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ABSTRACT

The determination of water use patterns of plants in a coastal ecosystem is critical to our understanding of local eco-hydrological processes and predicting trends in ecological succession under the background of global climate change. The water use patterns of *Ziziphus jujuba*, the dominant species on the Chenier Island in the Yellow River Delta, were examined following summer rainfall events. Stable oxygen isotope analysis was employed to analyze the effects of rainfall on the stable isotopic composition in potential water sources in *Z. jujuba*. The IsoSource model was used to estimate the contributions of potential water sources for xylem water in *Z. jujuba*. The results showed heavy rainfall could recharge both soil and groundwater but contributed little to the $\delta^{18}O$ values in deep soil water (60–100 cm) and groundwater. Light rainfall had an effect only on surface soil water (0–40 cm). *Z. jujuba* mainly absorbed deep soil water on non-rainy days. Rainwater became the predominant water source for *Z. jujuba* during and immediately after heavy rainfall. Switching the plant's main water source between deep soil water and rainwater provided *Z. jujuba* with a competitive advantage and improved the water use efficiency of *Z. jujuba* in this coastal ecosystem.

Introduction

Water is a very important resource and limiting factor for plants in arid and semiarid regions of the world (Barati et al. 2015), and is also critical to the vegetation of coastal zones (Corbin et al. 2005). During the past decades, the seawater intrusion induced by rising sea levels under global climate change has been projected to have profound effects on coastal ecosystems (Akumu et al. 2011; Chandrajith et al. 2013). The interaction between seawater and groundwater causes the variations in the salinity of soil and groundwater in coastal areas (Sternberg et al. 1991; Spalding & Hester 2007). Soil salinity is an important physiological stress factor for water uptake of coastal vegetation (Dorostkar et al. 2016) and hence can influence species composition, growth rates and ecosystem productivity (Wilson et al. 1996). The dynamics of water availability in soils and water used by plants critically influence species distribution and ecosystem functions (Sternberg et al. 1991; Gazis & Feng 2004; Barati et al. 2016). Plant water use strategies based on the availability of water from different sources (e.g. rainwater, seawater, soil water and groundwater) have profound implications

for soil–plant eco-hydrological processes, such as the hydraulic redistribution of water (Brooks et al. 2002, 2006). A study on the water uptake patterns of coastal plants would promote our understanding of species coexistence and community succession in such areas.

Stable isotope technology is an effective tool that can be used to determine water use patterns of plant species (Ehleringer & Dawson 1992; Cook & O'Grady 2006; Xu et al. 2011; Wei et al. 2013). The hydrogen and oxygen isotope compositions vary significantly in different water sources because water from different sources exhibit various physical processes (Dawson et al. 2002). Little fractionation of hydrogen and/or oxygen isotopes occurs during water uptake by root systems in most cases (Ehleringer et al. 1985; Dawson & Ehleringer 1991). Thus, stable isotopes of hydrogen and/or oxygen can be used to determine the various sources of water used by plants. The water isotopes composition of the plant xylem water reflects the isotopic information of the water uptake by plant roots (Dawson & Ehleringer 1991; Dawson et al. 2002). Therefore, we can determine the water uptake patterns of plants by comparing the hydrogen and/or oxygen isotopic compositions between xylem water and potential water sources used by the plant (Ehleringer et al. 1991; Jackson et al. 1995; Phillips & Ehleringer 1995). Previous studies have successfully used the natural abundance of water isotopes to calculate the contributions of different water sources to plant water use (Jackson et al. 1995; Ewe et al. 2007). The stable isotope method has also been used to quantitatively analyze hydrological processes and water use in different habitats (Sternberg et al. 1991; Xu et al. 2011) and demonstrates the differences in season-derived soil water in arid and semiarid ecosystems (Phillips & Ehleringer 1995; Dawson & Pate 1996; Dodd et al. 1998). However, in the coastal and arid habitats, studies have also demonstrated that salt-excluding plant species and woody xerophytes fractionate the hydrogen isotopes during water uptake (Sternberg & Swart 1987; Sternberg et al. 1991; Lin & Sternberg 1993; Ellsworth & Williams 2007).

