence in the forest belt of Qilian Mountain. This study provides an effective basis for local water resource use and ecological protection.

2. Study area

The Qilian Mountains are located in the central part of the Eurasian continent, on the northeastern edge of the Qinghai-Tibet Plateau. The eastern region is dominated by water erosion, with large variations in mountainous terrain and an average elevation of over 4,000 meters. Permafrost is developed at elevations of 3,500 to 3,700 meters, and areas above 4,500 meters are characterized by modern glacier development. The region has a plateau continental climate, with hot summers and cold winters, strong solar radiation, and large temperature differences between day and night. The average annual temperature is below 4°C, with extreme highs of 37.6°C and extreme lows of -35.8°C. The annual sunshine hours range from 2,500 to 3,300 hours, with a total solar radiation of 5,916 to 15,000 megajoules per square meter. The average annual precipitation is 400 millimeters, and the annual evaporation ranges from 1,137 to 2,581 millimeters. The average wind speed is around 2 meters per second, and the frost-free period lasts from 23.6 to 193 days. The Shiyang River originates from the Daxueshan on the northern side of the Lenglong Ridge in the eastern section of the Qilian Mountains, serving as a major water source for the city of Wuwei. The soil types in the eastern section are diverse, but with low organic matter content. The distribution of vegetation shows distinct zonal characteristics, with mountainous forest-grassland zones (2,600 to 3,400 meters), subalpine shrub-meadow zones (3,200 to 3,500 meters), and high mountain sub-ice-snow sparse vegetation zones (>3,500 meters) at elevations above 2,700 meters. The main types of natural forest vegetation include Qinghai spruce forest, Qilian juniper forest, and Chinese pine forest, with Qinghai spruce being the dominant tree species (Zhu et al., 2022).

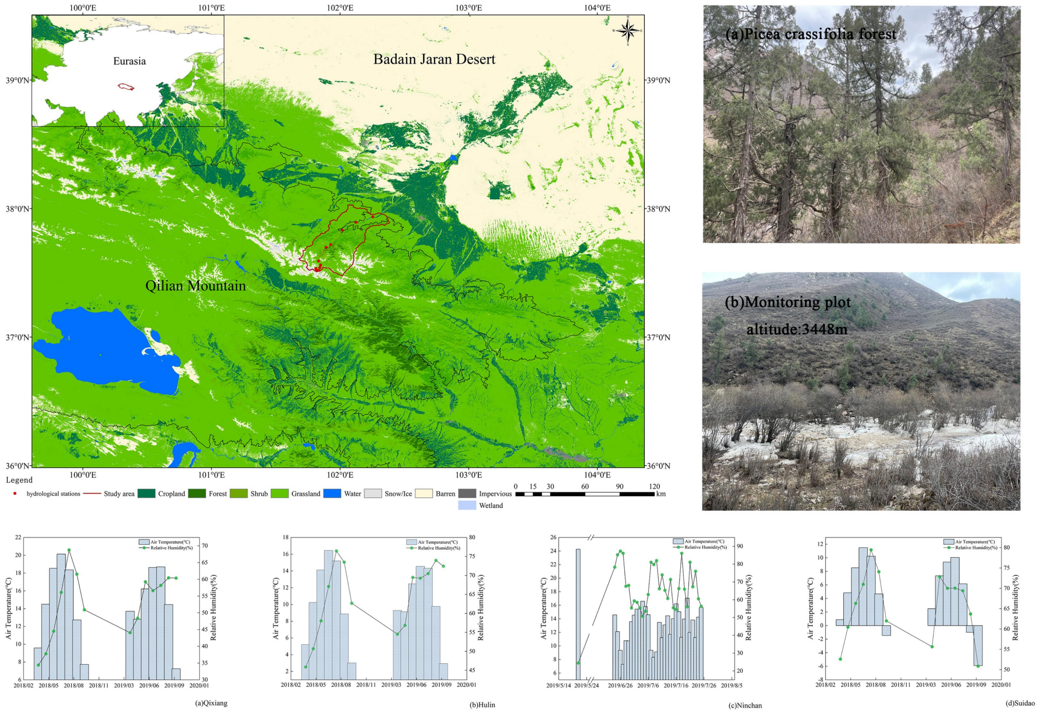


Figure 1 Location of the study area and changes in meteorological conditions

3. Materials and methods

3.1 Materials Sources

3.1.1 Sampling network

Table 1 Sampling Point Locations and Sample Quantity Information

Parameter \ Station		Qixiang	Hulin	Ninchan	Suidao
	Altitude(m)	2543	2721	3068	3448
Local climate	Temperature(℃/a)	3	3.2	3.3	-0.9
	Precipitation(mm/a)	510	469.44	394	475
	Relative humidity（%/a）	52.9	56.1	66.6	69.2
Samplings number	Precipitation	53	108	91	135
	Soil water	220	560	560	560
	Xylem water	236	56	56	56

3.1.2 Sample collection

We use an automatic weather station in 2018 and 2019 to record meteorological data, in which a rain gauge is used to collect precipitation and transfer samples to 100ml containers after each rain. Drill holes 0 ~ 5 cm, 5 ~ 10 cm, 10 ~ 20 cm, 20 ~ 30 cm, 30 ~ 40 cm, 30 ~ 50 cm, 50 ~ 60 cm, 60 ~ 70 cm, 70 ~ 80 cm, 80 ~ 90 cm, 90 in the sample plot by using soil drill ~ 100 cm. The soil samples were divided into two parts, one of which was placed in a 50 ml glass bottle. The bottle was sealed with a subfilm and transported to the observation station within 10 hours after the sampling date was marked for cryopreservation to detect stable isotope data. The other part of the sample was placed in a 50ml aluminum box and the soil moisture content was determined by drying method. When collecting plant samples, we used scissors to collect vegetation xylem stems, peeled off the bark, and put them in 50ml glass bottles sealed and frozen for experimental analysis.

We utilized the monthly potential evapotranspiration dataset of China, with a spatial resolution of 0.0083333° (approximately 1 km), covering the period from January 1990 to December 2021. The data is measured in units of 0.1 mm. This dataset is derived from the China 1 km monthly mean temperature, minimum temperature, and maximum temperature dataset(Peng et al.,2022;Dinget al.,2020;Ding et al.,2021), using the Hargreaves equation for estimating potential evapotranspiration (Peng et al., 2017). The formula is as follows: P_{ET} = 0.0023 × S0 × (MaxT − MinT)0.5 × (MeanT + 17.8), where P_{ET} represents potential evapotranspiration in mm/month, MaxT, MinT, and MeanT are the monthly maximum temperature, minimum temperature, and mean temperature, respectively. S0 represents the theoretical solar radiation reaching the top of the Earth's atmosphere, calculated based on solar constant, distance between Earth and the sun, Julian day, and latitude. For data storage convenience, the values are stored as int16 type in NETCDF (nc) files. The surface evapotranspiration data were obtained from the MODIS-based daily surface evapotranspiration data of the Qilian Mountains (2019), with a spatial resolution of 0.01°（Yao et al., 2017;Yao et al., 2020）.

