Water Use Characteristics of the Common Tree Species in Rock-dominated and Thin-soil Environments in Subtropical Monsoon Climate Region

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Water use characteristics of the common tree species in rock-dominated and thin-soil environments in subtropical monsoon climate region

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Abstract

Variations in precipitation pattern under climate changes influence water availability that have important implications for plants water use and vegetation sustainability. However, the water use characteristic of the main tree species under different temporal-spatial of water availability remain poorly understood, especially in high temporal-spatial heterogeneity area, such as subtropical monsoon climate region of China. We investigated water use characteristics of the most widely and common natural trees, *Mallotus philippensis* and *Celtis biondii*, in edaphic and rocky habitats. We measured the δD and $\delta^{18}O$ values of xylem and soil water and water potential of plant leaves during the wet season in 2020. The results showed that the two species mainly absorbed soil water from shallow layers and switched for deeper layers during the late of the wet season in both habitats. But the plant water sources were different in edaphic and rocky habitats when the antecedent precipitation was much high, deep layers soil water in the former and still shallow layers in the latter. The two species had no significant differences in water uptake depth, but notably distinction in the diurnal water potential ranges. *M. philippensis* maintained less negative predawn and midday water potential, whereas *C. biondii* showed higher diurnal water potential ranges. Besides, the water potential of *C. biondii* were negatively associated with antecedent precipitation amount. These results indicate that there is significant eco-physiological niche segregation but no ecohydrological segregation co-existing species in communities. Besides, antecedent precipitation amount and habitat differences were the main factors influencing the plant water uptake depth. While the relationship between leaf physiological traits and water availability was affected by the species types, rather than the habitats. Furthermore, during the long drought in growing season, there are probable divergent responses of *M. philippensis* and *C.*

biondii, such as growth restriction and hydraulic failure. But when the precipitation is heavy and long, these natural species could increase the ecohydrological linkages between ecosystem and the deep-layer system in edaphic habitat.

Key words

Plant water source; Habitat; Stable isotope; Leaf water potential; Water use efficiency

1 Introduction

Increases in vegetation greenness have been reported around the world over the last three decades, manifested as the expanding of afforestation and reforestation (Forzieri et al., 2020; Piao et al., 2015; Zhu et al., 2016). While the forests maybe vulnerable to degradation due to global climate changes with new precipitation patterns (Aguirre et al., 2019; Gu et al., 2016; Malhi et al., 2008). Changes in characteristics of precipitation may result in changes in water availability that have implications for plants water use in ecosystem (Dietrich and Kahmen, 2019; Konapala et al., 2020). The variation of plants water use response to precipitation and water availability plays an important role in the sustainability of the restored vegetation and promotion of water cycle in critical zone (Anderegg et al., 2018; Chen et al., 2019; Macias, 2018).

The temporal-spatial heterogeneity of precipitation and water availability affect plant water use strategies (Liang et al., 2019; Zhao and Wang, 2018). At the point scale, the water source variability along soil profile is one of the most important factors for plants water uptake (Kuhnhammer et al., 2020). At the surface scale, the aquifer storage is distinct in different habitats, such as deep soil habitat (Wang et al., 2020a), outcrop habitat (Deng et al., 2020), soil with rock fragments habitat (Ceacero et al., 2020), which is related with the soil properties and plant water consuming. At different stages of the season, the plant water uptake depth maybe also divergent with the changes of rhizosphere water availability (Nie et al., 2012; Wang et al., 2020a). Some tree species may switch their water sources from shallow layers to stable layers from wet season with sufficient precipitation to dry season (Drake and Franks, 2003; Yang et al., 2015; Yang et al., 2017). Meanwhile, the amount of precipitation may be a critical factor affecting the water sources of trees. Liu et al. (2019b) found that following the rainfall events, *Platycladus orientalis* with dense and shallow fine root system absorbed more water from the soil surface layers and precipitation. While, other plants mostly take up water from deep and stable layers regardless of seasonal changes or precipitation events (Deng et al., 2020; Zunzunegui et al., 2018).

The divergent response of plant water uptake to the changes in precipitation and water availability was related with physiological characteristic. It has been suggested that the predawn and midday leaf water potential was used to describe the daily patterns of plant-water relations, coupling water among root zone, plant itself and atmosphere (Hochberg et al., 2018). Previous studies found that the plants relying on shallower water sources exhibited a larger diurnal range of leaf water potential, on the contrary, the narrower diurnal ranges usually linking with the deep and stable water sources (Ding et al., 2020; Eggemeyer et al., 2009; Liu et al., 2021). Moreover, the plant water efficiency (WUE_i) has been drawn attention to reflect plant water use characteristic together with plant water uptake (Craven et al., 2013; Hasselquist et al., 2010). Nie et al. (2014) explored the leaf WUE based on $\delta^{13}C$ values and found that the high WUE was corresponding with the deep water sources, indicating more conservative water-use strategies in subtropical monsoon climate region. Whereas, Wang et al. (2021) found that plantation trees increased water availability by increasing WUE_i instead of switching water sources responses to variations in precipitation on the Loess Plateau. The plant water uptake pattern was influenced by water availability and physiological traits in different ecosystems (Volkmann et al., 2016). However, the relationship between two factors affecting plant water uptake is unclear, especially in complex and fragile forest ecosystem, such as subtropical monsoon climate region, which limits the understanding of restored vegetation adaptability and rock-soil-water-plant-atmosphere interactions in critical zone.

Subtropical areas in China with a monsoon climate are ecologically sensitive areas of global change (Bruelheide and others 2014). At the same time, the subtropical monsoon climate region of China is suffering from rocky desertification. The ecological conservation projects facilitate to the subtropical monsoon climate region of tree cover in the globe now (Brandt et al., 2018; Delang and Zhen, 2015; Tong et al., 2020). The distribution of natural restored vegetation was fragmented with the heterogeneous habitats (Liu et al., 2019a). Plant water use strategies in different habitats is critical important for the evaluation of vegetation adaptation and the implementation of the next comprehensive treatment of rocky desertification. A number of previous studies were primarily focused on the water source of different types of plantation or natural vegetation in one certain habitat in the subtropical monsoon climate region (Deng et al., 2020; Ding et al., 2018). Few attached attentions to the common tree species in different habitats (Nie et al., 2012). Besides, rainwater and spring was treated as a potential water source for plants growing on outcrops assuming that they can use them stored in crevices/cracks directly (Nie et al., 2012). Actually, in most rocky habitat, there are lumps of relative thick soil surrounded by outcrops with substantial fine root where maybe the important water sources for tree species. However, previous studies failed to focus on the soil water availability for the plants due to the narrow distribution of soil than the continuous outcrops. With the global precipitation pattern changes, short-term drought or rainstorm was more frequent especially in the wet/growing season. However, it is unclear how the water uptake of common plants in the different habitats responds during the wet season with precipitation changes.

Based on the above analysis, we applied isotope techniques (δD, $\delta^{18}O$, and $\delta^{13}C$) and leaf water potential to determine the plant water use strategies of natural restoration in edaphic and rocky habitat with seasonal sampling during the growing season on the subtropical monsoon climate region of China. The primary objectives of the study were to (i) evaluate the water uptake pattern of species in two habitats for the temporal-spatial heterogeneity of water availability; (ii) investigate how the leaf water potential and water use efficiency of species responds to season variation with different precipitation; (iii) explore the relationship between plant physiological traits and water uptake pattern. The first hypothesis is that the plant water use pattern varies in the seasonal changes with different precipitation in two habitats, and the second is that the plant water uptake would coordinate with physiological characteristic of species, coupling with water availability.

2 Materials and methods

2.1 Study area and sampling sites characteristics

The study site is located in a small catchment (area = 1.14 km^2) in the Lutou Observation and Research Station for north Luoxiao national forest park (28°31′7″-28°38′N, 113°51′52″-113°58′24″E), which is situated in the northeast of Hunan Province, China. Along the part of the slope, the soil is mainly thin with a depth of 10-30 cm. At the foot of the slope and in the depression, the soil is relatively thick of 70-90 cm with amounts of rock fragments. The other part of the slope has a high exposed dolomite ratio, while the soil occurs discontinuous only in carbonate rock gaps. Thus, the habitats were variable with the different outcrop ratio, such as edaphic habitat with low outcrop ratio, continuous broken rock habitat with patches of soil, isolated outcrops habitat, and so on. Springs sometimes appear at the bottom of hillslopes during the rainy season or after rains in the drought season. The region has a subtropical mountainous monsoon climate, with mean annual precipitation of 1450.8 mm and an annual temperature of 18.5℃. The wet season lasts from late April to the end of September and provides >60% of total annual rainfall, while the dry season extends from December to February (Nie et al., 2012). The growing season spans from April to October.

The area was undergone dramatic deforestation caused by farming, grazing, and burning, then under natural restoration and reforestation for almost 21 years (Jiang et al., 2014; Moore et al., 2016; Zhang et al., 2016). The distribution of natural restored vegetation was fragmented with the heterogeneous habitats. The secondary forest is usually found on dolomite outcrops and soil habitat at the foot of the slope (Nie et al., 2012). Plant species growing on outcrops usually emerge from cracks or crevices, or grow on protuberant rocks with their roots ultimately penetrating into cracks. Tree species are usually random growth on soil habitat with the long laterally extend of taproot.

