Authors' responses to Reviewers comments on the manuscript of "Differential response of plant transpiration to uptake of rainwater-recharged soil water for dominant tree species in the semiarid Loess Plateau". Manuscript ID: hess-2021-351.

Dear Reviewer,

We deeply appreciate you for giving us an opportunity to revise our manuscript. The point-to-point responses (responses in upright Roman) to the Reviewer comments (*original comment and query in Itali*) can be observed in the PDF file named "**Response to Reviewer 2**". In addition, the revised manuscript is highlighted the changes by using the red colored text in the manuscript (track-changes version), and append at the end of this file. We know that the revised manuscript is no need to upload at this time, we added it at this time to facilitate review our responses and corresponding revisions. The revised manuscript at the end of this PDF file can be ignored if it is no need.

Reviewer 2

Major Comments:

1. Personally, I find the terms 'rainwater uptake' and 'water consumption' (both central to this manuscript) rather ambiguous. I would recommend using 'transpiration' instead of 'water consumption. On the other hand, the term rainwater uptake can be confusing, as it seems to suggest that these trees take up water directly from rainfall. Some trees can indeed take up rainwater through their leaves, but this is not the case for the species included in this study. In my opinion, it would be better to refer instead to the 'uptake of recently recharged soil water' or similar (uptake of soil water that has been recharged from a recent rainfall event).

Response: Rewritten. Thanks for this meaningful suggestion, the terms of "water consumption" and "rainwater uptake" have been changed to "transpiration" and "uptake of rainwater-recharged soil water", respectively, throughout the revised manuscript. For example, the manuscript **Title** has been rewritten as "Differential response of plant transpiration to uptake of rainwater-recharged soil water for dominant tree species in the semiarid Loess Plateau" (Page 1 Lines 1-2).

In addition, the "RRS", abbreviation of "rainwater-recharged soil water", was used in this study for convenient reading and understanding. This abbreviation has been added at the first sentence in "**Abstract**" section as "Whether uptake of rainwater-recharged soil water (RRS) can increase plant transpiration in response to rainfall pulses requires investigation to evaluate the plant adaptability, especially in water limited regions where rainwater is the only replenishable soil water source." (Page 1 Lines 14-16). And this abbreviation has also been added at the first sentence in "**Introduction**" section as "Rainwater-recharged soil water (RRS) uptake by plants and plant transpiration in response to rainfall pulses drive the survival of plant species and ecosystem ecohydrological processes, especially in arid and semiarid regions where rainwater is the only replenishable soil water source (Berkelhammer et al., 2020; Gebauer and Ehleringer, 2000; West et al., 2012)." (Page 2 Lines 39-42).

The illustration to "rainwater-recharged soil water (RRS)" has also been added in the "**1 Introduction**" section as follows: "Generally, RRS uptake after a rainfall pulse refers to the root uptake of soil water that was recharged by recent rainwater, and can be quantified through water stable isotopes (Cheng et al., 2006; Meier et al., 2018)." (Page 2 Lines 42-44)

Furthermore, the abbreviation of "rainwater recharged soil water" is used for "RRS" but not "RRSW", mainly because the "RRSW" has been used as the abbreviation of "resistance rivet spot welding" based on research in *web of science*.

2. It would be very helpful if the authors could provide some additional information on the two studied tree species. The authors write (L.82-84): 'Hippophae rhamnoides and Populus tomentosa are typical dominant tree species, with high survival rate and drought tolerance, and occupy nearly 30% of the plantation area in this region (Liu et al., 2017; Tang et al., 2019)'. Could you give some species-specific information on e.g. their phenology or root system? How do the species differ, and are there any reasons to believe that they might respond differently to rain pulses in terms of transpiration and water source partitioning? Do you have any hypotheses? In addition, I would suggest the authors check the scientific names of the species. According to the World Flora Online, Hippophae rhamnoidesis not an accepted name but a synonym of Elaeagnus rhamnoides (L.) A.Nelson.

Response: Added and Corrected. In response to this meaningful suggestion, the relative sentences of species-specific information, two hypotheses, and the correct scientific names of the species have been added and corrected in the revised manuscript.

