Salix psammophila afforestations can cause a decline of the water table, prevent groundwater recharge and reduce effective infiltration

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Abstract

Afforestation can reduce desertification and soil erosion. However, the hydrologic implications of afforestation are not well investigated, especially in arid and semi-arid regions. China has the largest area of afforestation in the world, with one-third of the world's total plantation forests. How the shrubs affect evapotranspiration, soil moisture dynamics and groundwater recharge remains unclear. We designed two pairs of lysimeters, one being 1.2 m deep and the other one 4.2 m deep. Each pair consists of one lysimeter with bare soil, while on the other one a shrub is planted. The different water table depths were implemented to understand how depth to groundwater affects soil and water table dynamics under different hydrological conditions. Soil moisture, water table depth, sap flow, and rainfall were measured concurrently. Our study suggests that for the current meteorological conditions in the Ordos plateau recharge is reduced or even prohibited through the large-scale plantation *Salix psammophila*. Shrubs also raise the threshold of precipitation required to increase soil moisture. For the conditions we analysed, a minimum of 6 mm of precipitation was required for infiltration processes to commence. In addition to the hydrological analysis, the density of root distribution is assessed outside of the lysimeters for different water table depths. The results suggest that the root-density distribution is strongly affected by water table depth. Our results have important implications for the determination of the optimal shrub-density in future plantations, as well as for the conceptualization of plant roots in upcoming numerical models.

***Keywords*: *Salix psammophila*, lysimeter, groundwater recharge, root distribution, ecohydrology, evapotranspiration**

1. Introduction

The Ordos plateau is a complex and sensitive ecotone in the semiarid zone of northern China [Chen et al., 2002]. The Ordos Plateau is facing major environmental problems . One of the most important environmental problems is desertification. About 10,000 ha/year of land have become desert since the 1960s [Kamichika et al., 1989]. To control and prevent desertification effectively, the Chinese government started a reforestation project called the "Three North Forest Shelterbelts" at the beginning of the 1980s [Zhang et al., 2016]. In the year 2000, a policy called "Returning Farmland to Forest and Grassland" has been implemented in the Ordos plateau [Wang et al., 2010]. *Salix psammophila* has been planted not only to halt shifting dunes [Heshmati et al., 2011], but also to provide fuel, and timber in the Mu-Us desert region [Ohte et al., 2003]. *Salix psammophila* is a phreatophyte. Phreatophytes can take up water from the vadose zone as well as from the saturated zone and thus exert a significant influence on the hydrologic system [Naumburg et al., 2005; Le Maitre et al., 1999; Lubczynski, 2009; Banks et al., 2011; Schilling et al. 2014].

Since the 1990s water tables in the Ordos plateau have been dropping significantly, albeit not at the same rate throughout the basin. While the decline of water tables reduces non-productive phreatic evaporation rates [Brunner et al., 2008; Li et al., 2008] and therefore reduces the risk of salinization (Brunner et al. 2007), this decline caused several groundwater-dependent ecosystems to dry up, and the remaining lake-systems are in danger [Xu et al., 2007]. For example, due to increased irrigation, the groundwater level dropped 1-11 m in the Minqin Oasis, [Ma et al., 2005], causing significant ecological damage. With climate change, these problems could be accentuated (Yin et al. 2017). The decline of the water table also limits the development of the economy. Abundant mineral resources such as coal, petroleum, and natural gas have been found in the Mu Us desert. It is one of the largest regions for energy and chemical production in China [Yin et al., 2011]. Mining these resources requires a significant amount of water. Concurrently, there is an increased push to expand the afforested areas in the project area by planting *Salix psammophila*, potentially increasing the pressure on groundwater resources.

A quantitative approach on how *Salix psammophila* affect groundwater is therefore required to develop water resources plans that consider desertification, ecological water use as well as the requirements for the energy sector. Huang et al. [2016] calibrated a Hydrus-1D model taking into account the root water uptake of *Salix psammophila*. They found that the ratio of actual transpiration to potential transpiration decreased as a function of water table depth. Their study was based on a specific level of the groundwater table, fluctuations of the groundwater level were not considered. Groundwater level fluctuations can, however, be an important control of root development and growth (Rodriguez-Iturbe et al. 2007). Some studies have analyzed the influence of fluctuating water tables on the development of phreatophytes in this region. Yin et al. [2018] employed field and modelling approaches to study how native phreatophytes react to short-term pumping by carrying out a 23-day pumping test. They showed that the phreatophytes can recover from the stress induced by groundwater pumping as they can adapt to short periods of water stress using physiological and morphological traits.

The rooting depth of trees is a basic tree functional trait determining resilience [Maeght et al., 2013] toward drought and changing groundwater conditions, However, rooting depth is difficult to measure. Fan et al. [2017] analyzed a global synthesis of 2,200 root observations. The results indicated a strong sensitivity and plasticity of root distribution to local soil water profiles. The depth to groundwater might be one of the most important environmental factors.

Nevertheless, the current understanding of the growth of different types of roots and their role in taking up water in variable climatic conditions is still limited.

Precipitation is a major driver of biological processes in arid ecosystems [Zhao and Liu, 2010]. When trees take up water from large rainfall events, the transpiration and respiration of the trees will increase [Schwinning and Sala, 2004]. Consequently, the trees affect the water balance of the soil-groundwater [Huxman et al., 2004]. However, because of interception, small rainfall events might not necessarily lead to a significant increase of soil moisture or groundwater recharge. The role of trees on the critical (i.e. the minimal) rainfall intensity and duration which leads to groundwater recharge has not been explored for *Salix psammophila* in the climatic condition of the Ordos basin.

Accurate experimental data are needed to quantify how the presence of *Salix psammophila* affects infiltration and soil moisture as well as groundwater levels dynamics. Therefore, a set of four lysimeters was designed to study the relationship between evapotranspiration (ET), soil moisture- and groundwater dynamics in response to rainfall. Lysimeters constitute a powerful instrumental approach to carry out controlled experiments outside of the laboratory and under realistic conditions (Pütz et al. 2018). For areas where no surface runoff occurs, lysimeters account for all the relevant processes across the land-atmosphere interface. In our project area, the infiltration capacity of the soil is around 300 mm/h (Yair. 2001), while the most intense precipitation rates around 34.9 mm/h. Given that no surface runoff can occur, lysimeters constitute a holistic approach to observe infiltration, storage and evaporation processes for this particular project area. The lysimeters were specifically designed to explore the role of groundwater levels in this context. In addition to the analysis of the lysimeters, the distribution of the roots of two shrubs that were growing outside of the lysimeters were analysed. These two shrubs developed over significantly different depths to groundwater. Based on these experimental approaches, the following points are elaborated in this paper: (1) the influence of *Salix psammophila* on groundwater recharge and water table dynamics, (2) the influence of *Salix psammophila* on the soil water balance, (3) the root adaptability to different water table depths. Addressing these questions is also not only important from a scientific point of view, but also is critical for water resources management purposes.