According to the distribution of these typical habitats, thick soil with rock fragments habitat (edaphic habitat for short) and one continuous stone outcrops with soil fragments (rocky habitat for short) were chosen at the foot of the Northwest-facing hillslope in two 20×20m sample plots (Fig. 1). The two habitats are 50 meters apart, while the elevation difference was about 5 meters. In the edaphic habitat, the soil is relatively thick (about 90cm deep), horizontally interrupted by smally outcrops, and vertically interrupted by small rocks. At the soil profile, the upper layer soil (0-30 cm) is well-drained, while the lower layers (30-70 cm) are sticky with a low soil saturated hydraulic conductivity (Ks) (Fu et al., 2015). Underneath the soil is a high-weathered dolomite bedrock zone (70-90cm). The outcrop ratio is about 20% in this habitat. This habitat is covered by dense vegetation, with *Mallotus philippensis*, *Rhus chinensis*, and *Celtis biondii* dominating the tree layer. *Vitex negundo* and *Pyracantha fortuneana* dominate the shrub layer. In the rocky habitat, the outcrop ratio is more than 80%, and the range of height from the top of the outcrop to the soil in the rock gaps is from 0.3m to 3m. The soil inlaid in the rock in a spotty pattern and is discontinuous (average 30cm deep). Similarly, high-weathered dolomite bedrock zone is under the soil. The vegetation is sparse in this habitat. The tree layer is dominated by *M. philippensis*, *Ficus tinctoria*, and *C. biondii*, and the shrub layer is dominated by *V. negundo*. There is a intermittent spring outflow near the two habitats at the bottom of the hillslope.

2.2 Plant and soil sampling

Plant and soil sampling were conducted simultaneously at the two habitats bimonthly on Jun 12 (middle wet season with high antecedent precipitation), August 5 (middle wet season with low antecedent precipitation) and October 18 (early dry season) 2020. Besides, we also sampled on May 18 in early wet season with 20-day drought. Two common species, adult *M. philippensis* (DBH of from 5 to 11cm) and *C. biondii* (DBH of from 6 to 12cm) at each of the habitats, were selected for the study. We selected four individuals per species for analysis. The leaf and plant xylem samples from every selected plant were collected in each habitat. every selected plant was collected in each stand-age tree per month. The fully sun-exposed, mature and healthy leaves in the upper canopy from each selected plant were collected in different directions on each sampling date. The leaves were mixed and packed into craft paper bags and brought them back to the laboratory for measuring the plant leaves $\delta^{13}C$. Shoots ranging from 0.3 to 0.5 cm in diameter and 3 to 5cm in length were collected at mid-day from stems more than 2 years old; the outer bark and phloem of the shoots were removed to obtain the xylem sample.

Soil samples were obtained in two habitats from six depth intervals (0-10, 10-20, 20-30, 30-50, 50-70, 70-90 cm) with an auger (sampling only at 70cm deep in the rocky habitat); and, five replicates were collected at each layer. Among them, the high-weathered bedrock samples were collected between 70-90cm in the edaphic habitat and 50-70cm in the rocky habitat. A subsample of the soil samples was stored at -20 °C for isotopic analysis, whereas the remainder of the samples were sealed for measurement of gravimetric soil water content, obtained by oven drying for one day. The volumetric water content (VWC) was converted according to gravimetric water content and bulk density of each layer.

2.3 Precipitation and spring sampling

Rainwater samples were routinely collected for each rain event above 5mm from May 2020 to December 2020. The isotopic values of precipitation were not collected from January to April due to the COVID-19 pandemic impacting. The collection equipment was designed based on the new device for monthly rainfall sampling for the Global Network of Isotopes in Precipitation (Agency, 2002). The rainwater samples were stored in cap vials, wrapped in parafilm and stored in a freezer until the analysis of stable isotopes. Temporal distribution of rainfall data and other meteorological data were collected at a meteorological station located in the middle of the same small catchment. Spring water discharged from June 1 to November 29, but cutoff between July 25 to August 29. The spring was sampled regularly during the outflow period. Both rainwater and spring water were stored in cap vials, wrapped in parafilm, and frozen until stable isotope analysis.

2.4 Isotopic analyses

The water was extracted from xylem and soil using automatic cryogenic vacuum distillation water extraction system (LI-2100, LICA, Beijing, China) (Ehleringer et al., 2000; Li et al., 2007). The δD and $\delta^{18}O$ in xylem and soil water samples were measured with liquid water isotope ratio infrared spectroscopy (IRIS, DLT- 100, Los Gatos Research, Mountain View, CA, USA) at the Key Laboratory for Agro-ecological Processes in Subtropical Region, Chinese Academy of Sciences. The $\delta^{13}C$ in the plant leaves were analyzed using an isotope ratio mass spectrometer (IRMS, MAT253, Thermo Fisher Scientific, Bremen, Germany).

The isotope composition is reported in δ notation relative to V-SMOW as

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

Where X represents D, ^{18}O, or ^{13}C. R_{sample} and $R_{standard}$ are the ratio D/H, $^{18}O/^{16}O$, or $^{13}C/^{12}C$ ratio of a measured sample and a standard sample, respectively. The standard deviation for repeat measurements was ±1‰ for δD, ±0.2‰ for $\delta^{18}O$ and ±0.15‰ for $\delta^{13}C$.

Extracting water from plant xylem using cryogenic vacuum distillation can mix organic materials (e.g., methanol and ethanol) that may affect the spectroscopy and lead to erroneous stable isotope values when analyzing with IRIS (Liu et al., 2013; Schultz et al., 2011). We have corrected the isotopic values of xylem according to Liu et al. (2021).

2.5 Leaf water potential

Predawn and midday water potentials (Ψ_{pd} and Ψ_{md}, respectively) of leaves were measured in the wet seasons (simultaneously with isotope sampling) with a pressure chamber (PMS Instruments Co., Corvallis, OR, USA). Samples (n= 5 per species) were collected from branches that were fully exposed to the sun, 2/3 of the way up of the canopy, at least 2 m above ground and for predawn water potential between 4:00 to 6:00 h and midday measurements were subsequently conducted between 12:00 and 14:00 h on the same day.

2.6 Data analysis

Soil water is the primary vegetation water source on the subtropical monsoon climate region, and spring as the potential deep water sources. Plant water source partitioning was determined by the Bayesian mixing model MixSIAR (version 3.1.7) (Stock and Semmens, 2013). The raw isotopic ratios of the xylem water were input into MixSIAR as the mixture data. The averages and standard deviations of the soil water isotopes in the different soil layers were the source data. The discrimination was set to zero for both δD and $\delta^{18}O$ because there is generally no isotopic discrimination of water during plant water uptake by roots (Ehleringer and Dawson, 2010).

For the subsequent analysis and comparison, the plant water sources were divided into shallow (0-30 cm), middle (30-70 cm in the edaphic habitat and 30-50 cm in the rocky habitat), deep (70-90 cm in the edaphic habitat and 50-70 cm in the rocky habitat) layers and spring according to the soil texture and fluctuations and patterns of isotopic ratios in the soil water, VWC and the impact of rainfall pulse. (1) shallow soil layer: The variability of soil water isotopic compositions and VWC in this layer were larger, and was vulnerable to rainfall pulse and evaporation with seasons. (2) middle soil layer: The variability of soil water isotopic compositions and SWC in this layer were lower than that of 0-30 cm soil layer. The impact of rainfall pulse and evaporation were moderate. Both the clay content and soil bulk density were higher than the shallow layers. (3) deep soil layer: This layer was high-weathered bedrock with high leakage and low water holding capacity in the rocky habitat and high water moisture in the edaphic habitat, respectively.

Independent-samples T test and One-way ANOVA were used to detect the differences in plant water sources and water potential among the species, habitats and their seasonal differences. Post hoc comparisons were based on Tukey's HSD. Moreover, Pearson correlation was used to conduct the correlation analysis, and the figures were plotted with Origin software version 9.0.

3 Results

3.1 Meteorological factors and isotopic compositions of precipitation

The total precipitation was approximately 2121 mm in 2020 (Fig. 1), 52.69% higher than the multiyear mean (1961- 2017) precipitation (1450.8 mm) (Ding et al., 2020). While the distribution of rainfall was temporally uneven (Fig. 1), 79.32% of the rainfall occurred during the wet season. It was noted that there are two extreme precipitation events in Sep. 7 (282.2mm) and Jun. 7 (115.2mm). On the other hand, no effective rainfall records were collected in the 20 days from Apr. to May in the wet season. The first sampling took place after the 20-day drought. The other three samplings were conducted in the sunny day after 1-2 days of rainfalls. The accumulated precipitation amount ten days before the last three samplings were 283.6mm, 49.4mm, and 55.4mm, respectively.