The Chenier Island of the Yellow River Delta (YRD) is located at the Binzhou Shell Dike Islands and Wetlands National Nature Reserve in China. The vegetative species in this region include shrubs and herbaceous plants. Although this is a coastal region, the soil physical characteristics result in very low soil water content. Additionally, only limited freshwater resources are available. In summer, precipitation provides the main dynamic source of freshwater recharge in this region. Seawater intrusion also creates the salt stress on coastal plants here. Previous studies in this region focused on biodiversity, plant physiological characteristics and soil physicochemical properties with few efforts made to determine the water use patterns of plants. We initiated a field study to examine the water use patterns of a dominant species (*Ziziphus jujuba* var. *spinosa* Hu) on the Chenier Island in the YRD. This region was chosen because (1) it serves as a typical coastal ecosystem in the YRD that plays a significant role in decreasing coastal erosion, and protecting coastal aquaculture; and (2) it is sensitive to changes in hydrological conditions, such as the potential for an increasing frequency in drought stress and seawater intrusion. An analysis of the water use patterns of *Z. jujuba* can provide useful information related to understanding the mechanisms that contribute to species coexistence (Yang et al. 2011) and hydrology management for this region. The objectives of this study were to determine (1) the isotopic characteristics of *Z. jujuba* xylem and soil water after a rainfall event and (2) the water use patterns of *Z. jujuba* in the wet season.

Materials and methods

Study area

Our study was conducted within a *Z. jujuba* shrubland in the Chenier Island of the YRD (38°13′40.4″ N, 117°56′43.7″E) along the northern coast of Shandong Province, China. The warm, temperate continental monsoon climate is characterized with a dry windy spring and hot rainy summers that are influenced by the East Asian monsoon. The mean annual precipitation was 552.4 mm, of which 71% occurs between June and September. The mean annual temperature is 12.7°C, averaging −2.4°

C in winter and 26.7°C in summer. The mean annual evaporation was 2430.6 mm, or about 4.4 times the precipitation.

The typical Chenier Island of the study area was created by coastal sand formed with debris from shells. The topography of the Chenier Island is characterized with higher in the middle and lower on both the south and the north sides that are caused by tidal wash. *Z. jujuba* is a 1.5–2.5 m tall xerophytic species that is widely distributed on the top of the Chenier Island where the water table is deeper than 3 m; thus, the plants are relatively less affected by seawater than plants in other areas of the island.

Sample collection

In July 2013, three 10 m × 10 m plots were established in the field site. Climatic data related to precipitation, air and soil temperature, and air humidity were continuously recorded at an automatic climatic station on the Chenier Island. The samples of soil, plant xylem and shallow groundwater were collected as background values before the 20.4-mm rainfall event in July 2013 and also collected for a 6-day period after the selected rainfall event at each plot.

At each of the three plots, three soil samples were collected by a 4.5 cm diameter soil corer at each depth of 0–20, 20–40, 40–60 and 60–100 cm. Simultaneously, soils of each layer were also sampled for soil particle size and gravimetric water content analysis. Three individuals for *Z. jujuba* xylem were selected in each plot as soil was sampled. Thirty-six soil samples and nine *Z. jujuba* xylem samples were collected every day.

Rainwater samples were collected using plastic buckets with the bottom covered by liquid paraffin to prevent rainwater evaporation. Three rainwater samples were collected in triplicate from three individual rainfall events, 20.4, 3 and 6.6 mm on 26, 27 and 29 July 2013, respectively, for a total of nine samples. Three shallow groundwater samples were also collected from a vitrified-clay tube vertically installed into a depth of 200 cm in each plot.

All samples were immediately placed in glass bottles and sealed with parafilm. Rainwater and groundwater samples were stored at 4°C and other samples were stored at −20°C in a refrigerator prior to laboratory analysis.