2. Materials and methods

2.1 Study site description

The experimental site is located in the Mu Us Desert, Northwestern China. The climate is continental and semiarid. A hydrological station is located at the Henan County national weather station (Fig. 1) and meteorological data were obtained from this station. There are 50 years of meteorological data (from 1957-2006), the long-term average annual air temperature is 8.0°C, and the observed extreme temperatures are -34.3 and 36.7°C in January 1958 and July 1959, respectively. The mean annual precipitation (1985-2008) is 340 mm, of which 70% falls as rain between July and September [Zhang et al., 2019]. The mean annual potential evapotranspiration (PET) from 1985 to 2008 is 2266 mm. The growing season is from May to October and the dryness index (Potential ET divided by precipitation) is 6.7. The typical soil is sand, and highly susceptible to wind erosion because of its coarse texture (the sand fraction can be larger than 88%). The landscape includes fixed, semi-fixed, and semi-mobile dunes, as well as inter-fixed dunes. The naturally occurring, the dominant vegetation type is *Salix psammophila*. The density of *Salix psammophila* has been artificially increased to approximately 30% of the Mu Us desert (44200 km^2).

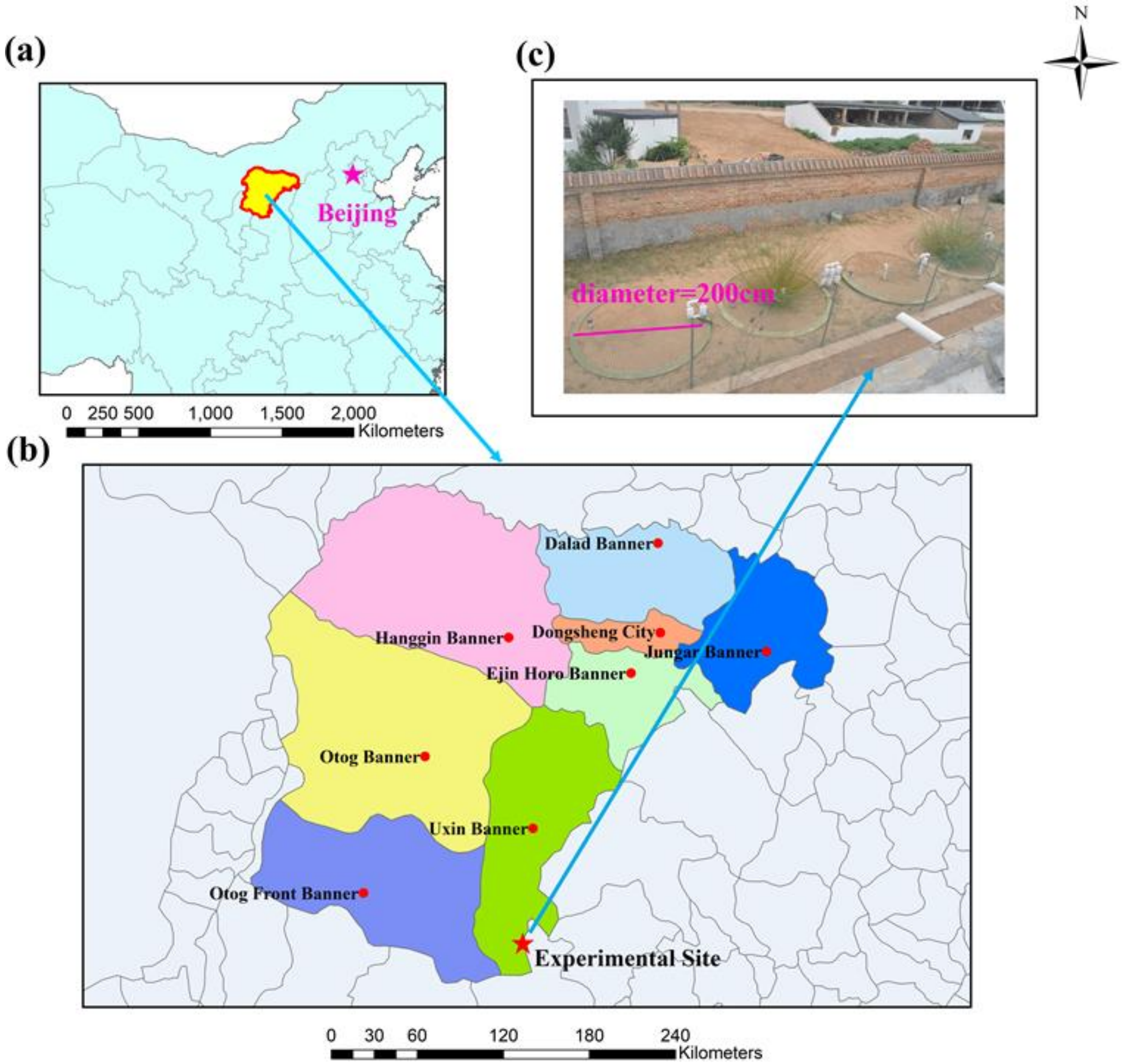

Fig. 1 Location of the field site. (a) Location map of Mu Us desert in Northwest China; (b) Location map of the experimental site within Uxin Banner; (c) experimental site (there are four lysimeters built up with the same diameter of 200 cm).

2.2 Field experiments with bare- and vegetated soil for two groundwater levels

To investigate how *Salix psammophila* responds to different water table depths, we designed two pairs of lysimeters filled with the soil material found locally with a bulk density of 1.55 g/cm^3. The results from a particle size analysis revealed that the sandy particles in the lysimeters account for more than 88% of the total particles. According to the United States Department of Agriculture textural soil classification, the soil can be classified as sand.

One pair of lysimeters is 1.2 m deep (subsequently labeled with the abbreviation *shal_*) and the other is 4.2 m deep (subsequently labelled with the abbreviation *deep_*). Water tables are monitored in all lysimeters. For each pair, one lysimeter features *Salix psammophila* and the other one is bare soil. We refer to these lysimeters as *shal_veg* and *shal_bare*, as well as *deep_veg* and *deep_bare*. The young *Salix psammophila* were dug out near the experimental site and planted for both vegetated lysimeters. They initially had the same rooting depths (30 cm). The two different groundwater depths for these pairs were implemented to assess the influence of the water table depth on the shrub behavior, soil water dynamics, and evapotranspiration. The lysimeters are sealed at the lower end. In Mu Us desert, shallow water table depths are common (Chen et al. 2018; Li et al. 2012). Growing *Salix psammophila* at locations of shallow water table depths is also common practice (Huang et al. 2016; Cheng et al. 2013). Therefore, we set two initial water table depths: one pair equal to 1 m which is less than the extinction depth of this soil type (equal to 1.05 m [Ma et al., 2019]); and the other pair (about 2.0 m): one equal to about 2.0 m and the other equal to 2.8 m.