3.2 Experimental Analysis

The isotopic data used in this study mainly include stable isotopes of precipitation, soil water, and xylem water. All isotopic samples were analyzed at the Stable Isotope Laboratory of Northwest Normal University. The precipitation samples were analyzed for hydrogen and oxygen stable isotopes using a liquid water isotope analyzer (DLT-100, Los Gatos Research, USA). After thawing the soil and vegetation samples, they were extracted using a low-temperature vacuum condensation device (LI-2100, LICA United Technology Limited, China), and the extracted water was subjected to isotopic analysis. Each water sample was tested six times to ensure accuracy, with the first two tests considered as interference and only the results of the subsequent four tests were averaged (Zhu et al., 2022). The isotopic measurements are represented by δ, which represents the deviation in parts per thousand of the ratio of two stable isotopes in the sample relative to the ratio in a standard sample. The International Atomic Energy Agency (IAEA) defined the Vienna Standard Mean Ocean Water (VSMOW) in 1968 as the standard for isotopic composition, which is derived from distilled seawater and has a similar isotopic composition to Standard Mean Ocean Water (SMOW).

$$\delta = \left(\frac{\delta_{Sampling}}{\delta_{Standard}} - 1\right) \times 1000‰ \qquad (1)$$

3.3 Research methods

3.3.1 Isotopic composition of atmospheric water vapour

The stable isotope composition of moisture in ambient air is calculated as follows(Gibson and Reid, 2014;Skrzypek et al., 2015):

$$\delta_A = \frac{\delta_{rain} - k\varepsilon^+}{1 + k\alpha^+ \times 10^{-3}} \qquad (2)$$

where k=1, or by fitting k to some fraction of 1 as the best fit to the local evaporation line, is the isotopic fractionation factor. Defined by $\varepsilon^+ = (\alpha^+ - 1) \times 1000$. α^+ about ^2H and ^{18}O are calculated as follows(Horita and Wesolowski, 1994):

$$10^3\ln^2\alpha^+ = 1158.8T^3/10^9 - 1620.1T^2/10^6 + 794.84T/10^3 - 161.04 + 2.9992 \times 10^9/T^3 \quad (3)$$

$$10^3\ln^{18}\alpha^+ = -7.685 + 6.7123\times 10^3/T - 1.6664\times 10^6/T^2 + 0.35041 \times 10^9/T^3 \quad (4)$$

3.3.2 Isotopic composition of soil evaporation

The Craig-Gordon model was used to calculate the stable isotopic composition of soil evaporation water vapour, δ_E, using the following equation(Craig and Gordon, 1965;Yepez et al., 2005).

$$\delta_E = \frac{\alpha_e^{-1}\delta_s - h\ \ \delta_A - \varepsilon_{eq} - (1-h\ \ )\varepsilon_k}{(1-h\ \ ) + 10^{-3}(1-h\ \ )\varepsilon_k} \quad (5)$$

where α_e(>1) is the equilibrium factor calculated as a function of water surface temperature, δs is the stable isotopic composition of liquid water at the evaporating surface of the soil (0 ~ 10 cm average stable isotopic composition of soil water), δ_A is the stable isotopic composition of atmospheric water vapour near the surface, Ɛeq represents the equilibrium fractionation corresponding to Ɛeq = (1-1/αe) × 1000, Ɛk is the kinetic fractionation factor of O^2 is approximately 18.9‰ and h is the atmospheric relative humidity(Gibson and Reid, 2010). For $\delta^{18}O$, α_e is calculated as follows(Raz-Yaseef et al., 2010):

$$\alpha_e = \frac{1.137\times10^6/T^2 - 0.4156\times10^3/T - 2.0667}{1000} + 1 \quad (6)$$

Where T is the soil Kelvin temperature (K) at a depth of 5 cm.

3.3.3 Isotopic composition of plant transpiration

When transpiration is strong, leaf water is in "isotopic stable state", that is, the isotopic composition of leaf transpiration water is equivalent to that of water absorbed by the roots of rain plants at noon. Therefore, the stable isotopic composition of water in plant xylem can be used to represent the stable isotopic composition of water vapor in plant transpiration. The expression is as follows(Aron et al., 2020):

$$\delta_T = \delta_X \quad (7)$$

where δ_x is the isotopic ratio of xylem water and δ_T is the isotopic ratio of transpiration.

3.3.4 Evapotranspiration isotope assessment

The Keeling Plot model describes the linear relationship between the oxygen isotope composition of atmospheric water vapour and its reciprocal concentration . The intercept of the curve on the Y-axis represents the oxygen isotopic composition of evapotranspiration (δ_{ET}) and is expressed as(Keeling, 1958;Wang et al., 2015):

$$\delta_a = \frac{C_b(\delta_b - \delta_{ET})}{C_a} + \delta_{ET} \qquad (8)$$

Where δ_a and C_a represent the atmospheric water vapour oxygen isotopic composition (‰) and water vapour concentration in the ecosystem boundary layer, δ_b and C_b represent the background atmospheric water vapour oxygen isotopic composition and background atmospheric water vapour concentration, and δ_{ET} is the ecosystem evapotranspiration oxygen isotopic composition.

3.3.5 Ecosystem evapotranspiration partitioning

The determination of evapotranspiration by means of biotic and abiotic isotopic composition can be used to improve the understanding of community structure and ecosystem function in Qinghai spruce forests in the Qilian Mountains. Based on the isotope mass balance approach to consider the distribution of major and minor isotopes, the partitioning of evapotranspiration can be achieved using two end-member mixing models (E and T) with the following expression(Kool et al.,2014;Wei et al., 2018):

$$\frac{T}{ET} = \frac{\delta_{ET} - \delta_E}{\delta_T - \delta_E} \qquad (9)$$

where δ_{ET}, δ_E and δ_T are the isotopic compositions of evapotranspiration (ET), soil evapotranspiration (E) and plant evapotranspiration (T), respectively, and the isotopic values of the three can be obtained by both direct observation and model estimation.

3.3.6 Three-component mixing model

Assuming that precipitation vapor is a mixture of advective water vapour and recirculating water vapour, it is understood that the proportion of both precipitation and precipitation water vapour has the same nature. The proportion of precipitation occupied by advective vapour is calculated as follow(Kong et al., 2013; Wang et al., 2022):

$$f_{re} = \frac{P_{tr}+P_{ev}}{P_{tr}+P_{ev}+P_{adv}} \quad (10)$$

where P_{tr}, P_{ev} and P_{adv} are precipitation produced by transpiration, surface evaporation and advection, respectively.

This can be calculated using the following formula(Brubaker et al., 1993; Sang et al., 2023):

$$\delta_{pv} = \delta_{tr} f_{tr} + \delta_{ev} f_{ev} + \delta_{adv} f_{adv} \quad (11)$$

$$f_{ev} + f_{tv} + f_{adv} = 1 \quad (12)$$

where f_{tr}, f_{ev} and f_{adv} are the proportional contributions of transpiration, surface evaporation and advection to precipitation, respectively, and δ_{pv}, δ_{tr}, δ_{ev} and δ_{adv} values are the stable isotopes in precipitating transpiration, transpiration, surface evaporation and advective vapour, respectively. f_{tr},f_{ev} and f_{adv} are calculated by Isoerror software, based on dual isotopes and three sources(Ver. 1.3.1, https://www.epa.gov/)(Phillips and Gregg, 2001). δpv is calculated using the following formula:

$$\delta_{pv} = \frac{\delta_p - k\varepsilon^+}{1+k\varepsilon^+} \quad (13)$$

Using the C-G model to calculate δ_{ev}, the formula is as follows:

$$\delta_e = \frac{\delta_s/\alpha^+ - h\delta_{adv} - \varepsilon}{1-h+\varepsilon_k} \quad (14)$$

Including the δs is the isotopic composition of liquid water evaporation front, δ_{adv} is advection steam, h is relative humidity, α^+ is equilibrium fractionation factor, ε_k is kinetic fractionation factor, ε is total fractionation factor.

$$\varepsilon = \varepsilon^+/\alpha^+ + \varepsilon_k \quad (15)$$

$$\varepsilon_k = (1-h)\theta_n C_k \quad (16)$$

h is the relative humidity, C_k is the kinetic fractionation constant, δ^2H is 25.1‰, $\delta^{18}O$ is 28.5‰.The weight coefficient θ of small water body is 1, and θ of large water body is 0.5. n ranges from 0.5 (fully turbulent transport, with reduced kinetic fractionation, suitable for lake or saturated soil conditions) to 1 (fully diffused transport, suitable for very dry soil conditions), with a kinetic fractionation coefficient of about 12.2-24.5‰ for ε_k (^2H) in a dry atmosphere (h=0). The kinetic separation coefficient of εk (^{18}O) is about 13.8-27.7‰.