Sample analysis

Water in all samples was extracted using the cryogenic vacuum distillation method (Ehleringer et al. 2000). The water δ values of samples were determined by a Liquid Water Isotope Analyzer (Los Gatos Research, Mountain View, CA, USA) at the Shandong Provincial Key Laboratory of Eco-Environmental Science for the Yellow River Delta, Binzhou University, China. Only $\delta^{18}O$ data of samples were used for the analysis of water use patterns because *Z. jujuba* as a xerophyte may have hydrogen stable isotope fractionation during root water uptake. The precision of $\delta^{18}O$ was 0.25‰. Isotopic values can be expressed in δ units, described by Equation (1):

$$\delta^{18}O\text{‰} = \left[\left(R_{sample}/R_{standard} \right) - 1 \right] \tag{1}$$

where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ ratios of the sample and the Vienna Standard Mean Ocean Water, respectively (Sternberg & Swart 1987). To eliminate the spectral contamination, the $\delta^{18}O$ values of the xylem water were corrected by a standard curve following the method processed by Schultz et al. (2011).

Deionized water (DI; simplicity UV, Millipore Inc., Milford, MA, USA) were spiked with varying concentrations of methanol or ethanol (99.9% chromatographic pure). The concentration gradient for methanol (μL L^{-1}) was 0, 20, 30, 40, 60, 80, 120, 140, 160, 180, 200, 240, 320, 360, 400, 440, 480, 520, 560, 600, 640, 680, 720, 760 and 800. The concentration gradient for ethanol (mL·L^{-1}) was: 0, 2, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 32, 36 and 40. Three repetitions were done for each concentration.

The $\delta^{18}O$ values of above solution were measured by an isotope ratio infrared spectroscopy analyzer – the Liquid Water Isotope Analyzer (Los Gatos Research). With the Spectral Contamination Identifier, a type of post-processing software, the narrow-band (NB) and broad-band (BB) metrics represented by methanol and ethanol contamination were calculated, respectively. The relationships between NB, BB and the offsets of $\delta^{18}O$ values were obtained with Equations (2) and (3), respectively:

$$\Delta\delta^{18}O(y) \sim \ln NB(x) : y = 0.013x^3 - 0.053x^2 + 0.635x + 0.063, R^2 = 0.998 \tag{2}$$

$$\Delta\delta^{18}O(y) \sim BB(x) : y = -5.827x + 5.808, R^2 = 0.948 \tag{3}$$

The methanol resulted in more positive isotope values, and the offsets should be subtracted from the original isotope values. The ethanol resulted in more negative $\delta^{18}O$ values, and the offsets should be added to the original $\delta^{18}O$ values. The main contaminant in our samples was methanol, which is within the range of 10–200 $\mu L \cdot L^{-1}$.

Soil physical properties analysis

Soil gravimetric water content was calculated as [(fresh weight - dry weight)/dry weight × 100%]. Soil size was partitioned into six grades: very fine sand (<0.1 mm), fine sand (0.1–0.25 mm), medium sand (0.25–0.5 mm), coarse sand (0.5–1.0 mm), very coarse sand (1.0–2.0 mm) and gravel (>2.0 mm). The percent of each grade was used to distinguish the soil texture using Equation (4):

$$P_i = W_i/W_t \times 100\% \tag{4}$$

where P_i is the weight percentages of grade i, W_i is the weight of grade i and W_t is the total weight of all grades; i represents different grades (i = 1, 2, 3, 4, 5, 6). The percentage of each respective grade in each layer was calculated individually.

Data analysis

The proportional contributions of different water sources to Z. jujuba were determined by the method proposed by Phillips and Gregg (2003). This method was informative in determining bounds for the contributions of more than three water sources. In this method, all possible combinations of each source contribution (0–100%) are examined in small increments (e.g. 1%). The probable solution is not a single value, but a range of potential source contributions.