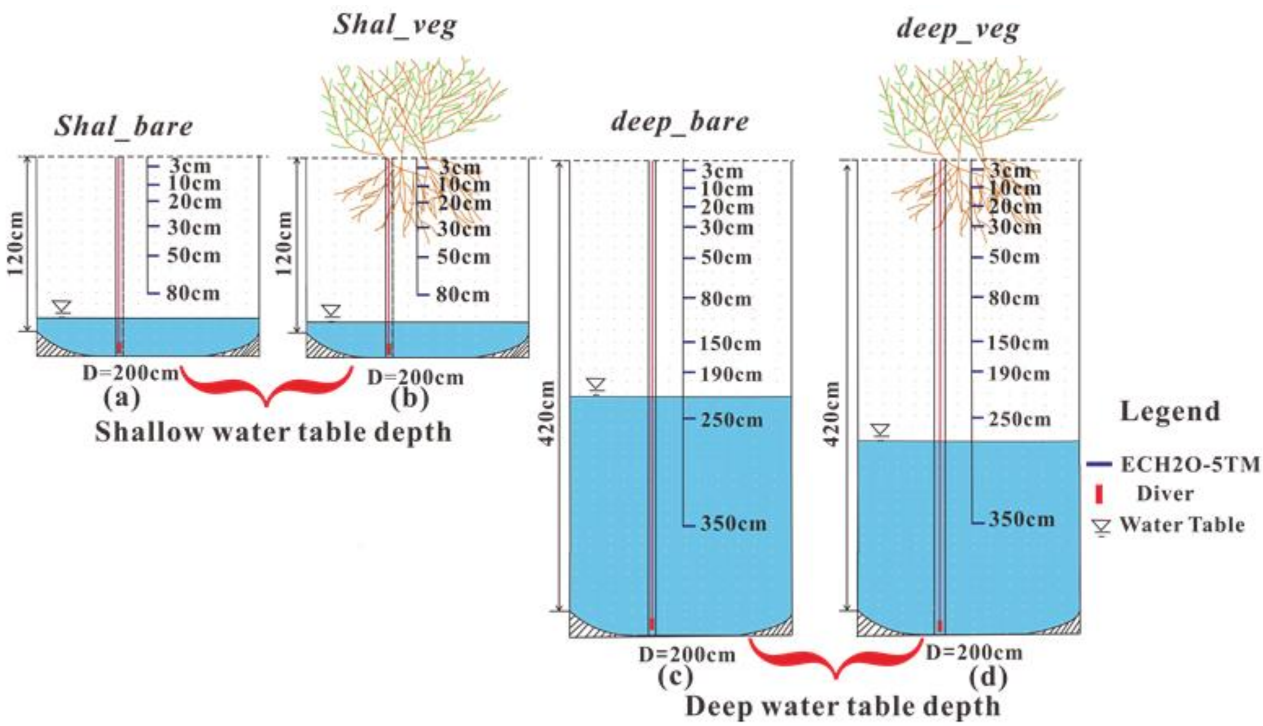

Fig. 2 Two pairs of lysimeters with different water-table depths. (a) *shal_bare* has no vegetation and an initial water-table depth of about 1 m; (b) *shal_veg* has a *Salix psammophila* with an initial water-table depth of about 1 m; (c) *deep_bare* has no vegetation with a water-table depth of about 2 m; (d) *deep_veg* also has a *Salix psammophila* plant with water table depth about 2.8 m.

2.3. Data collection

We measured volumetric soil moisture content in the *shal_* lysimeters at the depths of 3, 10, 20, 30, 50, and 80 cm using ECH_2O-5TM probe (Decagon Inc., USA ±1 ∼ 2 %), and in the *deep_* lysimeters at the depths of 3, 10, 20, 30, 50, 80, 150, 190, 250 and 350 cm (Fig. 2). Following the protocol of Cobos and Chambers (2010), we calibrated the sensors before installation. The data were logged with an interval of 5 min. At the Henan County national weather station, precipitation, wind speed and direction (around 10m height), air pressure, relative humidity, and air temperature were measured and logged hourly. We also measured groundwater levels with an interval of 5 minutes for the two growing seasons from 1 July 2015 to 13 Oct 2015 (the first growing season) and from 23 April 2016 to 30 November 2016 (the second growing season) using CTD-diver installed at the bottom of the lysimeters. At the same time, we used another diver sensor Baro-Diver installed to measure the air pressure for correcting the measured groundwater level. Also, sap flow sensors EMS 62 (EMS Brno) with stem heat balance method [Domi et al., 2014] were installed in *deep_veg* to measure sap flow velocity from April to November 2016.

The root distributions under the different water table depths were measured at two nearby locations: one was from a dune depression with a low depth to groundwater, and the other was on a sand dune with a high depth to groundwater. The shrubs were dug out and the roots were sieved and washed at the sampling day. The cleaned roots of each sample were weighed.

2.4 Soil water balance and interception threshold

We estimated the water budgets (Gong et al. 2020) for all the four lysimeters using the following water balance equation:

$$\frac{dS}{dt} = P_e - ET - R \qquad (1)$$

where dS/dt is the total water storage change in the lysimeters (cm/d), P_e is the total precipitation (cm/d), ET is the actual evapotranspiration (cm/d), and R is the surface runoff (cm/d). The surface runoff during the experiment can be neglected because no runoff occurs in the lysimeters, which is also the case in the project area (Wu et al. 2012, Zhang et al. 2018). The daily average soil moisture at the different depths was interpolated between the measurement points using linear interpolation (Fig. 3). The total water storage in the lysimeter can be estimated as follows:

$$\frac{dS}{dt} = \Delta S_u + \Delta S_g \qquad (2)$$

where S_u is the water storage in the unsaturated zone and S_g is the water storage in the saturated zone. We can calculate S_u.and S_g according to Fig. 3.

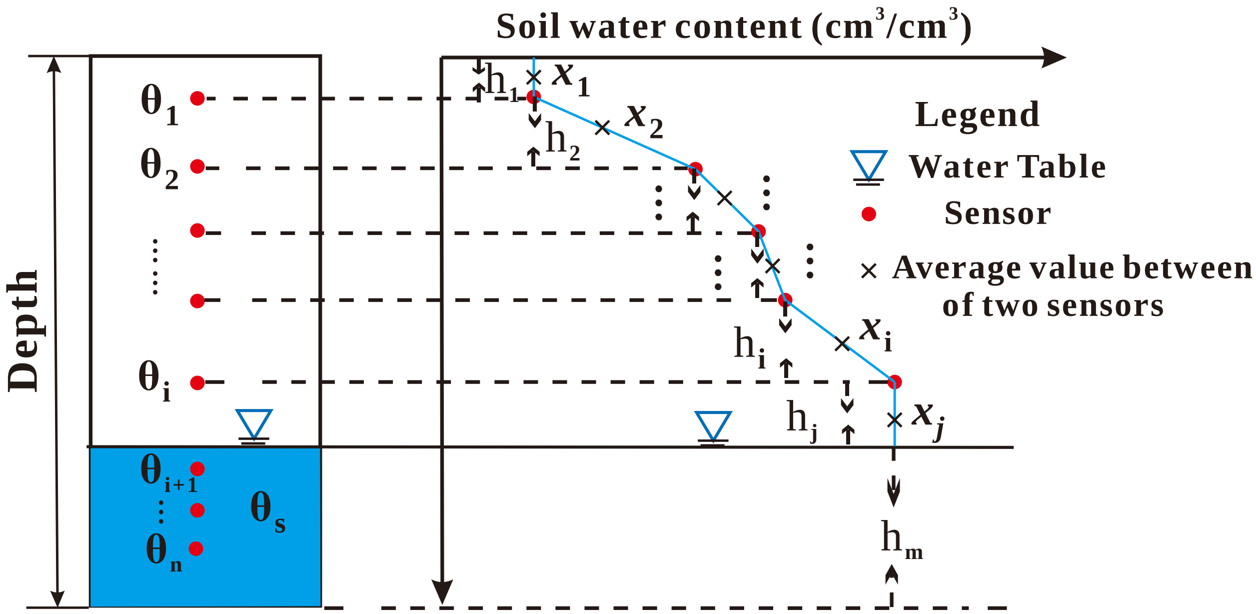

Fig 3. Schematic diagram of the sensors in the saturated and unsaturated zone and an example of soil water content profile (Gong et al. 2020). The change of storage and thus evapotranspiration can be estimated by comparing the soil moisture profiles and the groundwater levels between two periods in time (Daily, in this case). To calculate the water content on a specific day, the average values between two sensors (indicated with xi in the diagram) were weighted by the distance between sensors (h_i).