Firstly, in response to plant phynology and species-specific differ for these two studied plantation species, the relative sentences have been rewritten in "**1 Introduction**" section as follows: "*Hippophae rhamnoides* subsp. *sinensis* and *Populus tomentosa* are typical deciduous broadleaved tree species, with similar leaf expansion (April) and falling (November) periods, and occupy nearly 30% of the plantation area in this region (Liu et al., 2017; Tang et al., 2019). Our previous study indicated that *H. rhamnoides* generally took up soil water from 0−40 cm or > 100 cm soil depths and adopted large leaf water potential variation to cope with varied soil water conditions in this region (Tang et al., 2019). Meanwhile, *P. tomentosa* generally took up soil water from > 100 cm soil depth throughout the growing season in varied soil water conditions (Xi et al., 2018). In addition, mixed plantations of these two species were widely promoted by local government due to the higher soil and water conservation capacity than pure plantations in the original afforestation stage (Tang et al., 2019; Wang et al., 2020). Tang et al. (2019) also suggested that mixed afforestation with *Ulmus pumila*, a deciduous broadleaved tree species with similar leaf growth phenology to *H. rhamnoides*, increased the water source from 0−40 cm soil depth and the leaf water potential variation for *H. rhamnoides* compared with these values for this species in pure plantation." (Pages 3-4 Lines 81-93).

In previous studies, the water sources from soil depths were different between the two studied plantation species (Xi et al., 2018; Tang et al., 2019), with *H. rhamnoides* generally shifted its main water sources depending on soil water conditions, however, *P. tomentosa* generally absorbed relative stable deep soil water throughout the growing season in varied soil water conditions. These two plantation species exhibited similar leaf growth phenology such as leaf expansion (April) and falling (November) time. In addition, mixed with other plant species may altered the water sources and leaf water potential for *H. rhamnoides* or *P. tomentosa*. All of these different soil water uptake patterns for these two species in pure plantation, as well as the possibility of altered plant water sources and leaf water potential in mixed plantation, may affect the influence of rainwater-recharged soil water (RRS) uptake and leaf water potential on plant transpiration after rainfall pulses. And these affect may also different in pure and mixed plantations. Thus, "The specific objectives were as follow: (1) to investigate the influence of RRS uptake and leaf water potential on plant transpiration after rainfall events in pure plantation, and (2) to assess the mixed afforestation effect on these influences." (Page 4 Lines 100-102). And the two corresponding hypotheses can be observed in the second answer as follows.

Secondly, the two hypotheses have been added in the revised manuscript in "**1 Introduction**" section as follows: "Based on variations of plant water uptake from soil layers and/or leaf water potential for these species in Xi et al. (2018) and Tang et al. (2019), we hypothesize that (1) the influence of RRS uptake and leaf water potential on plant transpiration may differ for these species in pure plantations, and (2) these influences may differ for specific species in pure and mixed plantations." (Page 4 Lines 102-106).

The first hypothesis is mainly based on the majority of plant water sources from soil depths were different for these plantation species in pure plantation, which can be observed in Tang et al. (2019) and Xi et al. (2018). Thus, we hypothesis that the influence of RRS uptake on plant transpiration for these species may be different.

The second hypothesis is mainly based on our previous studies indicated that mixed afforestation between *H. rhamnoides* and *Ulmus pumila* altered both the majority of plant water sources from shallow soil layer and the leaf water potential for *H. rhamnoides*, compared with these values for this species in pure plantation (Tang et al., 2019). Thus, we hypothesis that mixed afforestation may alter the influence of RRS uptake and leaf water potential on plant transpiration for specific plant species, compared with these influences in pure plantation.

In addition, these tow hypotheses have also been test in "**4 Discussion**" section. In response to the first hypothesis, the relative sentence has been added: "Consistent with the first hypothesis, the influence of RRS uptake and physiological adjustment on plant transpiration was different for these species in pure plantations." (Page 20 Lines 445-446).

In response to the second hypothesis, the relative sentence has been added in "**4 Discussion**" section:

“In addition to these adjustments for specific plant species in mixed plantation, the significant influence of RUP and Ψ_{pd}–Ψ_m on SF_R for *P. tomentosa* in mixed plantation was also consistent with the second hypothesis (Fig. 6)” (Page 22 Lines 489-491).