The isotopic compositions of the precipitation showed a large fluctuation during the study period (Fig. 1). The mean δ D of the precipitation was -48.69 ‰, the mean $\delta^{18}O$ of the precipitation -7.88 ‰. The relatively depleted isotopic values of precipitation occurred when it rains continuously for a long time with high precipitation. The δD of ten days precipitation before three samplings in middle and late wet season were ranging from -23.55 to -57.52 ‰, -34.54 to -68.36 ‰, -40.76 to -51.02 ‰, respectively. The $\delta^{18}O$ of precipitation before three samplings were ranging from-5.27 ‰ to-8.15 ‰, -7.68 ‰ to-9.65 ‰, -6.54 ‰ to-7.4 ‰, respectively.

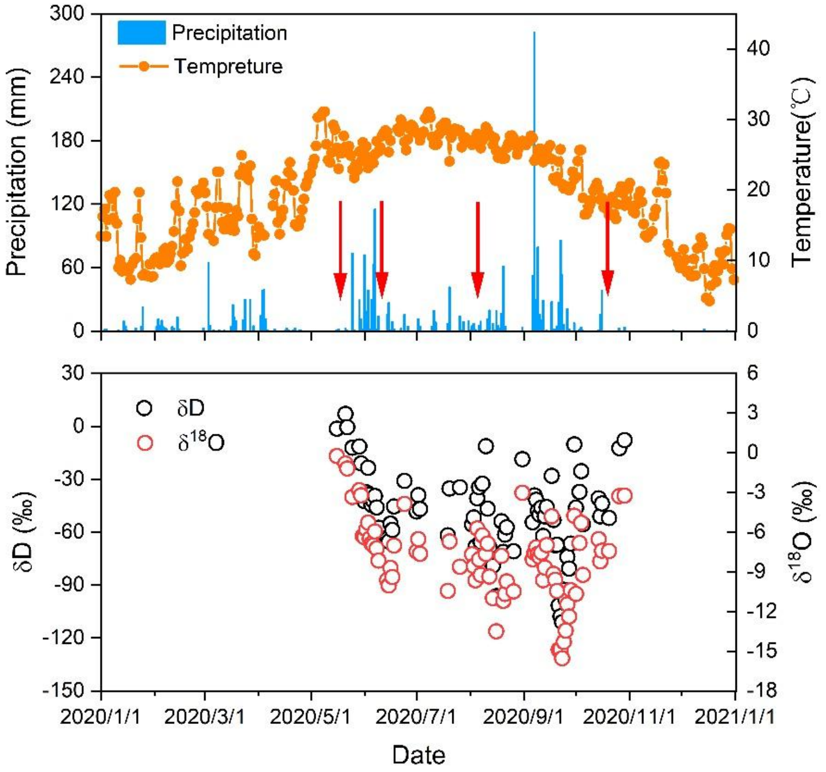

Fig. 1 Variations in precipitation, mean air temperature, and isotopic values (δD, δ^{18}O) in precipitation at a daily timescale in 2020. Arrows indicate sampling dates. (The isotopic values of precipitation were not collected from Jan. to Apr. due to the COVID-19 pandemic impacting.)

3.2 Variation in isotopic composition of soil water and spring

The δD and δ^{18}O values of soil water in the different habitat varied with soil depth and season (Fig. 2, Fig. 3). In edaphic habitat, the average δD value of soil water was -45.56 ± 16.05 ‰ (mean ± S.D.), and average δ^{18}O value was -6.55 ± 1.73 ‰. The average δD and δ^{18}O values of soil water in rocky habitat were −44.6 ± 16.58 ‰ and −6.7 ± 1.96 ‰, respectively. There were no significant differences ($p=0.84$ for δD, $p= 0.79$ for δ^{18}O) in the soil isotopic compositions in the different habitats. In the early wet season with 20-day drought, the soil water isotopes displayed depleted with soil depth (Fig. 2a, Fig. 3a). In the middle wet season with high precipitation before sampling, δD and δ^{18}O values of water at soil profile were consistent with recent rainfall values (Fig. 2b, Fig. 3b). In late two sampling, the soil water isotope composition converged at the top and bottom layers, which were similar to recent rainfall values (Fig. 2c, d). While the middle layer soil water showed more enriched isotopic values in the middle wet season or depleted in the late wet season and less variation with soil depth. The isotopic composition of spring changed across the sampling time. The isotopic values were less negative in the middle wet season than those in the late wet season.

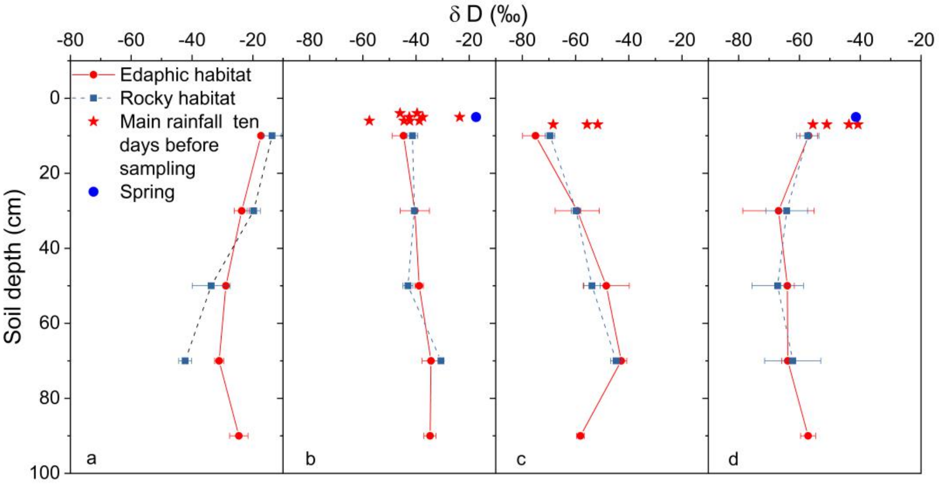

Fig. 2 Variation in mean (±S.D.) δD along the soil profile during the wet season (a, May sampling; b, Jun. sampling; c. Aug. sampling; d, Oct. sampling)

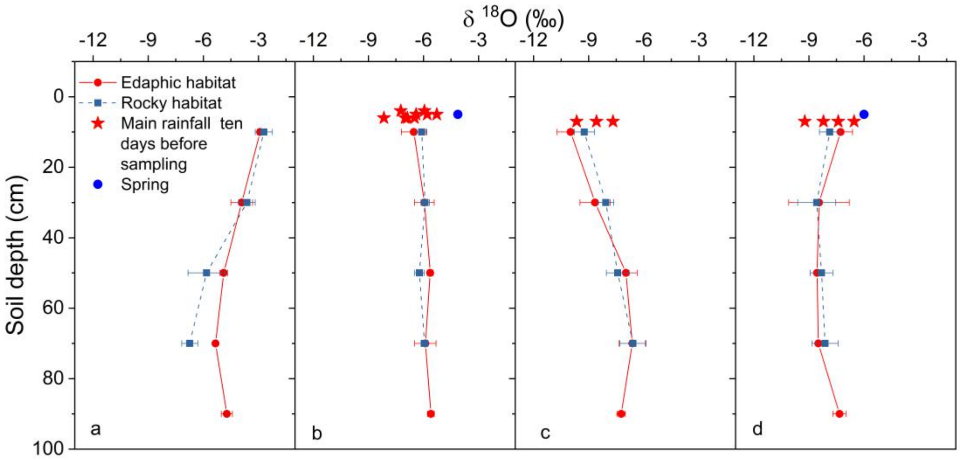

Fig. 3 Variation in mean (±S.D.) δ^{18}O along the soil profile during the wet season. (a, May sampling; b, Jun. sampling; c. Aug. sampling; d, Oct. sampling)

3.3. Variations in soil water content and water uptake patterns

The VWCs of the two habitats displayed clear vertical and seasonal variations (Fig. 4). The average VWCs were 43.42 ± 7.68% in edaphic habitat and 38.24 ± 8.42% in rocky habitat during the study periods. The VWCs of shallow soil layers in the two habitats differed significantly ($p<0.001$). However, the middle and deep soil moisture showed no significant differences in the two habitats. In the early wet season with 20-day drought, the VWC of the shallow layer was lowest in the two habitats and the soil moisture increased with depth (Fig. 4a). In the middle and late wet season, the VWC exhibited slightly increasing tendency along the soil profile in the edaphic habitat but decreasing tendency in the rocky habitat. Among them, the soil moisture in edaphic habitat had the highest values in middle wet season (Fig. 4c).