Statistical analysis was performed with SPSS (SPSS Inc., Chicago, IL, USA). One-way analysis of variance was used to test for differences in $\delta^{18}O$ values of plant xylem and soil water, and water content in each soil layer following a rain event. All statistically significant differences were tested at α = 0.05 level.

Results

The soil water content and composition of soil particles

Soil water content in four layers showed significant changes during the 6-day observation period after the rain event (Figure 1). Prior to the rain event, the soil water content showed no significant difference between depths of 40–60 and 60–100 cm (P = 0.766 > 0.05), but they were significantly higher than that of 20–40 cm (P < 0.05). Following the rainfall event (20.4 mm), soil water content in four layers increased significantly in the first day (P < 0.05). However, following the 3 mm rainfall on day 2, a little increase in soil water content occurred only at a depth of 0–20 cm, and the soil water content at a depth of 40–100 cm depth decreased significantly (P < 0.05). On day 3, soil water content at 0–20 cm depth decreased significantly (P < 0.05), and soil water content at depths
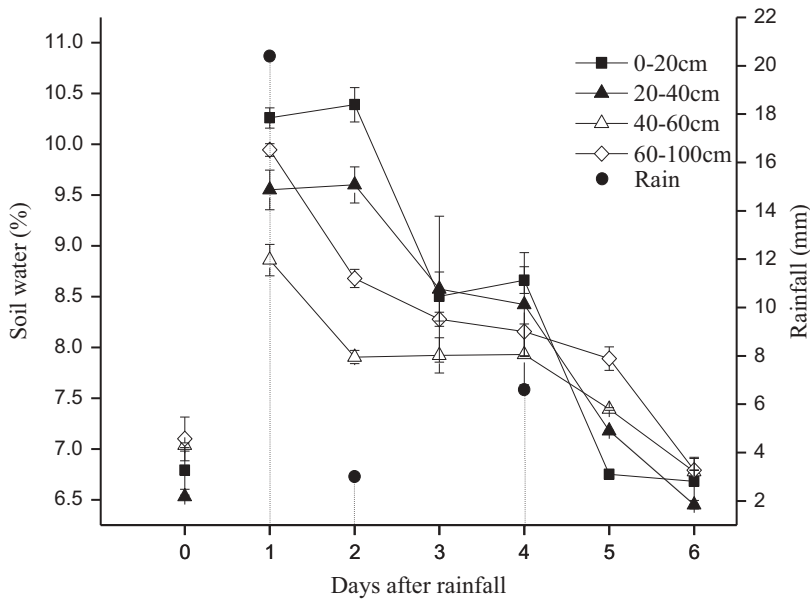
Figure 1. Soil gravimetric water content (mean ± 1 SE) at different soil depths before and after the 20.4-mm rainfall event ($n = 9$).

of 20–40 and 60–100 cm slightly decreased ($P = 0.056$, $P = 0.058 > 0.05$). Although a 6.6 mm rainfall occurred on day 4, no significant difference in soil water content was observed in four layers between days 3 and 4. After that, soil water content in all soil layers gradually declined and returned to their previous levels within 6 days.

The percentage of very fine sand was lower than that of other particle sizes in each layer (Table 1). Fine sand in four layers accounted for >20% of soil content. Coarse sand was mainly at depths of 0–40 cm and the percentage of it decreased with soil depth. The percentage of gravel gradually increased with soil depth.

Temporal changes in $\delta^{18}O$ values of different water sources

The $\delta^{18}O$ values of soil water and groundwater following the rainfall event showed different temporal changes (Figure 2). Prior to the rainfall event, the $\delta^{18}O$ value of soil water at a depth of 60–100 cm was significantly higher than that of soil water in other soil layers ($P < 0.05$), and the $\delta^{18}O$ value of soil water at a depth of 0–20 cm was significantly lower than that of soil water at depths of 20–40 and 40–60 cm ($P < 0.05$); no remarkable difference was observed in $\delta^{18}O$ values of soil water between 20–40 and 40–60 cm ($P = 0.936 > 0.05$). On day 1 after the first rainfall event, the $\delta^{18}O$ values of soil water at 0–20 and 20–40 cm depth significantly decreased ($P < 0.05$) and were close to that of rainwater. Compared with day 0, the $\delta^{18}O$ values of soil water at depths of

Table 1. Percentages of soil particle mass of different sizes to total size at different soil depths.