The advection water vapor isotope δ_{adv} in the three-component mixing model needs to be determined by the water vapor isotopic composition at the upwind position. Based on the HYSPLIT model, we found that the eastern Qilian Mountains was controlled by westerly winds, southeast monsoon and plateau monsoon in June, July and August, and by prevailing westerly winds in September and October. The clustering analysis of air masses in different months shows that air masses accumulate at the northern foot of Qilian Mountains and move from low altitude to high altitude along the valley. Xiying, at 2097 m above sea level, is therefore used as a headwind station from April to October. When steam isotopes show a depletion trend along the transport path, isotopic fractionation is assumed to be due to Rayleigh distillation, and the expression is as follow:

$$\delta_{adv} = \delta_{pv-adv} + (\alpha^{+} - 1)\ln F \quad (17)$$

Where $\delta_{pv\text{-}adv}$ is the isotopic composition in the vapor of the winds tation, and F is the ratio between the final vapor and the initial vapor. Since rainfall is positively correlated with the surface vapor pressure of the whole study area (c=1.657e, where c is the water vapor content in mm, e is the surface vapor pressure in hPa, R^2=0.94), we used the surface vapor pressure of each site to calculate the value of F. The recirculated water entering the air mass is not considered here, because the contribution of recirculated water to the total air column is very limited, and most of the available precipitation does not result in rainfall but escapes to other areas. If there is no depletion of isotope ratios along the transmission track, the vapor isotope ratio from the upwind station is applied directly, and the Rayleigh distillation equation is not applied.

The δp is corrected by the local evaporation line (LEL), and the LEL slope (SLEL) can be calculated as（Skrzypek et al.，2015):

$$S_{LEL} = \frac{(h-10^{-3}{}^{18}\varepsilon)[h({}^{2}\delta_{pv} - {}^{2}\delta_{p}) + {}^{2}\varepsilon(1+10^{-3}\,{}^{2}\delta_{pv})}{(h-10^{-3}\,{}^{2}\varepsilon)[h({}^{18}\delta_{pv} - {}^{18}\delta_{p}) + {}^{18}\varepsilon(1+10^{-3}{}^{18}\delta_{p})]} \quad (18)$$

Where h is the relative humidity, Ɛ is the total fractionation factor, and δ_{PV} and δ_P are the stable isotopic components of water vapor and precipitation.According to our research results, the LEL equation for the study area is $\delta^2H=3.86\delta^{18}O-19.88$ ($R^2=0.994$, $P < 0.0001$, n=19).

4. Results and analysis

4.1 Hydrogen and oxygen isotope variations in different water bodies

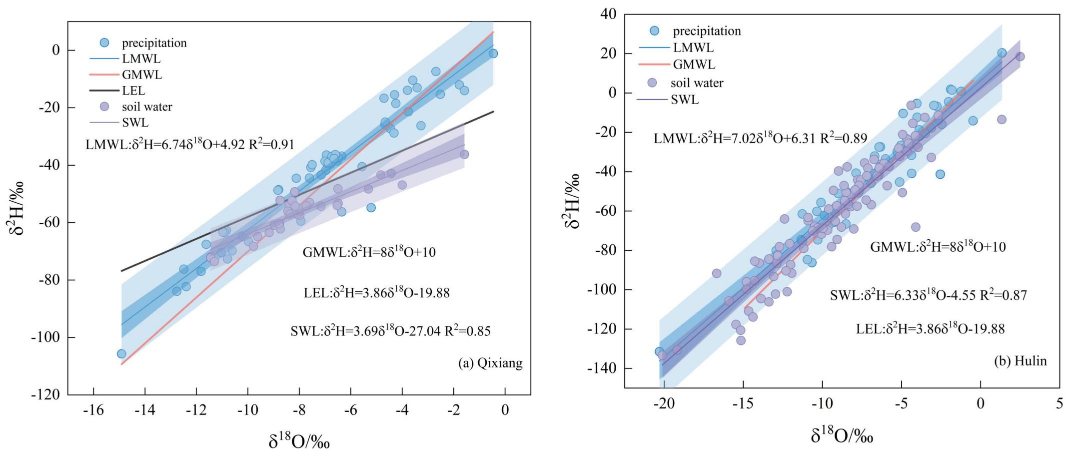
During the growth season of Qinghai spruce, the stable isotopes of precipitation exhibit specific patterns of fluctuation (Table 2). In the early stages of growth, the hydrogen and oxygen isotope values are generally low. As the temperature gradually increases, the extent of water evaporation and loss intensifies, leading to an enrichment of stable isotopes. The average δ^2H value of precipitation throughout the growth season is -45.52‰, fluctuating roughly between -238.62‰ and 63.43‰. The average δ18O value is -7.75‰, fluctuating roughly between -31.49‰ and 14.79‰. There is not a significant depletion or enrichment of stable isotopes in the wood tissues, with a fluctuation range of -76.95‰ to 23.87‰ for δ^2H and -11.92‰ to 24.77‰ for $\delta^{18}O$. Shallow soil water shows a less pronounced enrichment of heavy isotopes compared to precipitation and wood tissues, with a lower degree of fluctuation observed during late spring and the beginning of summer.

Table 2 Stable isotopes of different water bodies during the growing season

Average / Period	δ^2H/‰			$\delta^{18}O$/‰		
	Precipitation	Xylem water	Soil water （0~10cm）	Precipitation	Xylem water	Soil water （0~10cm）
4	-69.15	-39.02	-53.10	-10.25	2.56	-7.10
5	-39.09	-29.78	-45.38	-7.61	4.44	-6.42
6	-31.29	-45.83	-46.08	-5.74	-2.83	-6.12
7	-32.39	-47.63	-47.71	-5.33	-0.97	-7.06

8	-48.88	-44.55	-68.85	-7.79	-2.06	-9.07
9	-29.38	-42.62	-49.20	-6.46	-1.83	-6.79
10	-68.43	-44.57	-54.88	-11.06	-2.25	-7.96

LMWL exhibits variations across different vertical gradients, primarily influenced by temperature and humidity. It is noteworthy that relative humidity is generally low at all four heights within the forest, resulting in local meteoric water lines (LMWL) being lower than the global meteoric water line (GMWL). At an elevation of 2543m, which represents the lowest layer of tree growth, the temperature can reach up to 20℃ in July, and the slope of the local meteoric water line (LMWL) is 6.74. At 2721m, the average temperature throughout the growing season is 10.4℃, with a maximum temperature of 16.45℃ in July and an average relative humidity of 64.38%. The slope of LMWL is 7.02 (Figure 2, d). At the Suidao station located at an elevation of 3448m, the slope of the precipitation regression line is 7.75, which is close to the slope of the GMWL but exhibits the largest deviation from the local evaporation line (Figure 2, a). The soil water line (SWL) in the forest's lower layer is smaller and closer to the local evaporation line, indicating stronger evaporative fractionation and dynamic fractionation compared to the other three sampling zones. The slopes of the SWL are smaller than the slopes of LMWL, indicating that precipitation is the main source of soil moisture replenishment.