Another aspect we can explore with our experimental setup is the identification of the critical threshold of precipitation required for infiltration to occur. The critical threshold corresponds to the interception capacity of the shrubs. By continuously comparing the changes of moisture content in the topmost soil zone with the measured precipitation rates, this threshold can be readily identified.

3. Results

3.1 Precipitation, potential ET and air temperature

During the two growing seasons (1 July 2015 to 13 Oct 2015 and from 1 April 2016 to 30 November 2016), there 93 rainfall events occured, which resulted in a total of 508.1 mm. The average precipitation per event was 5.5 mm, with individual events ranging from 0.1 to 58.1 mm. In summary, light rainfall events (< 10.0 mm) were the most frequent, whereas heavy events (≥ 10.0 mm) were infrequent but constitute a major contribution to the total precipitation.

We used the Penman-Monteith equation [Allen et al., 1998] to calculate potential evapotranspiration (ET_0). The potential ET provides general information on the climatic forcing conditions in the project area. Note, however, that actual evapotranspiration rates were calculated using our lysimeter data (See section 2.4). Fig. 4b depicts potential evapotranspiration from July 1, 2015 to July 31, 2016. Potential evapotranspiration is closely following air temperature. The mean potential evapotranspiration was 3.4 mm/day with a standard deviation of 2.5 mm/day.

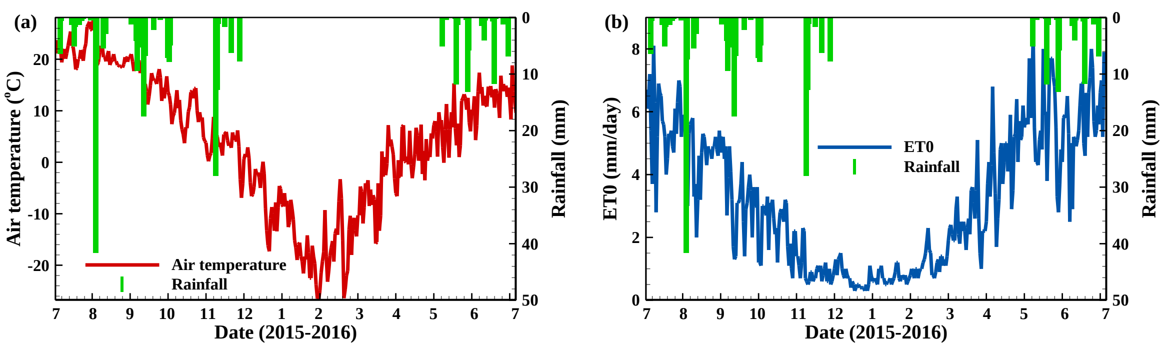

Fig. 4 Rainfall and air temperature at the field site (a), Potential evapotranspiration (ET_0) and rainfall (b).

3.2. Water Table Dynamics

The water table of the *shal_bare* and *shal_veg* showed a much more rapid response to rainfall and ET than that of the *deep_ bare* and *deep_veg*. The thicknesses of the vadose zone of *deep_ bare* and *deep_veg* were much larger than the extinction depth, and therefore the water table depth did not respond so rapidly as *shal_bare*. The water table of *deep_bare* and *deep_veg* showed a gradual rise in the first growing season (same amount of rainfall as *shall* lysimeters), because ET was less than for *shal_bare* and *shal_veg* and there was a net recharge from the unsaturated zone.

In the first growing season (2015), groundwater levels in *shal_bare* and *shal_veg* declined due to ET (Fig. 5a). From July 1 to August 31, the downward trends were basically the same for the two *shal_* lysimeters because transpiration was relatively small in the first growing season. After September 23, the water table depth in *shal_veg* was deeper than for *shal_bare*. It indicates that shrubs began to take up groundwater resources as a result of roots growing vertically. On the other hand, rainfall events smaller than 5 mm/day did not affect groundwater levels in the two *shal_* lysimeters. Rainfall events larger than 5 mm/day resulted in a response of the groundwater table, whose magnitude depended on rainfall amount and soil water content. Note that the shrubs were very small at this stage, so the effect of interception was not important.

In the second growing season (2016), groundwater levels for *shal_veg* and *shal_bare* started to deviate significantly as the shrubs grew larger with an increasing effect of root water uptake in *shal_veg*. The Diver sensor was placed 1 m below the ground surface to measure groundwater level (Fig. 2b), and the recorded water table depth remained constant at 1 m depth in *shal_veg* after June 6, 2016, indicating that the water table depth was below 1 m (Fig. 5b). There was almost no groundwater in *shal_veg* as indicated by in-situ groundwater level measurements on September 19, 2016 and soil moisture measurements (Fig. 6e). Besides, the water table depth decreased with ~0.63 cm/day in *shal_bare* after middle August 2016. In this case, evaporation from bare ground caused the groundwater level to decrease (Fig. 5b).

The initial water table depth of the *deep_bare* lysimeter was around 2m, and the *deep_veg* lysimeter was about 2.8m, respectively. Due to technical reasons, the water table depths could not be set to an equal level at the beginning of the experiment. The groundwater levels in *deep_veg* and *deep_bare* show similar dynamics during the first growing season (Fig 5c). The groundwater levels increased with 0.38 and 0.3 cm/day in *deep_veg* and *deep_bare*, respectively. It implies that root water uptake did not prevent groundwater recharge from occurring.

In the second growing season, groundwater levels continuously decreased with ~0.54 cm/day in *deep_veg* (Fig 5d). The difference in groundwater levels of *deep_veg* compared to *deep_bare* is indicative of the rate of *Salix psammophila* to uptake soil moisture and groundwater. The groundwater level decline was larger in the dry period (from April 23 to July 31 2016) (0.65 cm/day) than in the wet period (from August 1 to November 30 2016) (0.4 cm/day). This indicates that heavy rainfall would slow down *Salix psammophila* consumption of groundwater. Groundwater levels still increased during the second growing season at a rate of ~0.13 cm/day for *deep_bare*.

Overall, our results show that the presence of vegetation affects the groundwater table in the following way: (1) in the first growing season (2015.7.1-2015.10.13), *Salix psammophila* had no effect on the water table depth of *deep_veg*, and a small effect on the *shal_veg*. (2) After the beginning of the second growing season (starting around May 2016 and finishing around November), *Salix psammophila* affected the groundwater levels. Firstly, *Salix psammophila* affected the shallow groundwater in *shal_veg* from May 1 (Fig. 5b). While *Salix psammophila* influenced significantly the deep groundwater level in *deep_veg* from June 11 (Fig. 5d). (3) Although heavy rainfall events occurred from August 12 to August 20, 2016 (the amount of rainfall was 150 mm), groundwater levels did not increase in *shal_veg* (Fig. 5b) and *deep_veg* (Fig. 5d). However, the groundwater level increased by 42.5 cm in *deep_bare*. This suggests that *Salix psammophila* absorbed the infiltrating water in *shal_veg* and *deep_veg*. While analyzing groundwater level dynamics provides insights into groundwater recharge, little can be said about soil moisture storage dynamics. The soil moisture loggers provide additional information on this aspect.