Thirdly, in response to plant root distribution of these species, the plant root distribution was conducted in our present study. The method to investigate the plant root distribution were in the “2.5 Plant fine root investigation” subsection in “**2 Materials and methods**” section. (Page 9 Lines 220-227).

The results can be observed as in **Figure S2** as follows. The detailed sentences of these results to illustrated the plant water sources of these two species can be observed in “4.1 RRS uptake enhances plant transpiration for *H. rhamnoides* but not *P. tomentosa* in pure plantations” subsection in **“4 Discussion”** section as follows: “This may be mainly due to the greater proportions of fine root surface area distributed in the shallow soil layer for *H. rhamnoides* (40.85 ± 3.14%) compared to *P. tomentosa* (21.94 ± 2.3%) (Fig. S4).” (Page 19 Lines 422-424).

Also, in “4.2 RRS uptake enhances plant transpiration for coexisting species in mixed plantation” subsection in **“4 Discussion”** section as follows: “Mixed afforestation significant increased Ψ_{pd} for *P. tomentosa*, possibly due to the advantage of access to soil moisture recharged by rainwater through an increased root surface area in the shallow soil layer for this species in the mixed plantation (Fig. S4).” (Page 21 Lines 484-486).

Thus, the description of root distribution between these two species was not emphasized “**1 Introduction**” section.

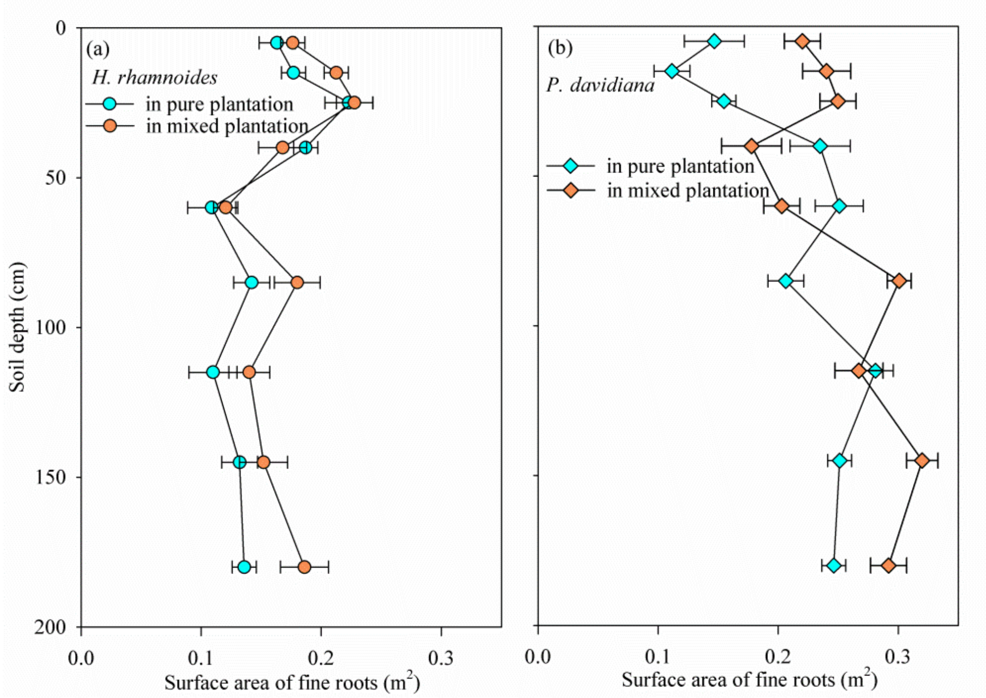
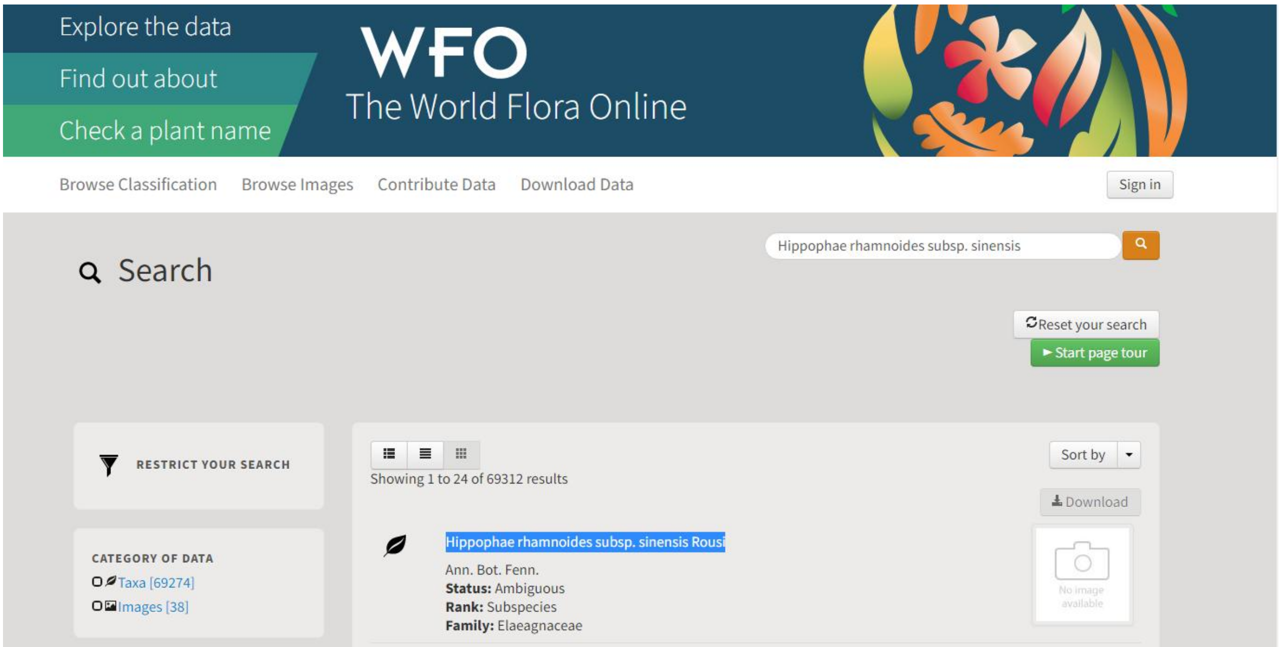