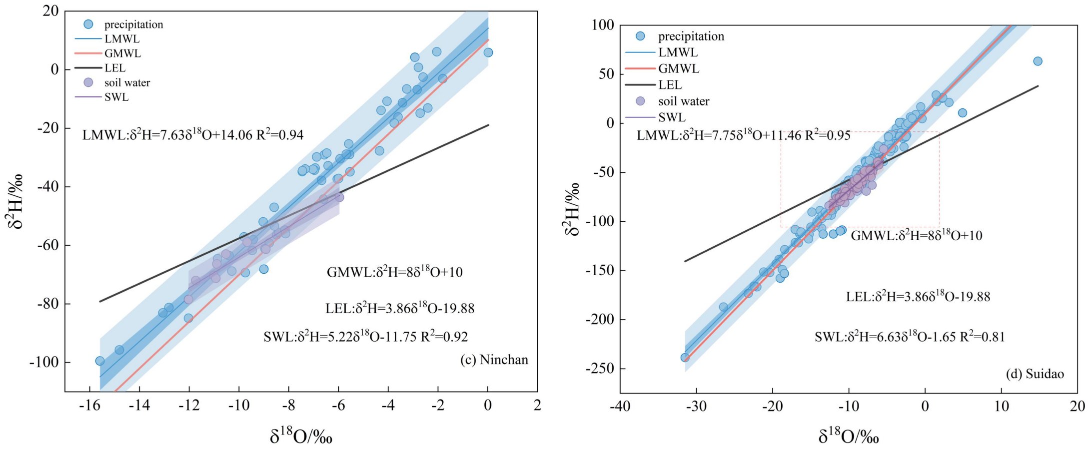


Figure 2 (a) Hydrogen and oxygen stable isotope linkages, (b) Precipitation and oxygen isotope changes in different water bodies.

Unsaturated water vapor leads to non-equilibrium fractionation during the process of precipitation, with an average d-excess value of 16.58‰ throughout the growing season (Figure 3, a). In May and September, due to higher relative humidity compared to other periods, the evaporation rate of water vapor is faster. The deuterium values show slow fluctuations from June to August, with significant fluctuations starting from mid-August, indicating that local evaporation is gradually enhanced over time due to the influence of temperature and relative humidity, leading to increased non-equilibrium evaporation. The average lc-excess value of precipitation in the lower layer of forest distribution is -8.18‰, while the average lc-excess value of precipitation in the middle, upper-middle, and canopy layers is close to 0. This is because the fractionation effect of evaporation is more pronounced at lower elevations. At higher elevations, influenced by rainfall and snowmelt, the soil moisture content in all soil layers is above 30% (Figure 3, b). Towards the end of the growing season, as temperatures decrease, tree leaves fall to the forest floor, forming a litter layer that retains moisture in the soil.

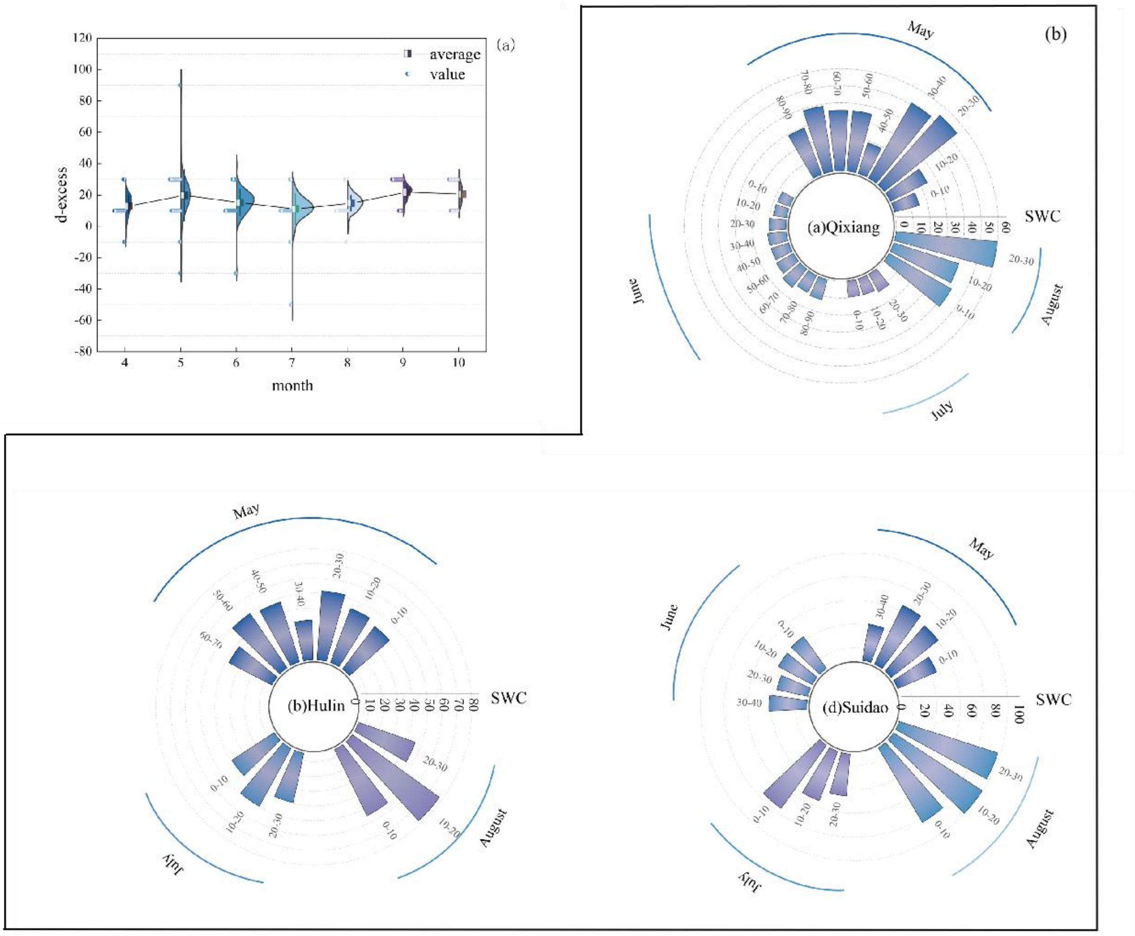


Figure 3 (a) Variation in soil water content, (b) Comparison between atmospheric water vapour oxygen isotopes and d-excess

4.2 Soil evaporation, plant transpiration and ecosystem evapotranspiration

Table 3 Evaporation and transpiration at different altitudes during the growing season

Site	Type	April	May	June	July	August	September	October
Qixiang	δ_T	2.22	-5.87	-4.59	-0.72	-1.72	-1.78	-2.26
	δ_E	-30.32	-28.68	-27.33	-29.12	-28.68	-26.32	-27.27
	δ_{ET}	-20.19	-20.05	-11.63	-9.87	-13.56	-15.85	-21.56
Hulin	δ_T	-5.34	-3.58	-4.13	-0.34	-2.35	-4.25	-1.97
	δ_E	-29.68	-27.28	-25.8	-27.75	-24.56	-25.21	-27.88
	δ_{ET}	-21.59	-22.36	-8.93	-10.17	-11.57	-18.8	/