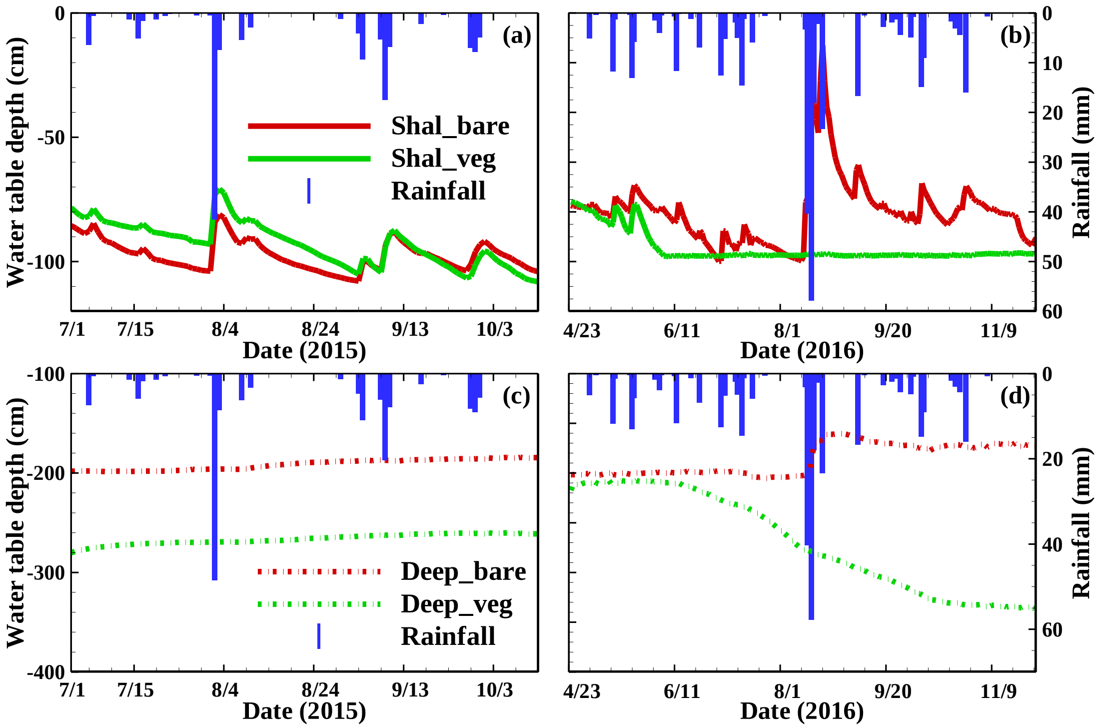

Fig. 5. The fluctuation of water table depths during the experimental periods (2015.7.1-2015.10.13 and 2016.4.23-2016.11.30) for the four different lysimeters. (a) and (b) represent water table depth changes with time in the two growing seasons for the two *shal*_lysimeters (green and red lines indicate *shal_veg* and *shal_bare*, respectively); (c) and (d) show water table depth changes with time in two growing seasons for the two *deep*_lysimeters (green and red dotted lines are for *deep_veg* and *deep_bare*, respectively). The blue bar indicates that rainfall events occurred.

3.3 Soil Water Dynamics and critical precipitation threshold for infiltration

Figure 6 shows a comparison of soil moisture variations in the lysimeters with shrubs and without shrubs, illustrating the impact of soil water uptake by the *Salix psammophila* shrubs. Soil moisture kept relatively stable within the profile during the first growing season in *shal_veg* (Fig. 6a). Compared to Fig. 6b, *Salix psammophila* significantly affects the distribution of soil moisture content from the ground surface to 50 cm depth. In the spring of the second growing season of 2016, soil moisture at different depths slightly decreased in response to the transpiration demand. With the further growth of *Salix psammophila* and large transpiration demand in summer (from July to September 2016), soil moisture content significantly decreased from the ground surface to 80 cm depth. Soil moisture content at deeper depths did not directly respond to rainfall events during the experimental periods, with the exception of a few heavy precipitation events (e.g., 13 August 2016). It can be seen that infiltrated water firstly increased soil moisture, which is subsequently consumed by *Salix psammophila*.

In *shal_bare*, the effects of soil surface evaporation only extend down to 20 cm depth (the left panel of Fig. 6b). Below 20 cm depth in *shal_bare* in 2015, soil moisture content shows only very small fluctuations, while soil moisture content in the upper 20 cm falls and rises quickly in response to evaporation and infiltration of rainfall. During the second growing season (Fig. 6f), evaporation could cause soil moisture to decrease until 70cm depth. However, when heavy rainfall events occurred (e.g., 13 August 2016), soil moisture content rapidly increased between the ground surface and a depth of 70cm.