Figure S4. Variation in average (mean ± SD) surface area of fine root at different soil depths for *H. rhamnoides* and *P. tomentosa* in pure (a) and mixed (b) plantations. Error bars indicate the standard deviation (n = 3).

Fourthly, thanks for this careful examination; the Latin name of previous "*Hippophae rhamnoidesis*" has been corrected to "*Hippophae rhamnoides* subsp. *sinensis*" at the first appearance in "**Abstract**" and "**1 Introduction**" section, respectively, in the revised manuscript. Then, the acronym name "*H. rhamnoides*" was used throughout the manuscript.

The revised name of *Hippophae rhamnoides* subsp. *sinensis* can be observed in studies in Huang et al. (2018), and also in *World Flora Online* as follows:



References:

Huang, J. H., Li, G. Q., Li, J., Zhang, X. Q., Yan, M. J., and Du, S.: Projecting the Range Shifts in Climatically Suitable Habitat for Chinese Sea Buckthorn under Climate Change Scenarios, Forests, 9, 2018.

Tang, Y. K., Wu, X., Chen, C., Jia, C., and Chen, Y. M.: Water source partitioning and nitrogen facilitation promote coexistence of nitrogen-fixing and neighbor species in mixed plantations in the semiarid Loess Plateau, Plant Soil, 445, 289-305, 10.1007/s11104-019-04301-9, 2019.

Xi, B. Y., Wang, Y., Jia, L. M., Bloomberg, M., Li, G. D., and Di, N.: Characteristics of fine root system and water uptake in a triploid Populus tomentosa plantation in the North China Plain: Implications for irrigation water management, Agr Water Manage, 117, 83-92, 2013.