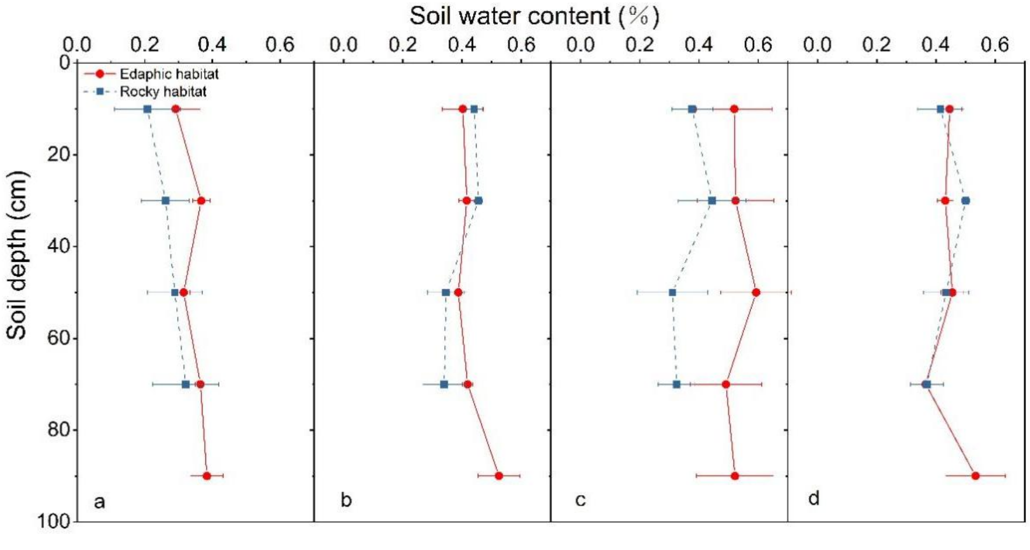

Fig. 4 Variation in mean (±S.D.) soil water content along the soil profile during the wet season. (a, May sampling; b, Jun. sampling; c. Aug. sampling; d, Oct. sampling)

The two tree species mainly took up soil moisture throughout the wet season in two habitats (Fig. 5). While the plants used different layers soil water in seasonal variation with no significant species differences (p>0.05). In the early wet season with 20-day drought and middle wet season with low precipitation before sampling, both *M. philippensis* and *C. biondii* in two habitats utilized the largest proportion of shallow soil water (64.97%, 0-30cm). In the middle wet season with high precipitation before sampling, two species in rocky habitat also absorbed more than 67.14% of its water from shallow soil layers. While the mean water uptake fractions of the two tree species in edaphic habitat were 64.45% for middle and deep soil layers (50-90cm,). In the late wet season, the *M. philippensis* and *C. biondii* in edaphic habitat obtained more than 74.82% of its water from the shallow and deep soil layers. While in rocky habitat, the two species mainly extracted soil water from shallow and middle layers (82.13%).

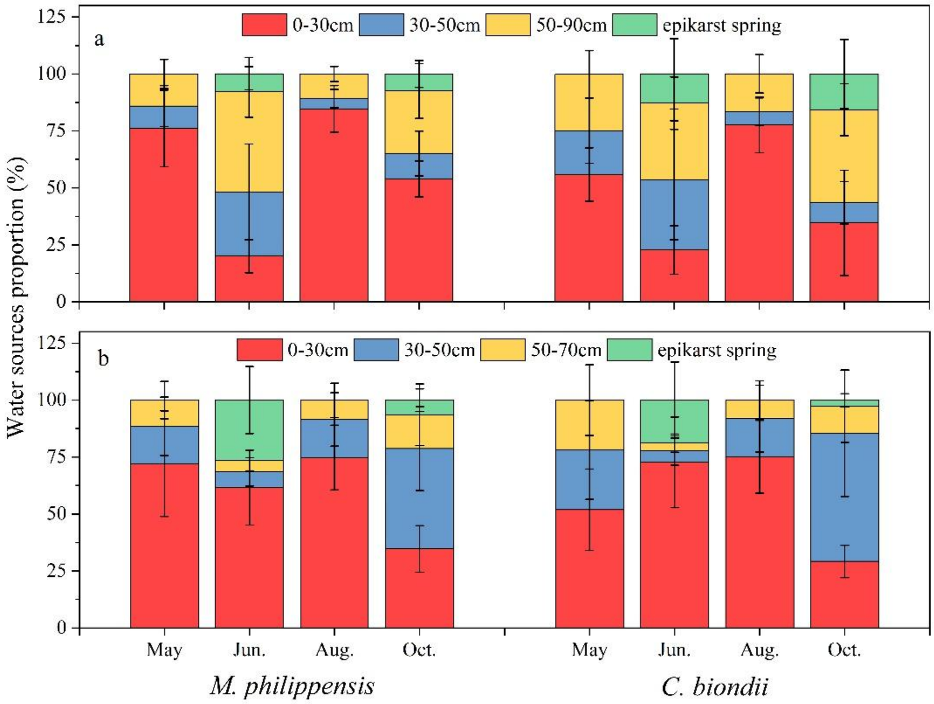

Fig. 5 Variation in mean (±S.D.) water source proportion for *M. philippensis* and *C. biondii* during the wet season. (a, Edaphic habitat; b, Rocky habitat)

3.4. Variations in water potential of plant leaves and its linkage water uptake depth

The ψ_{pd} and ψ_{md} of the two species exhibited profoundly seasonal variation during the sampling period ($p<0.01$), which were less negative in the middle wet season than those in the early and late wet season (Table 1). *C. biondii* had significant variation of leaf water potential in two habitats in the sampling period ($p<0.05$), but the leaf water potential of *M. philippensis* only showed significant different between two habitats in the early and late wet season ($p<0.05$). In addition, in the edaphic habitat, both values of ψ_{pd} and ψ_{md} for *M. philippensis* were significant different from *C. biondii* ($p<0.05$) in the early and late wet season. In the rocky habitat, the variation in ψ_{md} for *C. biondii* (-1.51±0.49MPa) showed significantly lower than *M. philippensis* (-0.52±0.26MPa) in the rocky habitat in the sampling period, while the ψ_{pd} for the two species had no significant variation ($p>0.05$).

Table 1 Comparisons of predawn water potential (ψ_{pd}) and midday water potential (ψ_{md}) (± SD) for *M. philippensis* and *C. biondii* between edaphic and rocky habitats

		Edaphic habitat (-MPa)		Rocky habitat (-MPa)	
		M. philippensis	*C. biondii*	*M. philippensis*	*C. biondii*
May	ψ_{pd}	-0.74±0.05Ba	-0.46±0.05Bb	-0.51±0.09Aa	-0.30±0.05Aa
	ψ_{md}	-1.29±0.14Ba	-2.47±0.19Bb	-0.93±0.05Aa	-2.04±0.15Ab
Jun.	ψ_{pd}	-0.23±0.05Aa	-0.24±0.02Aa	-0.20±0.05Aa	-0.26±0.02Aa
	ψ_{md}	-0.57±0.17Aa	-0.50±0.18Ba	-0.49±0.13Aa	-0.96±0.02Ab
Aug.	ψ_{pd}	-0.17±0.04Aa	-0.15±0.02Aa	-0.20±0.06Aa	-0.27±0.05Aa
	ψ_{md}	-0.29±0.08Aa	-1.53±0.06Bb	-0.21±0.02Aa	-1.07±0.55Ab
Oct.	ψ_{pd}	-0.39±0.11Aa	-0.74±0.31Bb	-0.31±0.1Aa	-0.44±0.08Aa
	ψ_{md}	-1.12±0.15Ba	-1.77±0.34Ab	-0.45±0.14Aa	-1.97±0.52Ab

Note: Capital letters within a column indicate significant differences of the same tree species between edaphic and rocky habitats at the 0.05 level; lowercase letters indicate significant differences between *M. philippensis* and *C. biondii* in the same habitat at the 0.05 level.

The diurnal ranges of water potential ($\Delta\psi$) exhibited significant variation in different species with seasonal changes ($p<0.01$). *M. philippensis* showed significant lower $\Delta\psi$ than *C. biondii* ($p<0.001$). The $\Delta\psi_{max}$ was in the early wet season for *C. biondii* (-1.84±0.19MPa) and in the late wet season for *M. philippensis* (-0.45±0.34MPa). And both two tree species displayed the minimum $\Delta\psi$ (-0.48±0.11MPa and 0.09±0.06MPa, respectively) in the middle wet season. Both two species had significant higher diurnal ranges of water potential in edaphic habitat than those in rocky habitat ($p<0.001$) during the sampling period, except for *C. biondii* in the middle wet season with low precipitation and late wet season. Furthermore, it was not significant correlation between the $\Delta\psi$ and water uptake depth for *M. philippensis* and *C. biondii* in two habitats.