Ninchan	δ_T	/	-3.45	-1.98	-1.05	-6.68	/	/
	δ_E	/	-20.57	-26.31	-29.08	-18.22	-18.15	-18.22
	δ_{ET}	/	/	-12.46	-7.57	/	/	/
Suidao	δ_T	/	-8.45	-6.98	-6.05	-6.68	/	/
	δ_E	-29.79	-27.32	-27.91	-23.83	-28.78	-25.8	-28.06
	δ_{ET}	-24.31	-16.14	-15.19	-10.07	-18.05	-23.02	-18.65

The Keeling plot method was used to analyze the stable isotope composition of ecosystem evapotranspiration (Figure 4). Its principle involves linearly fitting the water vapor concentration in the ecosystem boundary layer against the oxygen isotope composition, with the intercept on the y-axis representing the stable isotope value of δ_{ET}. The results indicate that at different heights within the distribution of deciduous trees, the average δ_{ET} value is -22.59‰. Throughout the entire growing season, δ_{ET} does not consistently decrease with increasing elevation. Specifically, near the treeline, there are higher stable isotope values, but in the middle and upper layers of the forest, there is a minimal value, indicating lower and less stable isotopic fractionation in that layer. At an elevation of 3448m, as the number of deciduous trees decreases and shrubs become dominant, the δ_{ET} value is -21.81‰(Table 3). We found that the stable isotope δ_E of soil evaporation at depths of 0-10cm is more enriched at lower elevations, particularly in April and May when the isotopic enrichment is more pronounced. From June to August, due to a significant increase in vegetation coverage, soil evaporation intensity decreases. In the early stage of the growing season, when leaves have not fully developed, the stable isotope composition of the xylem exhibits a relatively depleted characteristic. In July and August, when leaves are fully expanded, temperatures rise, and the rainy season in mountainous areas commences, transpiration becomes more intense.

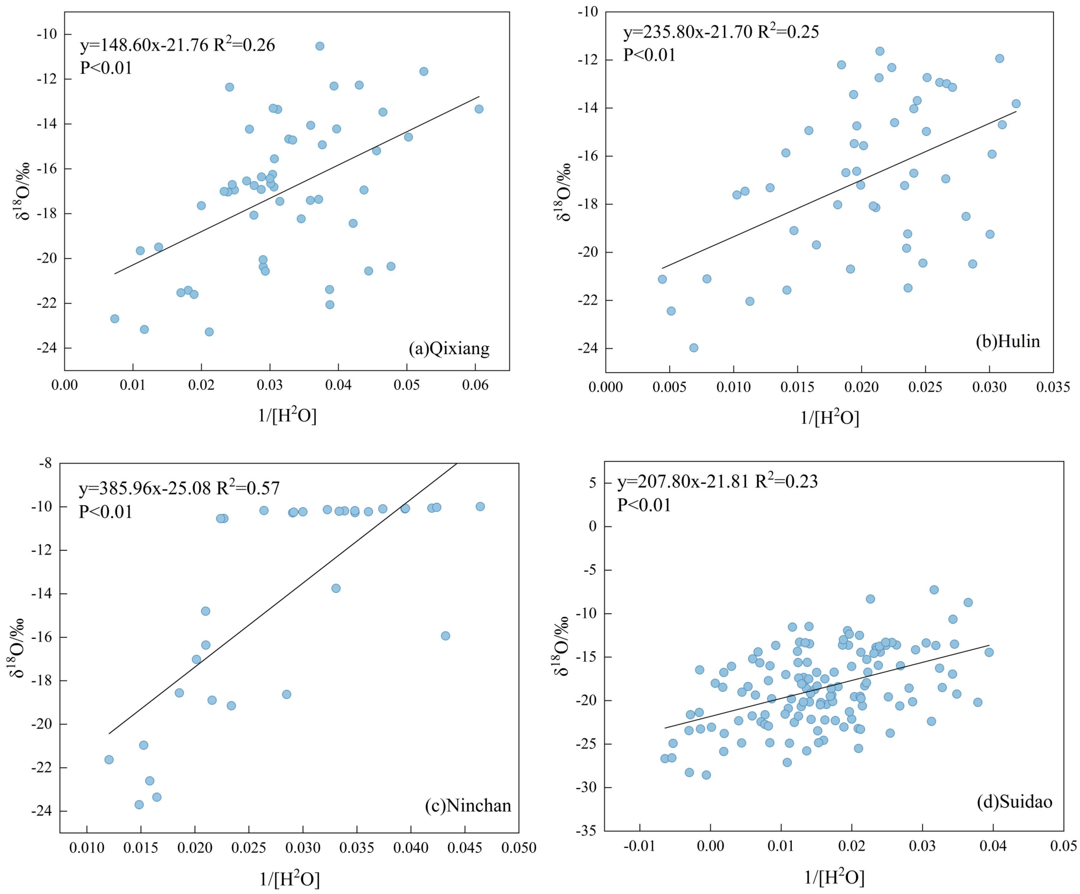


Figure 4 Each sampling point is fitted with a trend line based on the Keeling plot method

4.3 T/ET assessment of Qinghai spruce forest ecosystem in different months

We found that the canopy closure of deciduous trees significantly influences the evapotranspiration of the entire ecosystem (Figure 5). In April and May, as temperatures rise, surface vegetation exhibits weaker growth, resulting in a higher proportion of soil evaporation within the ecosystem, while transpiration by vegetation remains relatively low. During the rainy season in June to August, vegetation experiences vigorous growth, and transpiration reaches its peak in July. In September and October, soil evaporation becomes more dominant as temperatures, relative humidity, and rainfall gradually decrease, and deciduous tree leaves become wilted. At lower elevations, the T/ET ratio fluctuates between 0.20 and 0.70 in a distinct pattern, while above the treeline, transpiration ratios fluctuate between 0.20 and 0.80

in a similar pattern. Overall, summer is characterized as the peak season for transpiration, with a minimal contribution from soil evaporation.