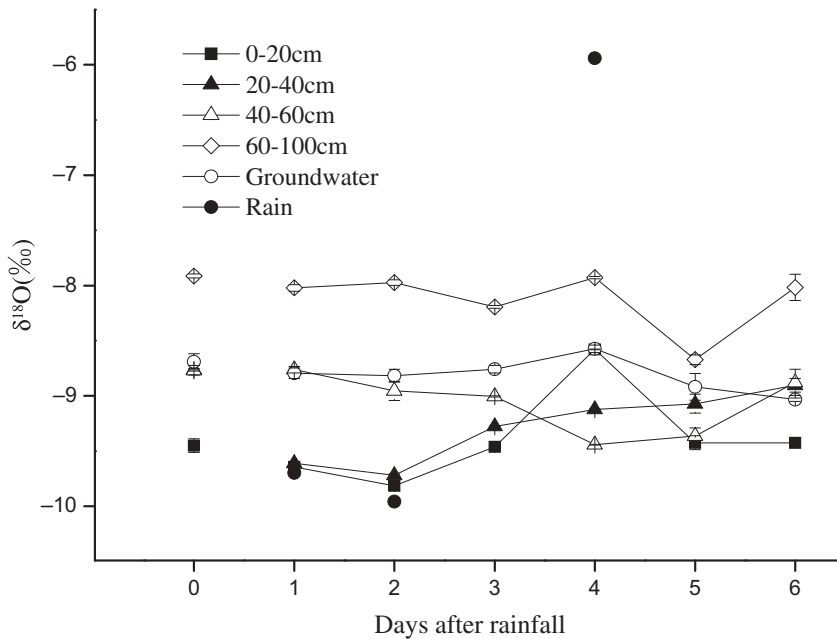| Soil depth (cm)	Soil particles size distribution (%)					
	Very fine sand (<0.1 mm)	Fine sand (0.1–0.25 mm)	Medium sand (0.25–0.5 mm)	Coarse sand (0.5–1.0 mm)	Very coarse sand (1.0–2.0 mm)	Gravel (>2.0 mm)
0–20	1.1	23.1	11.3	33.6	18.9	11.9
20–40	1.3	21.2	11.9	31.0	16.7	17.8
40–60	1.8	22.5	9.1	23.9	19.5	23.1
60–100	2.0	29.5	7.8	19.6	17.8	23.3

Figure 2. Temporal $\delta^{18}O$ changes (mean ± 1 SE) of soil water and groundwater before and after the 20.4-mm rainfall event ($n = 9$).

40–60 and 60–100 cm in the first 2 days after the rainfall event had no significant change ($P > 0.05$). On day 3, the $\delta^{18}O$ values of soil water at depths of 0–20 and 20–40 cm significantly increased ($P < 0.05$), whereas the $\delta^{18}O$ value of soil water at depth of 40–100 cm slightly decreased. Following the third rainfall event on day 4, the $\delta^{18}O$ value of rainwater was −5.93‰ and was significantly higher than that of rainwater on days 1 (−9.67‰) and 2 (−9.95‰; $P < 0.05$), and the $\delta^{18}O$ values of soil water at depths of 0–20 and 20–40 cm significantly increased ($P < 0.05$). In contrast, the $\delta^{18}O$ value of soil water at depth of 40–60 cm was significantly lower than the day before ($P < 0.05$; Figure 2). On day 6, the $\delta^{18}O$ values of soil water in all soil layers returned to their previous levels on day 0. For the groundwater, the $\delta^{18}O$ values remained relatively unchanged before and during the first 4 days after the first rainfall event and declined to a lower level on day 6 ($P < 0.05$).