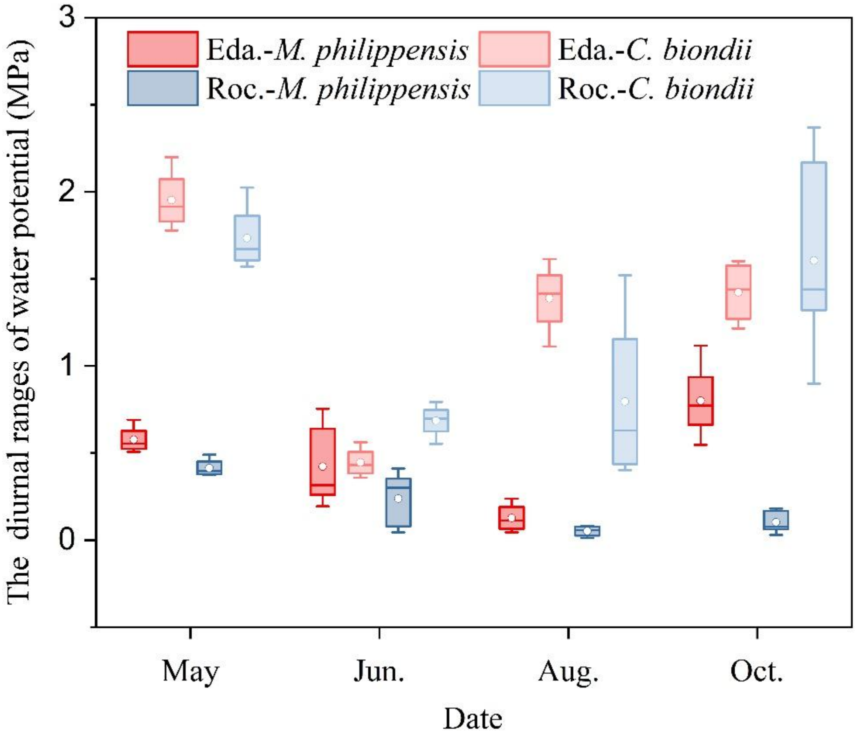

Fig. 6 Variation in mean (±S.D.) diurnal ranges of water potential for *M. philippensis* and *C. biondii* during the wet season.

3.5 Changes in plant uptake depth in response to precipitation amount in two habitats

The response of plant water source proportion in each soil layers to precipitation amount ten days before sampling were distinct in two habitats (Fig. 7). In the edaphic habitat, tree species absorbed less water from shallow layers and more deep soil water with the precipitation increases (Fig. 7a, c). While the trees maintained high water uptake from shallow layers in the rocky habitat whatever precipitation variations (Fig. 7d). Meanwhile, there were significant negative linear relationships between the water source proportion of middle and deep soil layers and precipitation (Fig. 7e, f).

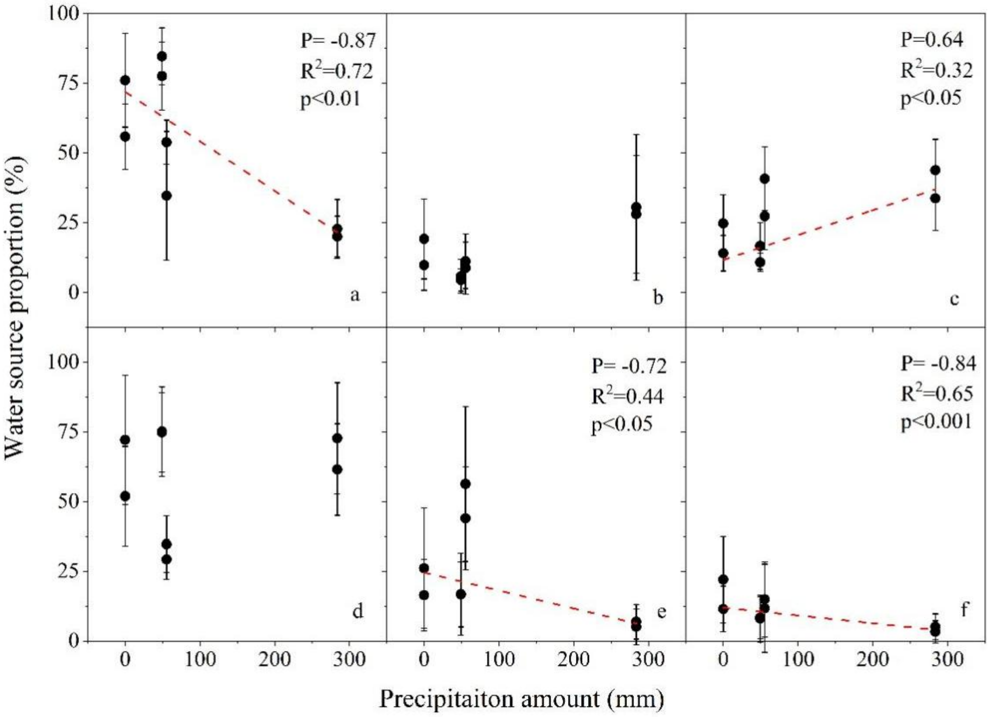

Fig. 7 Relationships between water source proportion for each soil layers (mean ±S.D.) and precipitation amount ten days before sampling. P is Pearson correlation, R^2 represents fitting degree of the relationship between water source proportion and precipitation amount; p is p-value of the fitting (a, b, c, plant water sources from shallow, middle, deep layers in edaphic habitat, respectively; d, e, f, plant water sources from

shallow, middle, deep layers in rocky habitat, respectively)

3.6 Contrasting leaf water potential responses to precipitation amount between two species

The response of the diurnal ranges of water potential to precipitation amount ten days before sampling were different in two tree species (Fig. 8). The $\Delta\psi$ of *M. philippensis* did not increase from no rain to high rainfall with relatively low values in two habitats. However, the diurnal ranges of water potential for *C. biondii* showed lower values with the precipitation increases in the edaphic and rocky habitat.

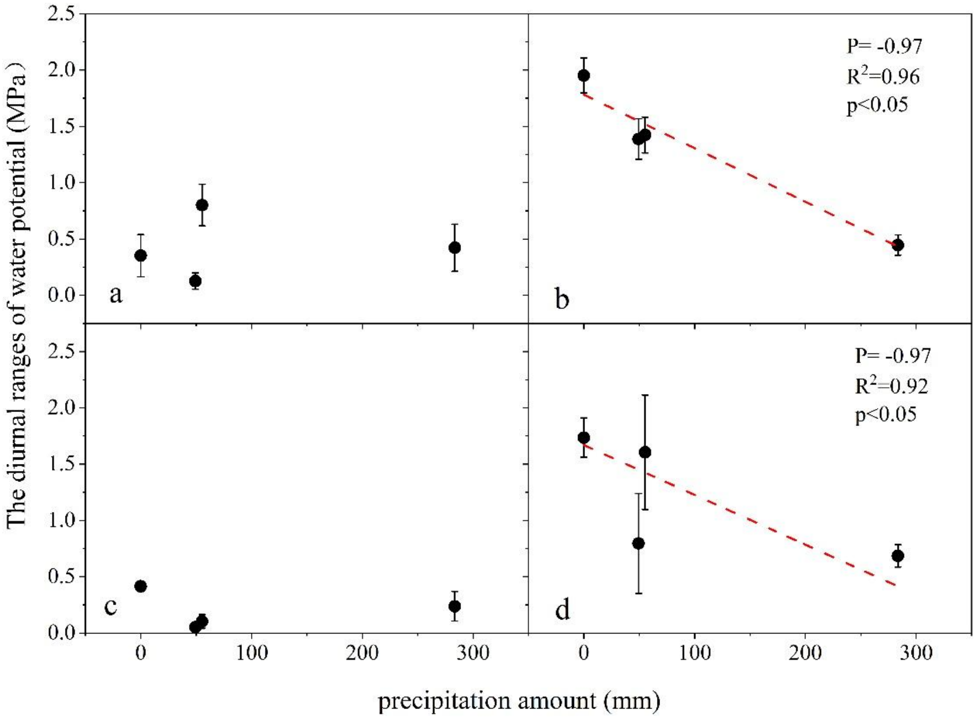

Fig. 8 **Relationships between the diurnal ranges of water potential (mean ±S.D.) and precipitation amount ten days before sampling. P is Pearson correlation, R^2 represents fitting degree of the relationship between the diurnal ranges of water potential and precipitation amount; p is p-value of the fitting (a, *M. philippensis* in edaphic habitat; b, *C. biondii* in edaphic habitat; c, *M. philippensis* in rocky habitat; b, *C. biondii* in rocky habitat)**

4 Discussion

4.1 Water uptake of tree species in two habitats

The variation of plant water uptake depth in two habitats was consistent, except the Jun. sampling with high antecedent precipitation. These two natural species, growing at the foot of the slope, mainly absorbed soil water from shallow layers in the early and middle wet season, and switched for deeper layers in the late wet season. This water use pattern has also been found in other natural species and plantations in the similar study area (Deng et al., 2020; Liu et al., 2021). But it was noted that the plants utilized shallow soil water rather than deep or water (no spring flowing) in the early wet season with 20-day drought, which was inconsistent with other studies in climate region (Deng et al., 2020; Liu et al., 2019b). For one thing, although the mean soil moisture was lower compared to other sampling, the VWC is still higher than that in semiarid climate region in the wet season (Tokumoto et al., 2014; Wang et al., 2020a). Meanwhile, with relatively lower wilting coefficient and high spatial heterogeneity (Fu et al., 2016), the shallow layers could also provide enough available water for plants. For another, this water use characteristics is adaptation for plants to save more energy for growth in the early wet season. Both *M. philippensis* and *C. biondii* grow quickly with high energy consuming in May as well as the early growing season. Although the deep soil layer has higher VWC, the energy required to take up water from the deep layer is greater than that of the upper layers (Liu et al., 2020a; Williams and Ehleringer, 2000). Thus, the trees extracted shallow soil water to relieve excessive energy consumption through physiological adjustments (Li et al., 2021; Moreno-Gutiérrez et al., 2012; Renninger et al., 2014). Previous studies showed that the plant species adjusted their hydraulic strategies, such as diurnal ranges of water potential, water use efficiency, in response of the environment changes (Hochberg et al., 2018; Liu et al., 2012; Nie et al., 2019a). In our study, *M. philippensis* and *C. biondii* exhibited the highest diurnal ranges of leaf water potential and leaf $\delta^{13}C$ in the early wet season with 20-day droughts, indicating that they tried their best to absorbed enough shallow soil water to balance carbon-water relations in tandem with high leaf-level intrinsic water use efficiency (WUEi) (Table S2). In the middle and late wet season, plants water uptake depth was from shallow to deeper layers. Soil water available may be the mainly reasons for the water use pattern (Gaines et al., 2016; Zhan et al., 2019).