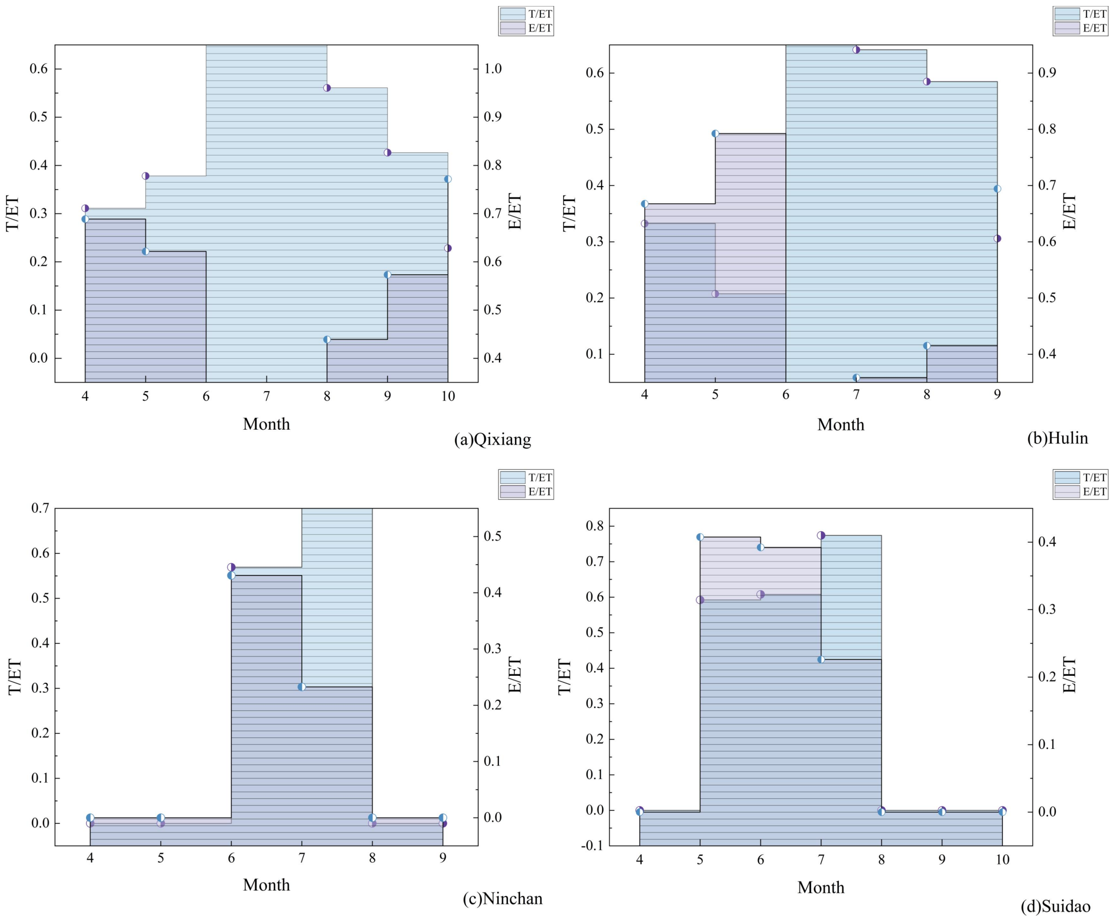


Figure 5 The proportion of soil evaporation and vegetation transpiration in evapotranspiration of ecosystem(0 represents missing data)

5. Discussions

5.1 Hydrological effects of changes in evapotranspiration

5.1.1 Impact on surface runoff

Comparing the differences of monthly potential evapotranspiration, surface evapotranspiration and precipitation in spruce forests (Table 4), the results clearly showed that rainfall fluctuated between 0-16mm, and the maximum rainfall was 15.7 mm in April, while the minimum value of surface evapotranspiration is 41.8 mm and the minimum value of potential evapotranspiration is 44.1mm. The difference between ET_P and ET shows that there is no effective water accumulation in all months. From this, an important conclusion can be drawn: due to the late arrival of the rainy season in mountainous areas and the uneven distribution of rainfall across different altitudinal gradients, surface runoff can not be collected in this area, which also proves that afforestation in this area will further enhance evapotranspiration, posing a threat to water distribution and utilisation.

Table 4 Month-by-month comparison of potential evapotranspiration, surface evapotranspiration and rainfall

Variable \ Month	4	5	6	7	8	9	10
ET_p/mm	76.6	87.6	106.5	128.3	118.1	80.0	44.1
ET/mm	51.5	66.3	93.3	108.9	110.7	81.2	41.8
P/mm	15.7	8.8	0	13.2	13.3	11.2	13.6

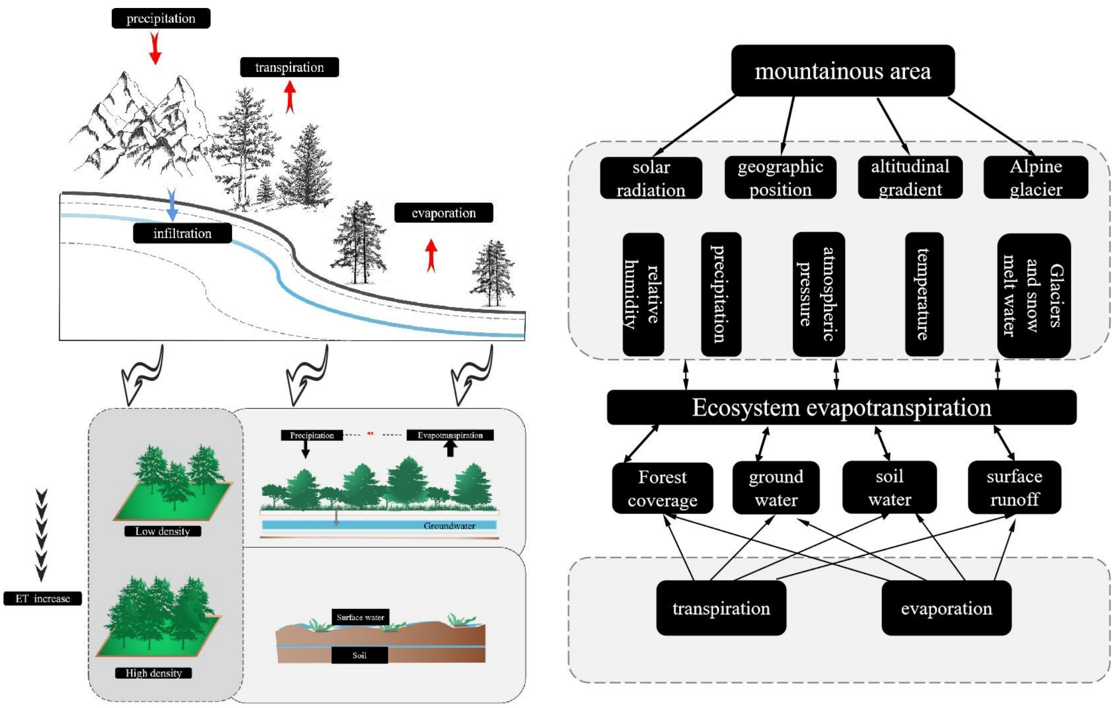


Figure 6 Conceptual model of the hydrological effects of changes in evapotranspiration

Some studies suggested that reducing forest density will result in less ET in seasonally dry forests. That reduced ET can be converted into increased groundwater and runoff to supply downstream social water (Wyatt, O'Donnell, & Springer, 2015). It has also been claimed that in some cases, the transient increase in water availability through reduced forest density can actually contribute to subsequent increases in vegetation cover and ultimately reduce runoff (Tague et al., 2019). By assessing the hydrological effects of afforestation through the water cycle in the Asia-Pacific region, it was found that in 7 of the 15 water-deficient areas, positive effects such as increased yield, precipitation, soil moisture and reduced drought risk were achieved through afforestation, and it was confirmed that the water-water cycle had a strong impact and evapotranspiration was increased (Teo et al., 2021). The water vapour content produced by forest transpiration is much higher than that lost by soil surface evaporation, most of the precipitation is intercepted and infiltrated by surface vegetation, and part of the soil water involved in infiltration is absorbed by the root zone of vegetation(Figure 6). Because of plants' high interception and evaporation ability and the absorption of groundwater by root zone, the proportion of transpiration was significantly higher than that of evaporation(Su et al., 2014). In this case, the groundwater amount decreases gradually with the T value increase. Under the influence of precipitation loss mainly due to plant transpiration, groundwater yield in this region decreases greatly, and has no significant contribution to the downstream water revenue.

5.1.2 Contribution to recirculating water vapour in precipitation

Our previous study in the eastern section of the Qilian Mountains (Zhang et al., 2021) indicated that above an altitude of 2100m, air masses gather from the northern foothills and move along the valley from low to high elevations. From June to August, the atmospheric circulation is influenced by westerlies, southeast monsoons, and plateau monsoons, while from September to October, the westerlies are the dominant factor. Therefore, we selected the Xiying station at an altitude of 2097m as our upwind site. The δ_{pv} values showed depletion in April and October, gradually enriching from June to August. The maximum δ^2H value was -76.02‰ (Table 5), and the minimum was -184.93‰, while the maximum $\delta^{18}O$ value was -11.89‰, and the minimum was -26.38‰. Above 2700 meters, there is a gradual decrease in precipitation vapor with increasing altitude. The δ_{ev} values exhibited significant fluctuations throughout each month, with different patterns at different locations. At 2721m, the δ_{ev} range varied between -172.3‰ and 96.39‰. From the forest's lower layer to the upper layer, the isotopic composition of the advected moisture from the valley gradually diminished, resulting in decreasing values of δ_{adv}.