Temporal changes in $\delta^{18}O$ values of plant xylem water

The $\delta^{8}O$ values of *Z. jujuba* xylem water fluctuated significantly during the study period (Figure 3). The $\delta^{18}O$ value of plant xylem water was −8.33‰ before the first rain event (20.4 mm). Following the rain event, the $\delta^{18}O$ value of plant xylem water significantly decreased from −8.33‰ to −9.57‰ ($P < 0.05$), which was close to that of rainwater (−9.67‰; Figure 3). Although there was a 3 mm rainfall on day 2, the $\delta^{18}O$ values of plant xylem water had no significant differences between days 1 and 2 ($P = 0.475 > 0.05$). A significant increase occurred in $\delta^{18}O$ values of plant xylem water on day 3 and ranged from −9.52‰ to −8.674‰ ($P < 0.05$). Following the third rainfall event, the $\delta^{18}O$ value of xylem water increased to −8.40‰ and was significantly higher than day 3 ($P < 0.05$). The $\delta^{18}O$ value of plant xylem water had a decrease on day 5, and then immediately increased to −8.37‰ on day 6, which did not significantly differ from day 0 ($P = 0.572 > 0.05$).
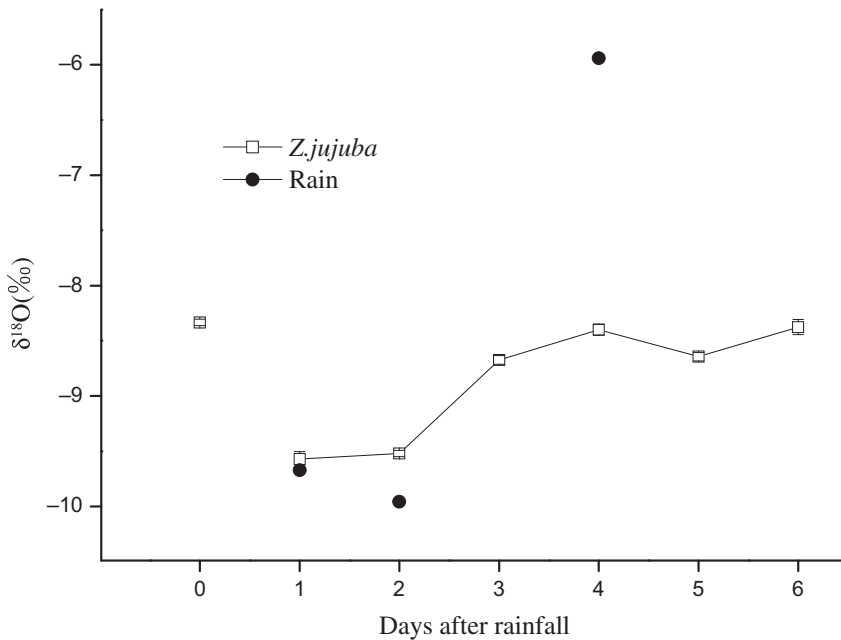
Figure 3. Temporal $\delta^{18}O$ changes (mean ± 1 SE) of *Z. jujuba* xylem water before and after the 20.4-mm rainfall event ($n = 9$).

Table 2. Contributions of potential water sources to *Z. jujuba* xylem water before and after rainfall events in July 2013.