3. The authors have done extensive field and lab work, which is extremely valuable. However, I find the material and method section a bit hard to follow given not only the number of measurements but also the use of multiple approaches to address the same question (for example RUP – rainwater uptake proportion - vs MixSIR, or MIXSir with 7 soil depth intervals vs. MIXSir with 3 soil layers). This affects as well the interpretation of the results. Therefore, I would suggest the authors clarify the different steps in the methodology better, whether the chosen approaches are complementary, and how.

Response: Added and Clarified. Thanks for these meaning and helpful suggestions. The number of measurements and the complementary of RUP calculation and MixSIR method were added and clarified in "**2 Materials and methods**" section in the revised manuscript.

Firstly, the sample numbers for plant stems and soil water collection have been added in the revised manuscript in “2.4 Rainwater, plant stem, soil water, and leaf sample collection and measurement” subsection in “**2 Materials and methods**” section as follows: “There were 180 stem and 945 soil samples for water extraction, and 180 leaf samples for Ψ_{pd} and Ψ_{m} measurement, respectively.” (Page 8 Lines 206-207).

Taken plant stem samples as an example: For *H. rhamnoides* in pure plantation: 1 stem for each individual in each plot×3 individual in each plot×3 plots for this plantation ×5 rainfall events= 45 stmes. Thus, the total plant stems were: 45 for *H. rhamnoides* in pure plantation+45 for *H. rhamnoides* in mixed plantation+45 for *P. tomentosa* in pure plantation+45 for *P. tomentosa* in mixed plantation=180 plant stems.

Secondly, the complementary between RUP and MixSIR method have been added in the revised manuscript in “2.6.2 Calculation of RRS uptake proportion and water sources from different soil layers” subsection in “**2 Materials and methods**” section as follows: “In addition to RUP, the water uptake proportions from different soil layers were calculated on the first day after a rainfall event using the MixSIR program, to complement the analysis of plant water source variations in response to rainfall pulses. The RUP method only calculated the proportion of recent rainwater in the plant stem and did not include soil water before the recent rainfall event (Gebauer and Ehleringer, 2000; Cheng et al., 2006). The water taken up from different soil layers by the plant is a mixture of soil water before the recent rainfall event and the recent rainwater.” (Pages 10-11 Lines 265-270).

The RUP is the core analysis in the present study, which is calculated as the proportion of rainwater in plant stem (Gebauer and Ehleringer, 2000; Cheng et al., 2006), and indicated the uptake of rainwater-recharged soil water proportion (RUP) by plant from a recent rainfall event. The water uptake proportion from different soil layers is calculated through MixSIR method, and is used to complement analysis the plant water sources variation after rainfall pulses for *H. rhamnoides* or *P. tomentosa*. The difference of these two methods can be observed in **Figure explain 1** as follows. Indeed, the soil water after a recent rainfall event is the mixture of soil water before recent rainfall event and recent rainwater (**Figure explain 1**). The basic difference between RUP and results from MixSIR calculation, is the former method only calculated the proportion of rainwater (rainwater-recharged soil water) in plant stem after a recent rainfall event and not including soil water before rainfall event.