When the antecedent precipitation was much high in the middle wet season, the plants still absorbed water from shallow layers in rocky habitat, but in edaphic habitat, they switched to deep layers soil water. These results suggested that the response of plant water source proportion in each soil layers to antecedent precipitation amount were distinct in two habitats. Water availability is the most important factor influencing the plants water uptake depth (Ding et al., 2020; Sanchez-Costa et al., 2015). Soil variabilities such as soil texture, bulk density, affected water holding capacity and migration along with soil profiles, and then regulated plant water use (Liu et al., 2021; Yang et al., 2019). The bulk density in the rocky habitat is lower than that in edaphic habitat, promoting the high water holding capacity. While in the thin deep layers with large cracks and crevices in the rocky habitat, moisture leaks into the layer flowing through the spring. The thick deep layer with fine cracks in the edaphic habitat, the storage water was higher than shallow layer after large and continuous precipitation. Therefore, the soil properties discrepancies are the main reasons for the different soil water available along the profile in two habitats. In addition, plant attributes also play critical role in affecting plant water use pattern in community scale. Many researchers found that the plants species in a certain community had overlapping water sources and enhanced water competition (Magh et al., 2020; Querejeta et al., 2007; Wolf et al., 2016). In edaphic habitat, the plant water competition will aggravate especially for the shallow water sources. Because the biodiversity and abundance will increase after high and continuous precipitation in the middle wet season, exhibiting the herbaceous and undershrub growing crazy and absorbing for shallow soil water (Jiang et al., 2020; Moran et al., 2009). Hence, the tree species would switch to the deep and stable water sources to reduce the competition and risky and maintain high transpiration demand. While in the rocky habitats with low biodiversity and abundance for herbaceous (Nie et al., 2019b), the shallow layers water was enough for their transpiration. Furthermore, the low diurnal ranges of water potential of *M. philippensis* and *C. biondii* also demonstrated that they were both in sufficient water supply in the two habitats (Fig. 6).

4.2 Water use characteristics and physiological changes in the different tree species

The two coexisting plants either in the edaphic or rocky habitat exhibited no significant differences in water uptake pattern with seasonal changes, indicating that they had the same eco-hydrological niche and no water source segregation. This result was inconsistent with a previous study in the similar study area, which found that the tree and shrub had different water use sources in the dry season (Nie et al., 2012). But other studies showed that the coexisting species usually had water competition in mixed stand in non-karst regions (Liu et al., 2020b; Magh et al., 2020). Nie et al. (2018) investigated three communities on adjacent rocky karst hill slopes, and found that different species within each community all exhibited a similar water source. Du et al. (2021) studied three karstic climax forest communities of a typical karst hill, also came to the same results. The similar root distribution of *M. philippensis* and *C. biondii* maybe the main reason for the same water uptake pattern (Ellsworth and Sternberg, 2015; Schwinning, 2010). Hence, the interspecific different in community was relatively low in subtropical monsoon climate region. However, as the above analysis, the water use pattern was different between the edaphic and rocky habitats for the same species. This suggested that the habitats may cause more influence for plant water use than the interspecific difference in community, especially when the antecedent precipitation was high.

Although the water uptake depth was similar for the two species, the two species had different physiological response to the water uptake. In our study, *M. philippensis* maintain the little diurnal ranges of water potential, high leaf $\delta^{13}C$ values, and much branching from the base of the trunk, while *C. biondii* had the inverse characteristics. Meanwhile, the $\Delta\psi$ of *C. biondii* under two habitats were negatively associated with antecedent precipitation amount, but the significant relationship was not observed in *M. philippensis*. Wang et al. (2020a) also found the same results of two species in the mixed plantation in the Loess Plateau. While Moreno-Gutiérrez et al. (2012) found the existence of species-specific eco-physiological niche segregation in dryland plant communities. A possible explanation was that the interspecific competition in the same habitat makes each tree species establish different hydrological niches for water uptake (González de Andrés et al., 2018; Williams and Ehleringer, 2000). However, in our study, there are significant eco-physiological niche segregation but no ecohydrological segregation for two species in the same habitat. This discrepancy may be attributed to sufficient precipitation and soil water availability for ecohydrological non-segregation (Asbjornsen et al., 2011) and interspecific different for eco-physiological segregation (Sánchez-Costa et al., 2015).

4.3 Implications for plant water adaptation under precipitation changes

With the increasing temperatures, precipitation patterns change seasonally and become more variable (Konapala et al., 2020), which could lead to the increase in either the severity of drought or extreme precipitation, especially in the growing season (Allen et al., 2010; Fan and Thomas, 2013; Messmer and Simmonds, 2021). When the drought or extreme precipitation occurs, soil water availability may influence the plants water use strategies.

In our study, plants absorbed shallow layers soil water by increasing the diurnal ranges of water potential for relieving the energy consumption to supply leaf rapid growth in the early wet season with 20-day drought. The tree species seek for the balance of water uptake and growth through the relatively high water use efficiency (Keep et al., 2021). However, if the drought is prolonged, soil moisture declines and fails to supply water for plants. Ding et al. (2020) conducted a 135-day rainfall exclusion experiment in the same catchment, and found two adverse responses along with different physiological characteristic to the severe water limitation: canopy defoliation and/or mortality and survive. In our study, *C. biondii*, as the profligate water use species, will exhibited larger $\Delta\psi$ and lower ψ_{md} for absorbing water sources (Ding et al., 2020). Once the ψ_{md} is lower than the hydraulic trait values, the species may suffer from hydraulic risky for xylem-cavitation and leaf turgor loss (Choat et al., 2012; Magh et al., 2020). On the contrary, *M. philippensis* displayed stable $\Delta\psi$ in the sampling period, indicating the rigorous stomatal control (Renninger et al., 2015). The tree growth rate of *M. philippensis* may slow due to the reduction in shallow soil water sources and the stoma close advanced.

Except for the drought in growing season, the frequency of rainstorm and extreme precipitation also has been increasing recently (Berg et al., 2013; Min et al., 2011). The heavy rainfall with long period caused the surface and subsurface runoff along the slope (Wang et al., 2020b) and flood in the depression in subtropical region (Chen et al., 2017). Plants are the main conduit for returning terrestrial water to the atmosphere, thereby exerting a strong effect on hydrologic fluxes of the terrestrial-atmospheric system (Asbjornsen et al., 2011). Hence, the vegetation ecohydrological functions and physiological responses raised more and more concerned in the extreme climate (Geekiyanage et al., 2019). In our study, the plants mainly utilized for deep layer soil water in the edaphic habitat and the diurnal ranges of water potential of *C. biondii* were shrunken when the precipitation was extreme high before ten days sampling. These results illustrated that the tree species could adjust their water use strategies and increase the ecohydrological linkages between ecosystem and the deep-layer system (Du et al., 2021).

5 Conclusions

In this study, stable isotope technique and pressure chamber were applied to detect the seasonal water use characteristic of two common tree species in edaphic and rocky habitats on the subtropical monsoon climate region. The results showed that the two species mainly absorbed soil water from shallow layers and switched for deeper layers during the late of the wet season in both habitats. But the plant water sources were different in edaphic and rocky habitats when the antecedent precipitation was much high, deep layers soil water in the former and still shallow layers in the latter. The two species had no significant differences in water uptake depth, but notably distinction in the diurnal water potential ranges in the same habitat. These results indicate that there is significant eco-physiological niche segregation but no ecohydrological segregation for co-existing species in communities. Besides, antecedent precipitation amount and habitat differences were the main factors influencing the plant water uptake depth. While the relationship between leaf physiological traits and water availability was affected by the species types, rather than the habitats. Thus, during the long drought in growing season, there are probable divergent responses of *M. philippensis* and *C. biondii*, such as growth restriction and hydraulic failure. But when the precipitation is heavy and long, these natural species could increase the ecohydrological linkages between ecosystem and the deep-layer system in edaphic habitat.

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Declarations of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Water use characteristics of the common tree species in rock-dominated and thin-soil environments in subtropical monsoon climate region”.

Supplementary Material

Table S1 Relationship between water uptake depth and the diurnal ranges of water potential for *M. philippensis* and *C. biondii* in edaphic and rocky habitats.