Table 5 Isotopic Composition of Precipitation Vapor, Surface Evaporation Vapor, and Vegetation Transpiration Vapor at Different Months and Altitudes

Month	Type	isotope	April	May	June	July	August	September	October
Qixiang	δpv	δ^2H/‰	-141.95	-123.83	-99.87	-115.99	-128.34	-120.9	-152.43
		$\delta^{18}O$/‰	-19.27	-16.58	-14.04	-15.91	-18.6	-17.22	-22.34
	δev	δ^2H/‰	-	-125.69	-123.69	-117.98	-134.57	-	-
		$\delta^{18}O$/‰	-	-30.21	-29.56	-28.62	-31.19	-	-
	δtr	δ^2H/‰	-39.9	-29.32	-46.19	-49.58	-45.15	-42.66	-44.64
		$\delta^{18}O$/‰	2.22	-5.87	-4.59	-0.72	-1.72	-1.78	-2.26
	δadv	δ^2H/‰	-145.57	-83.25	-81.12	-92	-109.62	-100.53	-122.62
		$\delta^{18}O$/‰	-20.24	-11.93	-10.73	-12.06	-15.31	-13.46	-18.16
Hulin	δpv	δ^2H/‰	-129.93	-123.29	-98.68	-113.98	-124.16	-118.52	-164.82
		$\delta^{18}O$/‰	-17.54	-16.62	-13.18	-15.48	-17.33	-17.88	-22.46
	δev	δ^2H/‰	-114.24	-117.01	-107.75	-123.44	-106.92	-96.39	-172.3
		$\delta^{18}O$/‰	-14.77	-16.35	-15.03	-16.7	-14.53	-12.78	-24.82
	δtr	δ^2H/‰	-24.12	-39.62	-35.97	-26.44	-35.85	-38.39	-40.53
		$\delta^{18}O$/‰	-5.34	-3.58	-4.13	-0.34	-2.35	-4.25	-1.97
	δadv	δ^2H/‰	-112.79	-115.67	-106.61	-122.19	-106.49	-95.7	-170.54
		$\delta^{18}O$/‰	-14.59	-16.15	-14.88	-16.54	-14.46	-12.69	-24.57
Ninchan	δpv	δ^2H/‰	-	-76.02	-139.21	-135.74	-129.96	-113.71	-184.93
		$\delta^{18}O$/‰	-	-11.89	-19.87	-18.7	-17.91	-16.77	-26.38
	δev	δ^2H/‰	-	-83.76	-81.42	-92.42	-110.24	-101.11	-123.42
		$\delta^{18}O$/‰	-	-12.01	-10.76	-12.09	-15.37	-13.49	-18.27
	δtr	δ^2H/‰	-	-25.58	-46.77	-37.77	-43.66	-	-
		$\delta^{18}O$/‰	-	-3.45	-1.98	-1.05	-6.68	-	-
	δadv	δ^2H/‰	-162.36	-113.49	-111.45	-106.16	-122.12	-114.67	-141.33
		$\delta^{18}O$/‰	-22.73	-15.94	-15.28	-14.46	-16.96	-16.58	-20.42
Suidao	δpv	δ^2H/‰	-167.86	-128.08	-124.95	-117.32	-137.73	-130.44	-155.52

	$\delta^{18}O$/‰	-22.9	-18.02	-17.28	-16.04	-19.09	-18.64	-21.59
δev	$\delta^{2}H$/‰	-164.16	-114.52	-112.37	-106.9	-122.96	-115.47	-142.85
	$\delta^{18}O$/‰	-22.98	-16.07	-15.41	-14.56	-17.08	-16.69	-20.64
δtr	$\delta^{2}H$/‰	-	-25.58	-46.77	-37.77	-43.66	-	-
	$\delta^{18}O$/‰	-	-8.45	-6.98	-6.05	-6.68	-	-
δadv	$\delta^{2}H$/‰	-162.38	-113.51	-111.47	-106.18	-122.14	-114.69	-141.36
	$\delta^{18}O$/‰	-22.73	-15.94	-15.28	-14.47	-16.97	-16.58	-20.42

In July, the ratio of vegetation transpiration to precipitation vapor is significantly higher compared to other months. The temperatures in the lower layers of the forest are relatively high, and the middle to upper layers are densely populated with spruce, resulting in a higher f_{tr} (transpiration ratio) throughout the entire growing season. Both the early and late stages of the growing season exhibit noticeably higher f_{ev} (evaporation ratio) compared to other months, with the middle and upper parts of the forest having a higher proportion of evaporated vapor. The average f_{adv} (advected vapor ratio) is 72%, with contributions exceeding 70% for all months except June and July (Figure 7).

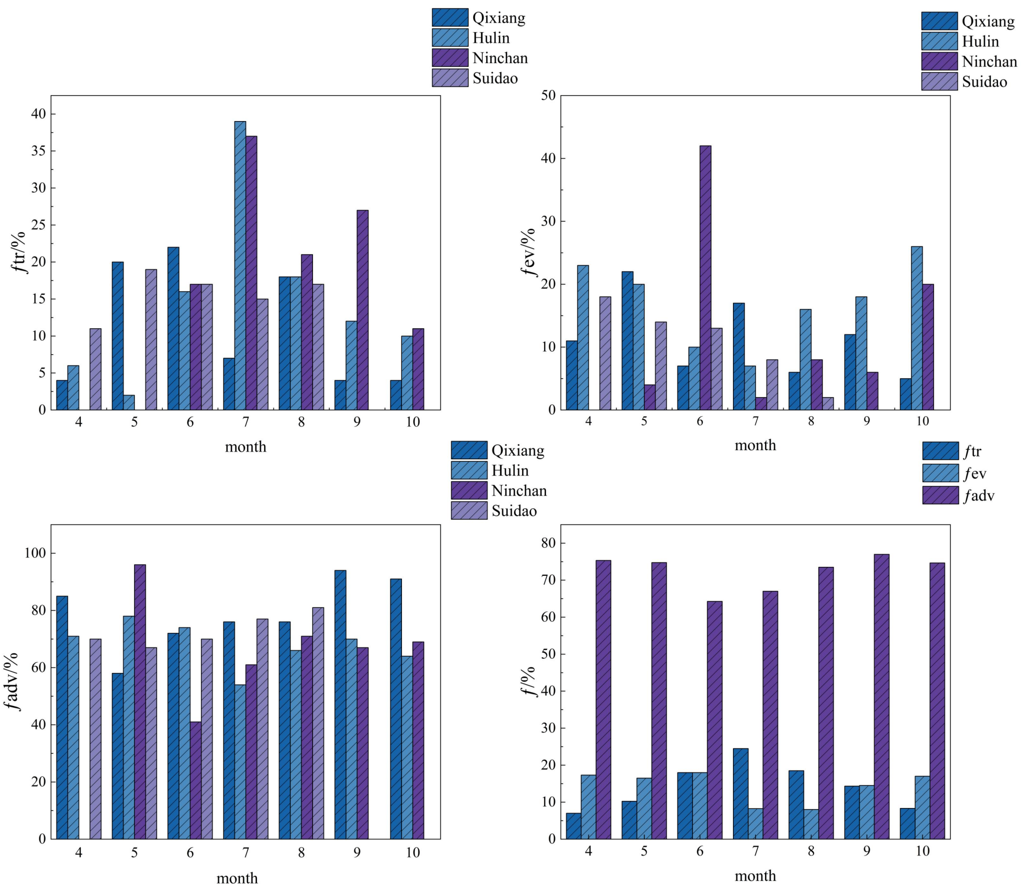


Figure 7 Comparison of f_{adv} (advective water vapour contribution), f_{ev} (surface evaporation water vapour contribution) and f_{tr} (plant transpiration water vapour contribution) for each of period