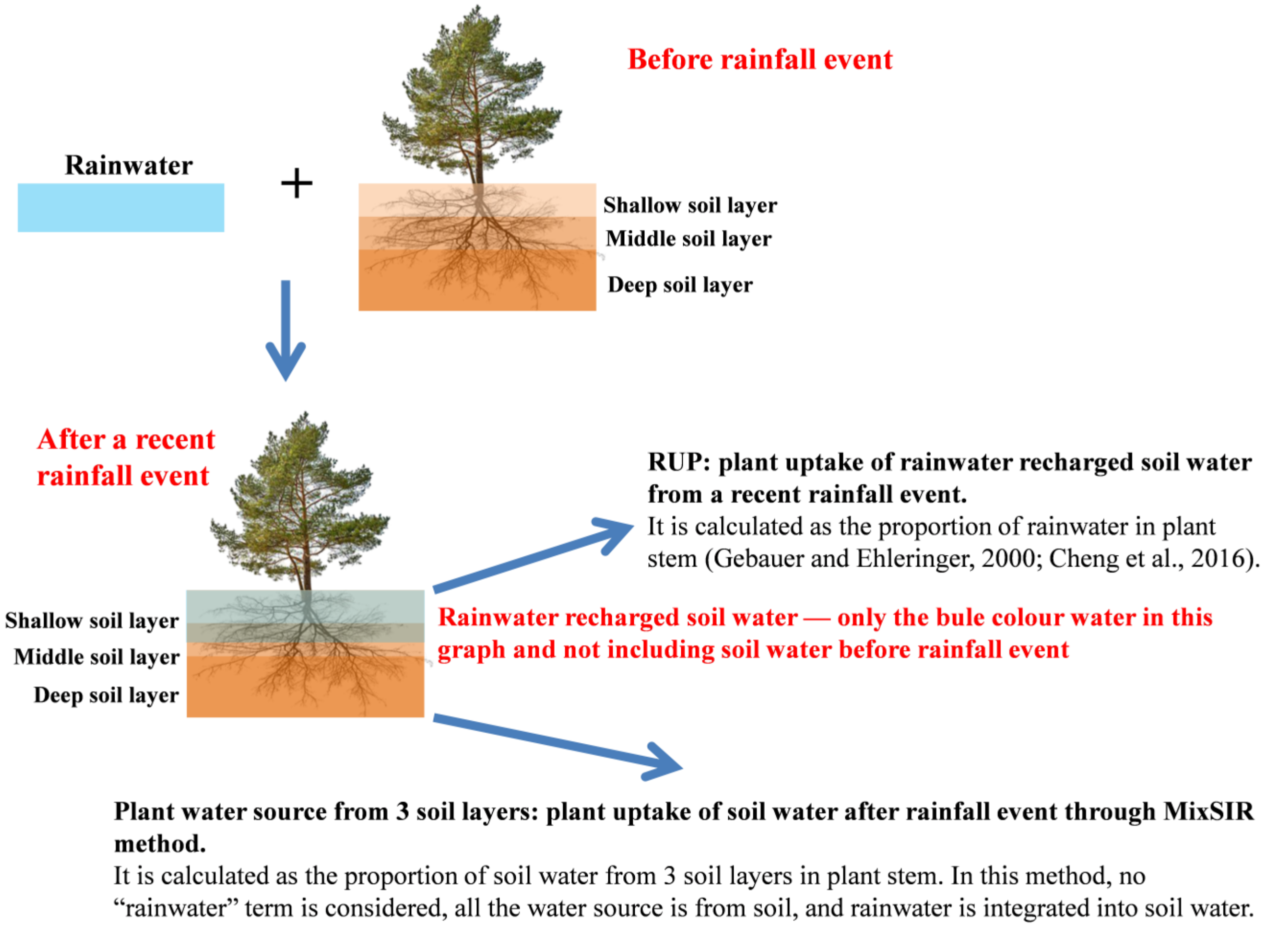


Figure explain 1 The schematic of plant uptake of rainwater-recharged soil water from a recent rainfall event and plant water source from 3 soil layers after rainfall event.

In the present study, the RUP and water sources from 3 soil layers is used to illustrate the mixed afforestation of these two species effect on plant water sources. The results indicated that mixed afforestation significantly increased the RUP for these two plant species, and significantly decreased the water uptake proportion from deep soil layer ($P < 0.05$).

The RUP and water sources from 3 soil layers were used to illustrate the two types of plant adaptation to cope with resource competition: (1) increased competition to rainwater-recharged soil water (RRS) from a recent rainfall event; and (2) minimized competition to deeps soil water, which is excessive consumption by plant and rainwater is the only replenish source to deep soil water. The detailed discussion of the first adaptation types can be observed in "4.2 RRS uptake enhances plant transpiration for coexisting species in mixed plantation" subsection in "**4 Discussion**" section as follows: "Generally, two types of adaptation can be adopted by plants to cope with resource competition: increased competition ability or minimized competition interactions (West et al., 2007). Consistent with the first adaptation type, mixed afforestation enhanced the RUP for *H. rhamnoides* and *P. tomentosa* (Figs. 3 and 7, Table S4)." (Page 21 Lines 479-482). The detailed discussion of the second adaptation types can be observed in same subsection as follows: "Furthermore, consistent with the second adaptation type, mixed afforestation significantly decreased the water uptake proportion from the deep soil layer for these species (Table S5)." (Page 21 Lines 495-496).