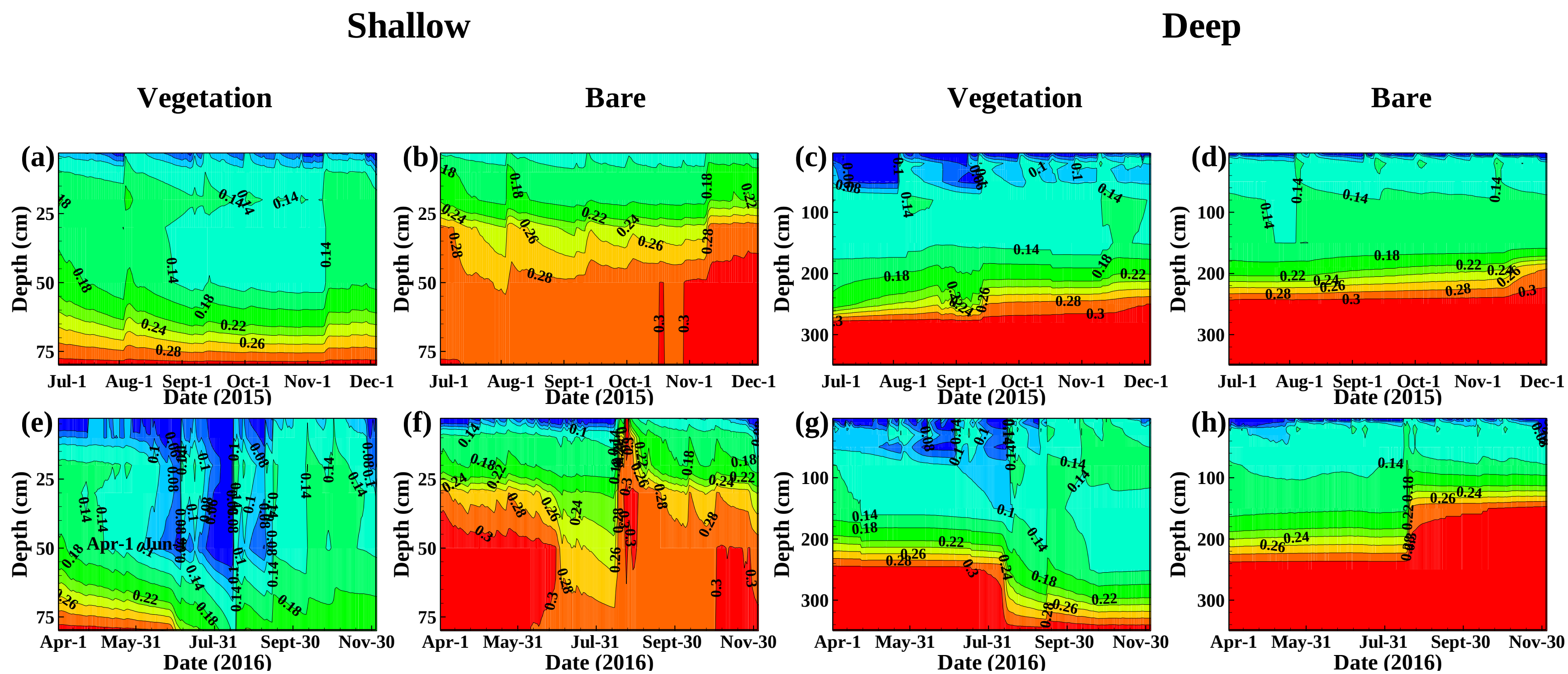

Fig. 6 Variation of soil moisture content. (a) and (b), (c) and (d), (e) and (f), and (g) and (h) represent soil moisture changes in space and time in two growing seasons (2015.7.1-2015.11.30 and 2016.4.1-2016.11.30) in *shal_veg*, *shal_bare*, *deep_veg* and *deep_bare*, respectively.

Unlike the *shal_veg* and *shal_bare*, the *deep_veg* features a relatively extended vadose zone (~ 2.8 m). Soil moisture content in the 0-60 cm soil layer was significantly lower than for *shal_veg* from July, 2015 onwards. This is related to the deeper water table depth, thus capillary rise has a limited influence on the soil water content of the upper soil layer of 0-60 cm. Compared to the first growing season, the main difference was that from August 2016 onwards soil moisture decreased for the 160-350 cm layer. The abrupt decrease in soil moisture content by the end of the second growing season is consistent with a decrease of the groundwater level (Fig. 5d).

Soil moisture content for the 0-10 cm soil layer (in *deep_bare*) was relatively low because of high atmospheric evaporative demand and limited or no capillary rise from the groundwater during the experimental period (Fig. 5d). Soil moisture content for the 150-250 cm layer showed an increasing trend as a result of the infiltration water during the period (Fig. 6h). This demonstrates that groundwater recharge took place under bare soil conditions.

To identify how the presence of vegetation affects the critical threshold of precipitation for infiltration to occur, the precipitation data can be juxtaposed with soil moisture data. Only for rainfall events exceeding 6.0 mm, an increase of soil moisture was observed for both vegetated and non-vegetated conditions. Under vegetated conditions, smaller precipitation events did not change the soil moisture in an observable way. For example, around August 12, 2016, soil moisture at a depth of 50 cm in the shallow, vegetated system was around 0.035 cm^3/cm^3, while for non-vegetated conditions soil moisture was 0.246 cm^3/cm^3. The increase of soil moisture in response to a precipitation event is also significantly affected by the presence of mature shrubs. For example, the change of soil moisture storage for non-vegetated conditions (5.98 cm) is larger than that of vegetated conditions (4.91 cm) during the same period.

3.4 Estimation of actual evapotranspiration (ET)

The cumulative ET estimation using the water balance equation for each lysimeter is shown in Fig. 7 for the two growing seasons. Assuming that the shrubs do not significantly affect the soil surface energy budgets, the differences in ET between the *shal_veg* and *shal_bare*, and between the *deep_veg* and *deep_bare* are indicative of differences in transpiration for the two different water table depths. The ratios of ET to precipitation averaged over the two seasons are 1.33 for *shal_veg*, 1.05 for *shal_bare*, 1.45 for *deep_veg* and 0.83 for *deep_bare*. For the two shrubs in *shal_veg* and *deep_veg*, groundwater contributes about 15.2% and 27.6% to total ET, respectively, through root water uptake, causing a drop in groundwater level (Fig. 5b and 5d). Without shrubs, *deep_bare* shows a net water gain as indicated by the rise of groundwater level at the end of the second growing season (see Fig. 5d).

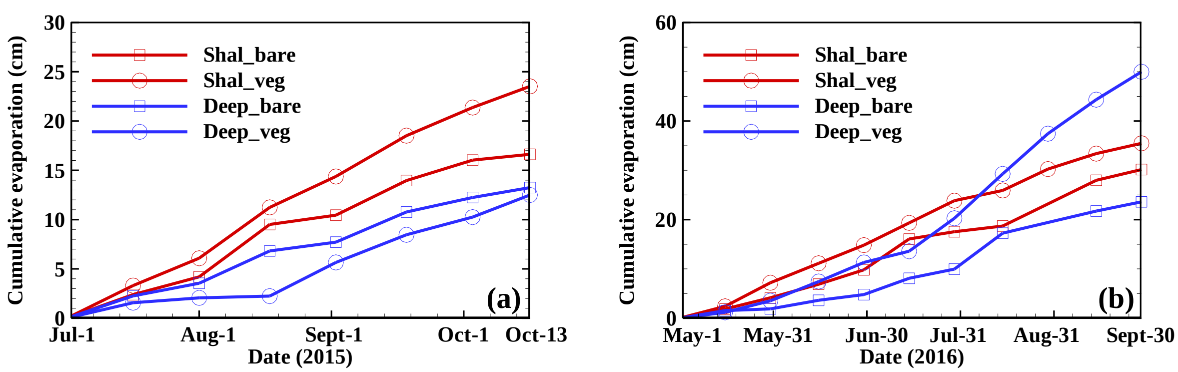

Figure. 7 The cumulative evapotranspiration in *shal_veg* (red circle line), *shal_bare* (red square line), *deep_veg* (blue circle line) and *deep_bare* (blue square line) for the years 2015 (left) and 2016 (right)

It was found that the cumulative evapotranspiration in *deep_veg* was smaller than that in *deep_bare* in 2015. The reasons for this apparently surprising result might be: (1) Water table depth was deeper in *deep_veg* than that in *deep_bare*. That means that soil moisture along the profile in *deep_bare* was higher than that in *deep_veg* (Fig. 6c and 6d); (2) *Salix psammophila* was small, it could not absorb much water from dry soil, and (3) surface ground obtained less water as a result of vegetation interception, for example, the change of soil moisture content at 3 cm depth in *deep_veg* and *deep_bare* were 0.019 cm^3/cm^3 and 0.038 cm^3/cm^3 respectively after a rainfall event (5.9 mm).

The total mean sap velocity of *Salix psammophila* in *deep_* was 0.015 kg/h with a standard deviation of 0.028 kg/h (Fig. 8). The value of sap velocity was highest in summer, followed by autumn, and the lowest in spring. It can be seen that heavy rainfall events caused sap flow to decrease even though heavy rainfall events effectively increased soil moisture for deep soil layers. That is because heavy rainfall is associated with less incoming radiation, higher relative air humidity and lower air temperature. Zhao and Liu [2010] obtained similar results.