Pearson Correlation	Edaphic habitat (-MPa)		Rocky habitat (-MPa)	
	M. philippensis	*C. biondii*	*M. philippensis*	*C. biondii*
Shallow layer	-0.41, p>0.05	0.77, p>0.05	0.328, p>0.05	-0.825, p>0.05
Middle layer	0.152, p>0.05	-0.837, p>0.05	-0.411, p>0.05	-0.78, p>0.05
Deep layer	0.441, p>0.05	-0.562, p>0.05	-0.064, p>0.05	-0.886, p>0.05

Table S2 Comparisons of δ^{13}C isotopic values for *M. philippensis* and *C. biondii* in edaphic and rocky habitats.

Pearson Correlation	Edaphic habitat (-MPa)		Rocky habitat (-MPa)	
	M. philippensis	*C. biondii*	*M. philippensis*	*C. biondii*
May	-25.78±0.85Aa	-26.67±0.73Aa	-25.66±0.57Aa	-26.93±0.05Aa
Jun.	-27.07±0.41Ba	-27.75±0.85Ba	-27.95±1.26Ba	-28.31±0.18Aa
Aug.	-27.65±0.69Ba	-28.8±0.42Ba	-27.43±0.18Ba	-29.51±0.27Bb
Oct.	-27.22±0.47Ba	-28.23±0.18Bb	-27.86±0.64Ba	-28.86±0.25Ba

Note: Capital letters within a column indicate significant differences of the same tree species among different seasons at the 0.05 level; lowercase letters indicate significant differences between *M. philippensis* and *C. biondii* in the same habitat at the 0.05 level.

References

Agency, I.A.E., 2002. A new device for monthly rainfall sampling for GNIP. Water and Environment News, 16: 5.

Aguirre, G.J. et al., 2019. Drier tropical forests are susceptible to functional changes in response to a long-term drought. Ecol Lett, 22: 855-865.

Allen, C.D. et al., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecol Manag, 259(4): 660-684.

Anderegg, W.R.L. et al., 2018. Hydraulic diversity of forests regulates ecosystem resilience during drought. Nature, 561(7724): 538-541.

Asbjornsen, H. et al., 2011. Ecohydrological advances and applications in plant–water relations research: a review. J Plant Ecol, 4(1-2): 3-22.

Berg, P., Moseley, C. and Haerter, J.O., 2013. Strong increase in convective precipitation in response to higher temperatures. Nat Geosci, 6(3): 181-185.

Brandt, M. et al., 2018. Satellite-Observed Major Greening and Biomass Increase in South China Karst During Recent Decade. Earth's Future, 6(7): 1017-1028.

Bruelheide H, Nadrowski K, Assmann T, Bauhus J, Both S, Buscot F, Chen XY, Ding BY, Durka W, Erfmeier A et al. 2014. Designing forest biodiversity experiments: general considerations illustrated by a new large experiment in subtropical china. Meth Ecol Evol 5:74–89.

Ceacero, C.J., Díaz-Hernández, J.L., Campo, A.D. and Navarro-Cerrillo, R.M., 2020. Soil rock fragment is stronger driver of spatio-temporal soil water dynamics and efficiency of water use than cultural management in holm oak plantations. Soil Till Res, 197.

Chen, C. et al., 2019. China and India lead in greening of the world through land-use management. Nat Sustain, 2: 122-129.

Chen, H.S., Hu, K., Nie, Y.P. and Wang, K.L., 2017. Analysis of soil water movement inside a footslope and a depression in a karst catchment, Southwest China. Sci Rep-UK, 7(1): 2544.

Choat, B. et al., 2012. Global convergence in the vulnerability of forests to drought. Nature, 491(7426): 752-756.

Craven, D., Hall, J.S., Ashton, M.S. and Berlyn, G.P., 2013. Water-use efficiency and whole-plant performance of nine tropical tree species at two sites with contrasting water availability in Panama. Trees, 27(3): 639-653.

Delang, C.O. and Zhen, Y., 2015. China’ s Grain for Green Program. Cham, Springer International.

Deng, Y. et al., 2020. Responses of plant water uptake to groundwater depth in limestone outcrops. J Hydrol, 590: 125377.

Dietrich, L. and Kahmen, A., 2019. Water relations of drought-stressed temperate trees benefit from short drought-intermitting rainfall events. Agr Forest Meteorol, 265: 70-77.

Ding, Y.L., Nie, Y.P., Chen, H.S., Wang, K.L. and Querejeta, J.I., 2020. Water uptake depth is coordinated with leaf water potential, water-use efficiency and drought vulnerability in karst vegetation. New Phytol.

Ding, Y.L. et al., 2018. A novel approach for estimating groundwater use by plants in rock-dominated habitats. J hydrol, 565: 760-769.

Drake, P.L. and Franks, P.J., 2003. Water resource partitioning, stem xylem hydraulic properties, and plant water use strategies in a seasonally dry riparian tropical rainforest. Oecologia, 137(3): 321-9.

Du, H. et al., 2021. Water depletion of climax forests over humid karst terrain: Patterns, controlling factors and implications. Agr Water Manage, 244.

Eggemeyer, K.D. et al., 2009. Seasonal changes in depth of water uptake for encroaching trees Juniperus virginiana and Pinus ponderosa and two dominant C4 grasses in a semiarid grassland. Tree Physiol, 29(2): 157-169.

Ehleringer, J.R. and Dawson, T.E., 2010. Water uptake by plants: perspectives from stable isotope composition. Plant Cell Environ, 15(9): 1073-1082.

Ehleringer, J.R., Roden, J. and Dawson, T.E., 2000. Assessing Ecosystem-Level Water Relations Through Stable Isotope Ratio Analyses. 181-214.

Ellsworth, P.Z. and Sternberg, L.S.L., 2015. Seasonal water use by deciduous and evergreen woody species in a scrub community is based on water availability and root distribution. Ecohydrol, 8(4): 538-551.

Fan, Z.X. and Thomas, A., 2013. Spatiotemporal variability of reference evapotranspiration and its contributing climatic factors in Yunnan Province, SW China, 1961–2004. Climatic Change, 116: 309-325.

Forzieri, G. et al., 2020. Increased control of vegetation on global terrestrial energy fluxes. Nat Clim Change, 10(4): 356-362.

Fu, T.G., Chen, H.S., Fu, Z.Y. and Wang, K.L., 2016. Surface soil water content and its controlling factors in a small karst catchment. Environ Earth Sci, 75(21): 1406.

Gaines, K.P. et al., 2016. Reliance on shallow soil water in a mixed-hardwood forest in central Pennsylvania. Tree Physiol, 36(4): 444-458.

Geekiyanage, N., Goodale, U.M., Cao, K.F. and Kitajima, K., 2019. Plant ecology of tropical and subtropical karst ecosystems. Biotropica, 51.

González de Andrés, E. et al., 2018. Tree-to-tree competition in mixed European beech-Scots pine forests has different impacts on growth and water-use efficiency depending on site conditions. J Ecol, 106(1): 59-75.

Gu, L.H., Pallardy, S.G., Hosman, K.P. and Sun, Y., 2016. Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. Agr Forest Meteorol, 217: 120-136.

Hasselquist, N.J., Allen, M.F. and Santiago, L.S., 2010. Water relations of evergreen and drought-deciduous trees along a seasonally dry tropical forest chronosequence.

Oecologia, 164(4): 881-890.

Hochberg, U., Rockwell, F.E., Holbrook, N.M. and Cochard, H., 2018. Iso/Anisohydry: A Plant-Environment Interaction Rather Than a Simple Hydraulic Trait. Trends Plant Sci, 23(2): 112-120.

Jiang, P. et al., 2020. Below-ground determinants and ecological implications of shrub species' degree of isohydry in subtropical pine plantations. New Phytol, 226(6): 1656-1666.

Jiang, Z.C., Lian, Y.Q. and Qin, X.Q., 2014. Rocky Desertification in Southwest China: Impacts, Causes, and Restoration. Earth-Sci Rev, 132(3): 1-12.

Keep, T. et al., 2021. To grow or survive: which are the strategies of a perennial grass to face severe seasonal stress? Funct Ecol.

Konapala, G., Mishra, A.K., Wada, Y. and Mann, M.E., 2020. Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. Nat Commun, 11(1): 3044.

Kuhnhammer, K. et al., 2020. Investigating the root plasticity response of Centaurea jacea to soil water availability changes from isotopic analysis. New Phytol, 226(1): 98-110.

Li, D.D., Liu, J.Q., Anne, V., Xi, B.Y. and Virginia, H.s., 2021. Understanding the relationship between biomass production and water use of Populus tomentosa trees throughout an entire short-rotation. Agr Water Manage, 246.

Li, S.G. et al., 2007. Plant water sources in the cold semiarid ecosystem of the upper Kherlen River catchment in Mongolia: A stable isotope approach. J Hydrol, 333(1): 109-117.

Liang, X.Y. et al., 2019. Precipitation has dominant influences on the variation of plant hydraulics of the native Castanopsis fargesii (Fagaceae) in subtropical China. Agr Forest Meteorol, 271: 83-91.

Liu, C.C., Liu, Y.G., Fan, D.Y. and Guo, K., 2012. Plant drought tolerance assessment for re-vegetation in heterogeneous karst landscapes of southwestern China. Flora, 207(1): 30-38.