Water sources	Contribution (%)						
	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
Soil water							
0–20 cm	6.9 (0–30)*	6.7 (0–37)	14.7 (0–78)	9.4 (0–41)	16.6 (0–60)	2.1 (0–11)	11.1 (0–48)
20–40 cm	12.6 (0–55)	3.5 (0–20)	17.3 (0–92)	11.2 (0.49)	9.9 (0–43)	4.0 (0–20)	17.9 (0–76)
40–60 cm	12.5 (0–55)	2.7 (0–16)	8.9 (0–48)	15.1 (0–65)	7.7 (0–34)	2.3 (0–12)	18.4 (0–78)
60–100 cm	54.2 (40–75)	1.3 (0–9)	4.2 (0–24)	42.5 (6–66)	45.0 (20–72)	85.3 (71–100)	37.1 (22–59)
Groundwater	13.8 (0–60)	2.9 (0–17)	7.7 (0–42)	21.9 (0–94)	18.8 (0–80)	6.2 (0–29)	15.5 (0–66)
Rainwater		82.9 (63–96)	47.1 (8–80)		2.0 (0–10)		

*$P < 0.5$.

Contributions of water sources to *Z. jujuba* xylem water

Through the IsoSource model, the proportional contributions of potential water sources for *Z. jujuba* displayed differences before and after the rainfall event in summer (Table 2). Prior to the first rainfall event, *Z. jujuba* mainly used soil water from 60 to 100 cm (54.2%), and the contribution of soil water from 0 to 60 cm was 32.0%, and the groundwater provided only a little water to *Z. jujuba*. Following the first rainfall event, the contribution of soil water from 60 to 100 cm decreased from 54.2% to 1.3%, and rainwater replaced the soil water from 60 to 100 cm to become the main water source for *Z. jujuba* (82.9%). Although a rainfall event happened on day 2, the precipitation was only 3 mm; therefore, the contribution of rainwater for *Z. jujuba* was 47.1%, which was lower than that on day 1. On day 3, the main water source of *Z. jujuba* water uptake transformed into soil water from 60 to 100 cm again. There was a 6.6-mm rainfall event on day 4, but the contribution of rainwater to *Z. jujuba* xylem water was only 2.0% and *Z. jujuba* still obtained a high proportion of soil water from 60 to 100 cm (45.0%). On day 5, the contribution of soil water from 60 to 100 cm increased to the highest level (85.3%) during the study period.

Discussion

The distribution of soil particle size is a fundamental property that greatly influences soil porosity as well as mechanical and hydraulic properties of soil (Lee & Ro 2014; Neyshaburi et al. 2015). In our study region, coarse sand, very coarse sand and gravel comprised the main parts of soil particles; in particular, the percentages of gravel in the soil profile were greater than 10% (Table 1). Thus, the soil texture contained more gravel soil as described in the United States Department of Agriculture system (Peng et al. 2015). In addition, the noncapillary porosity would increase with the increase of the percentage of gravel along the soil profile, and this reduced the capillary effect, which was beneficial to the hydraulic lift (Hall & Djerbib 2004; Mancarella & Simeone 2012). Therefore, it was difficult for the groundwater to recharge the soil water by the capillary effect.

Soil water is regulated by processes such as precipitation, storm surge, infiltration, plant uptake and transpiration (Xu et al. 2011). Precipitation was a unique freshwater source that recharged the soil water in the study area. The temporal changes in soil water content following the rainfall events depended on the precipitation intensity. We observed that the heavy rainfall event (e.g. 20.4 mm) could result in a significant increase in soil water content of all soil layers and even recharge the groundwater, but the light rains (3.0 and 6.6 mm) only had an effect on water content in the surface soil layers (0–40 cm) (Figure 1). In addition, we found that the soil water content at depths of 40–100 cm significantly decreased on day 2 because the water was absorbed by the plants with deep root systems (Reynolds et al. 2004). Additionally, we also found that the soil water content at a depth of 0–40 cm had a larger reduction than a depth of 60–100 cm on days 3 and 5 because the soil water at a depth of 0–40 cm was consumed by plants with shallow roots and soil surface evaporation. Furthermore, water partially infiltrated into the deep soil layers (60–100 cm) as the $\delta^{18}O$ values of soil water from deep soil layers decreased on day 5 (Figure 2). However, the rain effect on the soil water only lasted for a short 6-day period (Figure 1).