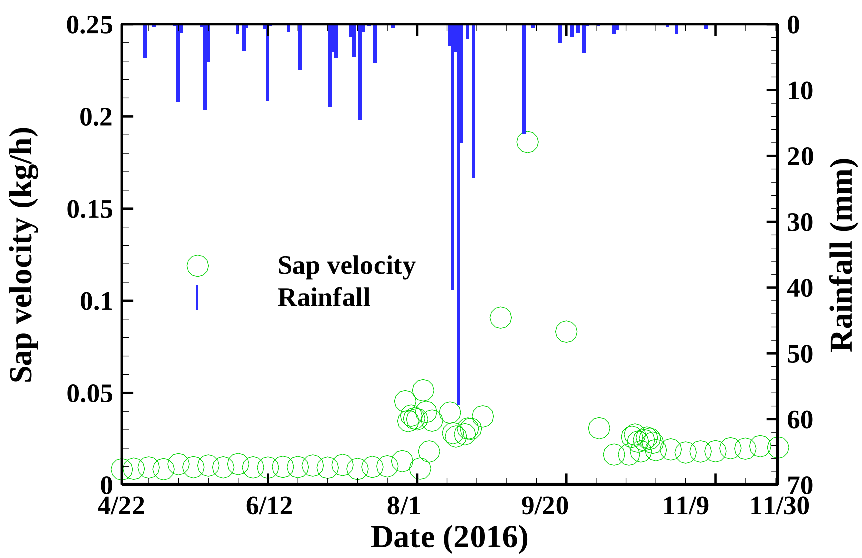

Fig. 8 Sap velocity (Kg/h) in response to rainfall event in *deep_veg*

3.5 Root distribution

To understand how different water table depth conditions affect the development of the root system, we analyzed the root distribution of two *Salix psammophila* taken from places near the field site with different water table depths (one from a sand dune, and the other one from a dune depression). The root distributions are different as a function of the water table depth (Fig. 9). The *Salix psammophila* in the dune depression has mainly roots between 0 and 60 cm depth. The root length density decreases with depth in this case, which is in correspondence to the findings of Zhu et al. [2016]. When the *Salix psammophila* is located on the sand dune, the maxima of the root densities are located between 0-20 cm and 80-120 cm depth. The root length density decreases with depth going downwards to 20-60 cm depth, but increases again for the layer between 60 and 120 cm depth and decreases below 120 cm depth. The root distribution indicates that *Salix psammophila* may not only absorb shallow soil water but also consume deep soil water when the groundwater level is relatively deep.

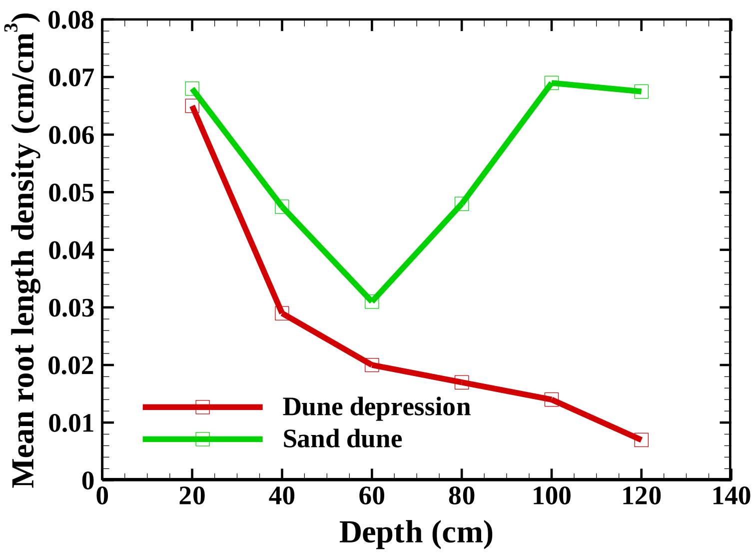

Fig. 9 Mean root length density as a function of depth for *Salix psammophila* (red box and green box represent root length density for dune depression and sand dune, respectively. Water table depth of sand dune was larger than that of dune depression).

4. Discussion

The three questions raised in the introduction are discussed in the following sections.

4.1 Influence of vegetation on groundwater recharge and water table dynamics

In our experimental setup with the lysimeters, groundwater recharge can easily be identified through a rising water table. Whether or not groundwater recharge occurs in response to precipitation depends on the intensity and duration of precipitation [Owor et al., 2009], the depth to groundwater [Nazarieh et al., 2018], the hydraulic properties of the unsaturated zone ［Wang et al., 2009] as well as the antecedent soil moisture conditions [Manfreda et al., 2005] which themselves are influenced by the presence of vegetation (see upcoming section 4.2). Many of these factors vary in time and it is thus not possible to define a “critical” precipitation amount that leads to groundwater recharge. However, our study clearly shows that the presence of mature shrubs greatly affects the potential groundwater recharge. In Fig. 5a (shallow conditions and at that time where the shrubs are still very small and their influence thus less important) even small rainfall events result in groundwater recharge for both vegetated and non-vegetated conditions. Note that essentially no groundwater recharge occurs for deep conditions, independent of the presence of vegetation. However, later during the year (2016) when the shrubs have grown considerably, groundwater recharge exclusively occurs for the non-vegetated, shallow conditions (see e.g. period after June 6, 2016). Not even the large precipitation event from August 15, 2016 of 58 mm resulted in groundwater recharge for the shallow, vegetated conditions.

During periods where no groundwater recharge occurs, the decline of the water table indicates a capillary rise, uptake through shrubs or phreatic (direct) evaporation. While the shrubs are still small (Fig. 5a) no significant difference in the decline of the water table between vegetated and non-vegetated lysimeters can be observed. However, as the shrubs grow, their consumption of groundwater is evident in the increased rate of decline of the water table for both shallow and deep groundwater table conditions. For *shal_veg* the average decline rate was 1.5 cm/day between May 23 and June 3, 2016, but only 0.8 cm/day for *shal_bare*. For *deep_veg* and *deep_bare*, the decline rates were 0.5 cm/day for the vegetated and 0.1 cm/day for the non-vegetated conditions for the period between August 21 and November 26, 2016, respectively. These results suggest that Salix *psammophila* consumes groundwater by extracting groundwater from the capillary fringe. This is consistent with Ohte et al. [2003] who observed that *Salix psammophila* used both soil water and groundwater. Our results confirm this observation, as the vegetated conditions can result both in a decline of the water table as well as a reduction of soil moisture.

4.2 The influence of the presence of shrubs (versus bare soil) on the soil water balance

The presence of shrubs can influence if and how soil moisture increases in response to precipitation events. Interception, for example, can prevent soil moisture in the upper soil layers to increase in response to precipitation. Our data clearly indicate that the presence of shrubs reduces and sometimes prevents an increase of soil moisture. The presence of vegetation thus reduces the potential for groundwater recharge. For precipitation events exceeding the minimal threshold of 6 mm, vegetation still exerts a major influence on soil moisture dynamics - not unexpectedly so. This indicates that for soil water dynamics, the annual cumulative precipitation rates are not informative. Only precipitation events exceeding this threshold should be considered. For the meteorological conditions prevailing in the project area, this is of significant importance because 15.8% of the annual precipitation (for the year 2016, for example) is composed of events smaller than this critical threshold. The interception loss is likely to increase with the growth of the shrubs.