Liu, H.Y. et al., 2019a. Rock crevices determine woody and herbaceous plant cover in the karst critical zone. Sci China Earth Sci, 62(11): 1756-1763.

Liu, W.N., Chen, H.S., Zou, Q.Y. and Nie, Y.P., 2021. Divergent root water uptake depth and coordinated hydraulic traits among typical karst plantations of subtropical China: Implication for plant water adaptation under precipitation changes. Agr Water Manage, 249.

Liu, W.R., Peng, X.H., Shen, Y.J. and Chen, X.M., 2013. Measurements of hydrogen and oxygen isotopes in liquid water by isotope ratio infrared spectroscopy (IRIS) and their spectral contamination corrections. Chin J Ecol 32(5): 1181-1186 (in Chinese with English abstract)

Liu, Z.Q., Jia, G.D. and Yu, X.X., 2020a. Variation of water uptake in degradation agroforestry shelterbelts on the North China Plain. Agr Ecosyst Environ, 287: 106697.

Liu, Z.Q., Jia, G.D. and Yu, X.X., 2020b. Water uptake and WUE of Apple tree-Corn Agroforestry in the Loess hilly region of China. Agr Water Manage, 234: 106138.

Liu, Z.Q., Yu, X.X. and Jia, G.D., 2019b. Water uptake by coniferous and broad-leaved forest in a rocky mountainous area of northern China. Agr Forest Meteorol, 265: 381-389.

Macias, F.M., 2018. Satellite images show China going green. Nature, 553(7689): 411-413.

Magh, R.K. et al., 2020. Competition for water rather than facilitation in mixed beech-fir forests after drying-wetting cycle. Journal of Hydrology, 587.

Malhi, Y. et al., 2008. Climate change, deforestation, and the fate of the Amazon. Science, 319(5860): 169-172.

Messmer, M. and Simmonds, I., 2021. Global analysis of cyclone-induced compound precipitation and wind extreme events. Weather Clim Extreme.

Min, S.K., Zhang, X., Zwiers, F.W. and Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. Nature, 470(7334): 378-381.

Moore, J.C. et al., 2016. Will China be the first to initiate climate engineering? Earth's Future, 4(12).

Moran, M.S. et al., 2009. Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature. Agricultural and Forest Meteorology, 149(1): 59-72.

Moreno-Gutiérrez, C., Dawson, T.E., Nicolas, E. and Querejeta, J.I., 2012. Isotopes reveal contrasting water use strategies among coexisting plant species in a Mediterranean ecosystem. New Phytol, 196(2): 489-496.

Nie, Y.P., Chen, H.S., Ding, Y.L., Wang, K.L. and Pugnaire, F., 2018. Water source segregation along successional stages in a degraded karst region of subtropical China. Journal of Vegetation Science, 29(5): 933-942.

Nie, Y.P. et al., 2019a. Qualitative identification of hydrologically different water sources used by plants in rock-dominated environments. Journal of hydrology, 573: 386-394.

Nie, Y.P., Chen, H.S., Wang, K.L. and Ding, Y.L., 2014. Seasonal variations in leaf δ13C values: implications for different water-use strategies among species growing on continuous dolomite outcrops in subtropical China. Acta Physiolo Plant, 36(10): 2571-2579.

Nie, Y.P., Chen, H.S., Wang, K.L. and Yang, J., 2012. Water source utilization by woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region of Southwest China. J Hydrol, 420: 264-274.

Nie, Y.P., Ding, Y.L., Zhang, H.L. and Chen, H.S., 2019b. Comparison of woody species composition between rocky outcrops and nearby matrix vegetation on degraded karst hillslopes of Southwest China. Journal of Forestry Research, 30(3): 911-920.

Piao, S. et al., 2015. Detection and attribution of vegetation greening trend in China over the last 30 years. Glob Chang Biol, 21(4): 1601-9.

Querejeta, J.I., Estrada-Medina, H., Allen, M.F. and Jiménez-Osornio, J.J., 2007. Water source partitioning among trees growing on shallow karst soils in a seasonally dry tropical climate. Oecologia, 152(1): 26-36.

Renninger, H.J., Carlo, N.J., Clark, K.L. and Schafer, K.V., 2015. Resource use and efficiency, and stomatal responses to environmental drivers of oak and pine species in an Atlantic Coastal Plain forest. Front Plant Sci, 6.

Renninger, H.J., Nicholas, C., Clark, K.L. and Schfer, K.V.R., 2014. Physiological strategies of co-occurring oaks in a water- and nutrient-limited ecosystem. Tree Physiol(2): 159-173.

Sanchez-Costa, E., Poyatos, R. and Sabate, S., 2015. Contrasting growth and water use strategies in four co-occurring Mediterranean tree species revealed by concurrent measurements of sap flow and stem diameter variations. Agr Forest Meteorol, 207: 24-37.

Sánchez-Costa, E., Poyatos, R. and Sabaté, S., 2015. Contrasting growth and water use strategies in four co-occurring Mediterranean tree species revealed by concurrent measurements of sap flow and stem diameter variations. Agricultural and Forest Meteorology, 207: 24-37.

Schultz, N.M., Griffis, T.J., Lee, X. and Baker, J.M., 2011. Identification and correction of spectral contamination in 2H/1H and 18O/16O measured in leaf, stem, and soil water. Rapid Commun Mass Sp, 25(21): 3360-3368.

Schwinning, S., 2010. The ecohydrology of roots in rocks. Ecohydrol, 3: 238-245.

Stock, B.C. and Semmens, B.X., 2013. MixSIAR GUI User Manual, version 3.1. http://conserver.

iugocafe.org/user/brice.semmens/MixSIAR.

Tokumoto, I. et al., 2014. Small-scale variability in water storage and plant available water in shallow, rocky soils. Plant Soil, 385(1-2): 193-204.

Tong, X. et al., 2020. Forest management in southern China generates short term extensive carbon sequestration. Nat Commun, 11(1): 129.

Volkmann, T., Haberer, K., Gessler, A. and Weiler, M., 2016. High‐resolution isotope measurements resolve rapid ecohydrological dynamics at the soil – plant interface. New Phytol, 210(3): 839-849.

Wang, J. et al., 2021. Age-related water use characteristics of Robinia pseudoacacia on the Loess Plateau. Agr Forest Meteorol, 301-302: 108344.

Wang, J., Fu, B.J., Wang, L.X., Lu, N. and Li, J.Y., 2020a. Water use characteristics of the common tree species in different plantation

types in the Loess Plateau of China. Agr Forest Meteorol, 288-289: 108020.

Wang, S., Fu, Z.Y., Chen, H.S., Nie, Y.P. and Xu, Q.X., 2020b. Mechanisms of surface and subsurface runoff generation in subtropical soil- systems: Implications of rainfall simulation experiments on karst slope. J Hydrol, 580: 124370.

Williams, D.G. and Ehleringer, J.R., 2000. Intra- and Interspecific Variation for Summer Precipitation Use in Pinyon-Juniper Woodlands. Ecol Monogr, 70(4): 517-537.

Wolf, A., Anderegg, W.R. and Pacala, S.W., 2016. Optimal stomatal behavior with competition for water and risk of hydraulic impairment. Proc Natl Acad Sci U S A, 113(46): E7222-E7230.

Yang, B., Wen, X.F. and Sun, X.M., 2015. Seasonal variations in depth of water uptake for a subtropical coniferous plantation subjected to drought in an East Asian monsoon region. Agr Forest Meteorol, 201: 218-228.

Yang, F.T., Feng, Z.M., Wang, H., Dai, X.Q. and Fu, X.L., 2017. Deep soil water extraction helps to drought avoidance but shallow soil water uptake during dry season controls the inter-annual variation in tree growth in four subtropical plantations. Agr Forest Meteorol, 234-235: 106-114.

Yang, J., Chen, H.S., Nie, Y.P. and Wang, K.L., 2019. Dynamic variations in profile soil water on karst hillslopes in Southwest China. Catena, 172: 655-663.

Yuan, D.X., Zhu, D.H. and Weng, J.T., 1994. Karstology of China. Geological Publishing House, Beijing, China (in Chinese).

Zhan, L.C., Chen, J.S., Li, L. and Xin, P., 2019. Plant water use strategies indicated by isotopic signatures of leaf water: Observations in southern and northern China. Agr Forest Meteorol, 276-277.

Zhang, J.Y., Dai, M.H., Wang, L.C. and Su, W., 2016. Household livelihood change under the rocky desertification control project in karst areas, Southwest China. Land Use Policy, 56: 8-15.

Zhao, Y. and Wang, L., 2018. Plant water use strategy in response to spatial and temporal variation in precipitation patterns in China: A stable isotope analysis. Forests, 9(3): 123.

Zhu, Z.C., Piao, S.L., Myneni, R.B., Huang, M. and Ning, Z., 2016. Greening of the Earth and its drivers. Nature Climate Change, 6(8): 182.

Zunzunegui, M. et al., 2018. Reliance on deep soil water in the tree species Argania spinosa. Tree Physiol, 38(5): 678-689.