Changes in $\delta^{18}O$ values of soil water following the rainfall events depended on the precipitation intensity, $\delta^{18}O$ signature in rainwater, plant activity and evaporation. We found that the $\delta^{18}O$ values of soil water from 60 to 100 cm was significantly higher than that of 0–60 cm because there were many light rainfall events with a low $\delta^{18}O$ signature that could not infiltrate into the deep soil layers (Figure 2). Furthermore, the result showed that the $\delta^{18}O$ values of soil water from 60 to 100 cm were significantly higher than those of groundwater, which indicated that the groundwater could not recharge the soil water. We found that the heavy rainfall could temporally increase the soil water content but contributed little to soil water $\delta^{18}O$ in the deeper soil layers (40–100 cm) and groundwater in the first 2 days probably because water consumption by water uptake of plant with deep root systems and soil water evaporation partially neutralized the rain effect (Xu et al. 2012). Over time, we observed that significant decreases occurred in $\delta^{18}O$ values of soil water at a depth of 40–60 cm on day 3, 60–100 cm and groundwater on day 5 probably because the soil water and rainwater with low $\delta^{18}O$ values infiltrated into the deep soil layers and groundwater (Figure 2).

The water use patterns by plants may determine the response of ecosystems to changes in environment water (Ewe et al. 1999). Consequently, tracing water sources used by plant species in coastal ecosystems is critical to understanding the response of coastal vegetation to global climate change in respect of water uptake (Sternberg & Swart 1987; Sternberg et al. 1991). Generally, the water absorbed by plant roots was a mixture of water from different sources (Wang et al. 2010). Previous studies have shown that plant species uptake water from specific sources, such as rainwater, soil water and groundwater (Ehleringer & Dawson 1992; Nie et al. 2011; Wei et al. 2013; Ghamarnia & Farmanifard 2014; Meißner et al. 2014). Our results showed that *Z. jujuba* mainly relied on deep soil water (60–100 cm) in non-rainy days. Although there was a fluctuation in the contribution of deep soil water during the lasted 4-day period, the contribution of deep soil water was higher than that of other water sources (Table 2). Following the first rainfall event, the main water source of *Z. jujuba* xylem water switched from deep soil water to rainwater (Table 2), which indicated that *Z. jujuba* was very sensitive to the heavy rainfall event in summer. Although the

contribution of rainwater was higher than other water sources, we supposed that the rainwater used by *Z. jujuba* was not from the second rainfall (3.0 mm) but from the first one (20.4 mm) because the contribution of the rainwater was lower than other water sources following the third rainfall event (6.6 mm). Consequently, we proposed that the light rainfall had little contribution to *Z. jujuba* water uptake. The ability to switch its main water sources between deep soil water and rainwater could give *Z. jujuba* a competitive advantage for water sources within the coastal ecosystem (Ehleringer & Dawson 1992).

Conclusion

In this study, the variations of stable oxygen isotopic composition in potential water sources following rainfall events and the water use patterns of *Z. jujuba* were determined on the Chenier Island in the YRD during a wet summer. A heavy rainfall event could recharge the soil water and groundwater but contributed little to the $\delta^{18}O$ values in deep soil water (60–100 cm) and groundwater; meanwhile, a light rainfall only had an effect on the surface soil water (0–40 cm).

Our results showed that *Z. jujuba* mainly absorbed deep soil water in non-rainy days as determined by the stable oxygen isotopic signature from potential water sources and xylem water. Rainwater became the predominant water source for *Z. jujuba* when there was a heavy rainfall event. Switching the main water source between deep soil water and rainwater could give *Z. jujuba* a competitive advantage related to water consumption and improve its water use efficiency in this coastal ecosystem.

Our study focused on the water use patterns of *Z. jujuba* only during the wet season, and the results may not represent the water use strategies in all seasons. The water use patterns of *Z. jujuba* in the dry season or during different stages of growth should be analyzed in our future studies.

Acknowledgment

Disclosure statement

Funding

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