4.3 Root growth and evapotranspiration under different water table conditions

Our previous analysis of soil moisture and water table dynamics suggests that *Salix psammophila* can consume groundwater (either directly or indirectly within the capillary zone above the water table), as well as soil water stored close to the surface. This requires an adaptation of the root system in response to the hydraulic conditions present. Based on analysis of two shrub root densities, the root length density of *Salix psammophila* has two maxima if the depth to groundwater is large: one between 0 and 20 cm depth, and another between 80 and 120 cm depth. Similar results have been found in other studies. For example, Huang et al. [2016] also observed two maxima of the root length density of *Salix psammophila*. Fan et al. [2017] pointed out that the presence of a water table can draw roots deeper to tap its capillary rise. They also found that the dimorphic roots or deep roots are frequently observed in upland shrubs in season-dry climates when groundwater becomes accessible.

The field analysis of root densities where the water table is much closer to the surface indicated that there was only one maximum of root density. There are two possible reasons for this: Either, the precipitation and subsequent increase of soil moisture in the upper soil layer is sufficient to provide all water required by the shrub. It is also possible that the capillary rise of groundwater provides a sufficient supply of water (or a combination of both). The shrubs thus do not need to increase its root density additionally in the capillary zone. Figure 10 shows a conceptual model of root distributions for two different water table conditions.

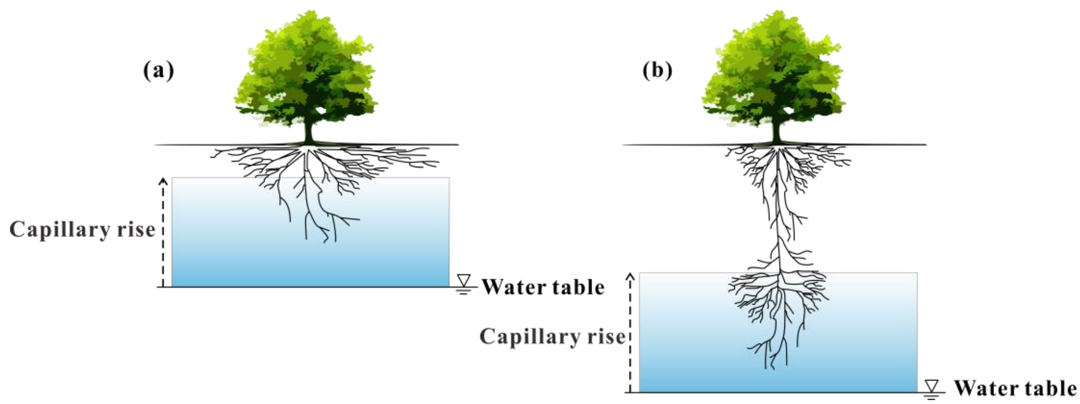

Fig. 10 Conceptual model of shrub rooting density for two different depths to groundwater. (a) The uppermost soil layers are supplied with water through precipitation, as well as capillary rise. Only one maximum of root density can be observed. (b) deep water table conditions with two maxima: Roots develop in the uppermost soil layers to efficiently uptake soil moisture originating from precipitation. A second maximum is observed in the capillary zone above the water table. Between the two maxima, soil moisture is consistently low and therefore the shrubs do not invest a lot of energy to grow their roots in this area.

To fully understand these adaptations of shrub roots in response to the hydraulic regime, more research is required. However, our results indicate that the distribution of roots significantly varies as a function of the hydraulic conditions. This is of outstanding importance and should be considered explicitly in any modeling attempt.

In this experimental setup, the total evapotranspiration rate of *Salix psammophila* under deep conditions was 9.0 % higher than for the shallow one. This might be related to the fact that with a developed dimorphic root system water uptake is increasingly efficient. The roots in the upper layer absorb the incoming precipitation, while the roots close to the capillary fringe above the water table continuously tap the upward flux sustained through capillary rise.

4.4 Implications for management

Our findings have important implications for the management of the *Salix psammophila* plantations in the Ordos plateau. To effectively control and prevent desertification, *Salix psammophila* has been planted in large areas. However, our results indicate that the presence of vegetation reduces or even prohibits groundwater recharge. Groundwater was consumed by *Salix psammophila*. However, *Salix psammophila* plantations are indeed suitable for afforestation due to their low cost and the ease with which they are established under extremely desertified conditions [An et al., 2007]. We recommend that the density of the planted *Salix psammophila* has to be carefully evaluated in the Mu Us desert region. Areas of bare ground between two *Salix psammophila* constitutes an important area for recharge. If the shrub density is not too high, groundwater recharge is maintained for current climate conditions. Further studies regarding the role of optimal water table depth and distance between two *Salix psammophila* shrubs are needed.

Lysimeters provide us with an excellent way that allows us to explore the complicated hydrological processes in realistic conditions. To a certain extent, our lysimeters may limit the growth of the roots. This might become an important point if the plants grow older. For the young plants we used this is not expected to be a signficant issue.

5. Conclusions

Four lysimeters were installed at the study site in the Mu Us desert of northwest China. Two of them were kept at a shallow water table depth and the other two at a relatively deep water table depth. Each of the pairs had one lysimeter with bare soil (*shal_bare* and *deep_bare*) and one lysimeter vegetated by *Salix psammophila* (*shal_veg* and *deep_veg*). Key atmospheric and vegetation variables and soil conditions (i.e. air temperature, precipitation, sap velocity, soil moisture content and groundwater level) were measured throughout the experiments from July 1 to December 1, 2015, and April 1 to November 30, 2016. The following conclusions can be drawn:

(1) For the current climate conditions in the project area, the presence of *Salix psammophila* reduces groundwater recharge through the increased of interception and transpiration. Our experiments showed this reduction independently of the depth to groundwater. If *Salix psammophila* are planted over large areas, the shrub density has to be carefully considered to jointly manage water resources and combat desertification. If the plant density is too high there is a significant risk to reduce groundwater recharge to negligible quantities.

(2) During the experimental period, the presence of shrubs increases the critical threshold of precipitation required to increase soil moisture due to interception. In our study, precipitation events smaller than 6 mm did not lead to an increase of soil moisture on the surface ground. For the annual water balance, this means that precipitation rates are effectively reduced by around 16%. This critical threshold is dependant on the canopy, and more mature shrubs will likely increase this number.

(3) Plants develop dimorphic systems to increase water uptake in the upper soil zone as well as from the capillary zone above the water table. The efficiency of water uptake and thus evapotranspiration rates are increased if dimorphic roots develop.

(4) From a methodological point of view, the lysimeters allowed for controlled experiments outside of the laboratory. Our study is an example of how lysimeters provided quantitative insights and valuable information into complex processes, such as infiltration and soil moisture dynamics under different vegetation and water table conditions.

Acknowledgements

This study was supported by National Natural Science Foundation of China (No. 41902249, U1603243, 41230314), and the Key Research and Development Program of Shaanxi (Program No. 2020SF-405). Gong Chengcheng is very grateful to the Chinese Scholarship Council (No. 201906560022) for providing an opportunity to be a visiting Ph.D. student at the University of Neuchâtel. The analysis was also partially supported by the SAFEA: High-End Foreign Experts Project (No. G20190027031). We greatly appreciate Qiangming Wang and Ming Zhao in the field experimental work. We thank the editor and one anonymous reviewer for their valuable comments which have helped to improve the paper significantly.

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