5.2 Uncertainty analysis

A higher sample size can reduce the margin of error. Therefore, we utilized isotopic data from four sites over a two-year period to evaluate the model. We used 404 xylem samples to calculate the contribution ratio of transpiration to ecosystem evapotranspiration. We examined the uncertainty of the model evaluation. When analyzing the evaporation characteristics in a semi-arid natural environment using the Craig-Gordon isotopic model, we first eliminated the influence of solar radiation and other meteorological variables on the calculation results. We focused on temperature, relative humidity, water vapor, and the initial isotopic values of water bodies. Particularly in semi-arid environments, the variations in temperature and relative humidity are crucial (Hernández-Pérez et al., 2020). To verify the calculation results, we found a strong correlation between the isotopes of soil evaporation and relative humidity, as demonstrated by the fitting of δ_E against relative humidity and temperature. This also indicates the reliability of the results obtained through the Craig-Gordon isotopic model. We employed the Keeling plot method to calculate δ_{ET}, which is based on isotopic mass balance and a two-endmember mixing model. This method assumes that the isotopic composition of the background atmosphere and source remains constant, with a very low probability of isotopic spatial variation (Good et al., 2012; Kool et al., 2014). Due to the higher reliability of oxygen isotopes compared to hydrogen isotopes (Han et al., 2022; Kale et al., 2022), we solely used oxygen isotopes to calculate the T/ET values. The results indicate that transpiration significantly outweighs evaporation during July and August, which aligns with previous research findings (Zhu et al., 2022). The correlation between T/ET and soil moisture content suggests that soil moisture is a crucial factor driving the variations in transpiration and evaporation ratios. Additionally, the estimation of isotopic composition of advected water vapor from the upwind sites contributes to increased uncertainty. In our study area, the sites are predominantly influenced by valley winds, with water vapor moving from the bottom of the valley to higher altitudes. Therefore, we selected lower elevation areas in the valley bottom as the source region for advected water vapor (Zhang et al., 2021).

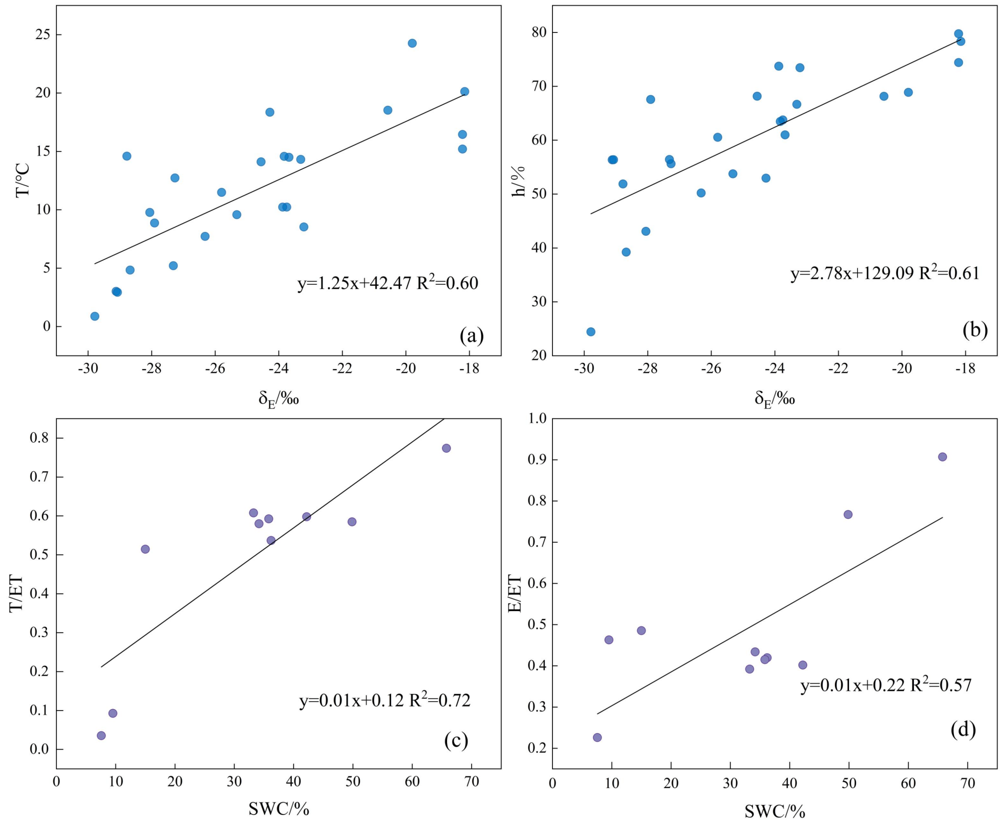


Figure 8 Correlation analysis of factors affecting uncertainty in impact assessment

6 Conclusions

This study utilizes isotopic data obtained from field observations during 2018-2019, combined with model simulations, to elucidate the mechanisms of evapotranspiration in the Qilian Mountains' spruce forests. The aim is to clarify the connection between evapotranspiration and local water cycling, as well as its hydrological effects. Isotopic methods were employed to assess T/ET (transpiration over evapotranspiration). The results indicate that July and August are the peak transpiration seasons for spruce, as they rely on favorable rainfall and thermal conditions. Both evaporation and transpiration are more intense during these months compared to other months, suggesting that transpiration by spruce trees is more significant than soil evaporation. Further quantification of the respective contributions of plant transpiration and soil evaporation to evapotranspiration reveals an average T/ET value of 0.57 during the study period, with a maximum value of 0.77 in July. Thus, it can be concluded that transpiration by forest trees constitutes the main component of evapotranspiration in the Qinghai spruce forest ecosystem. Analyzing the hydrological effects of spruce forest evapotranspiration, it is found that the evapotranspiration amount in each month is at least three times greater than the precipitation. Therefore, surface runoff formation in this area is challenging to rely on due to the significant influence of transpiration and evaporation. Comparing the contribution ratios of atmospheric water vapor from precipitation during spring, summer, and autumn, the results demonstrate that the period from June to August serves as the peak transpiration season for spruce forests, with plant transpiration accounting for as much as 25% of the total atmospheric water vapor, while surface evaporation contributes only 18%. In the context of global warming, drought and water scarcity, as well as climate changes dominated by relative humidity, have altered the ecological communities, ecosystem functions, ecosystem services, and land-climate interactions of spruce forests. Therefore, it is crucial to understand that the depletion of rainfall in this forest belt through evapotranspiration is vital for local water resource allocation and ecological conservation.

Acknowledgements

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author, stable isotope data are not publicly available due to privacy or ethical restrictions. Potential evapotranspiration and surface evapotranspiration data are available from the National Tibetan Plateau Scientific Data Centre(TPDC).

Competing Interests

We undersigned declare that this manuscript entitled "Hydrological effects of evapotranspiration in the Qilian Mountains forest belt" is original, has not been published before and is not currently being considered for publication elsewhere.

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.

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