Thus, the plant water sources from different soil layers based on MixSIR method is the complement analysis for RUP calculation in the present study. These two methods together were used to discuss the two types of plant adaptation to cope with resource competition.

Thirdly, the detailed method of how to calculated water uptake proportions from different soil layers through MixSIR method has been rewritten in "2.6.2 Calculation of RRS uptake proportion and water sources from different soil layers" subsection in "**2 Materials and methods**" section as follows: "Firstly, the 7 soil depths (0–10, 10–20, 20–30, 30–50, 50–100, 100–150, and 150–200 cm) were combined into three soil layers (shallow, middle, and deep) based on the variation of soil water $\delta^{18}O$ and δD and SW, to facilitate water source comparisons. The shallow soil layer (0–30 cm) was vulnerable to rainfall, and exhibited higher soil water $\delta^{18}O$ and δD values and larger water isotope and SW variations (Table S3, Fig. S3). The middle soil layer (30–100 cm) was less vulnerable to rainfall, with high soil water isotope values and large water isotope and SW variations. The deep soil layer (100–200 cm) was relative stable, with low soil water isotope values and small water isotope and SW variation compared with shallow and middle soil layers. In addition, based on independent-sample *t*-test, no significant difference ($P > 0.05$) in soil water $\delta^{18}O$ and δD between different soil depths in the same soil layer in each plot ensured the feasibility of the combination of the three soil layers (Phillips et al., 2005). Then, the water uptake proportions from three soil layers were calculated using the MixSIR program (Moore and Semmens, 2008), with model input parameters being the average $\delta^{18}O$

and δD values in plant stem water and soil water at each soil layer in each plot." (Pages 11 Lines 271-283)

In the present study, firstly, as suggested in Phillips et al. (2005), differences in soil water δ^{18}O and δD at 7 depths were determined by independent-sample *t*-test, to ensure the feasibility of combining the three potential soil layers (0–30, 30–100, and 100–200 cm). Then, the plant water sources from these 3 soil layers were quantified using MixSIR method.

Table S3 The average (mean ± SD) and coefficients of variation (CVs, SD/mean) of soil water δ^{18}O and δD on the first day after 5 selected rainfall events, and daily soil water content (SW) from DOY 152 to 273 (1 June to 30 September) in *H. rhamnoides* pure plantation, *P. tomentosa* pure plantation, and *H. rhamnoides*–*P. tomentosa* mixed plantation.

	Soil depth	soil water δ^{18}O (‰)		soil water δD (‰)		SW (m^3 m^{-3})	
		average	CV	average	CV	average	CV
H. rhamnoides pure plantation	0–30 cm	-5.61±1.57	27.99	-41.53±11.68	28.12	0.13±0.025	19.23
	30–100 cm	-7.14±0.92	12.89	-52.37±6.47	12.35	0.1±0.012	12
	100–200 cm	-9.3±0.69	7.42	-68.66±3.53	5.14	0.09±0.006	6.67
P. tomentosa pure plantation	0–30 cm	-5.43±1.69	31.12	-42.08±11.91	28.3	0.13±0.026	20
	30–100 cm	-7.49±0.73	9.75	-51.34±4.56	8.88	0.09±0.008	8.89
	100–200 cm	-9.39±0.34	3.62	-67.36±3.79	5.63	0.08±0.005	6.25
Mixed plantation	0–30 cm	-5.68±1.73	30.46	-41.67±10.67	25.61	0.12±0.021	17.5
	30–100 cm	-6.57±1.08	16.44	-47.8±5.78	12.09	0.1±0.011	11
	100–200 cm	-9.07±0.5	5.51	-64.47±2.45	3.8	0.09±0.005	5.56

There are 45, 30, and 30 data for calculated the average water δ^{18}O and δD of shallow, middle, and deep soil layer in each plantation, respectively. The absolute value was used for CVs of soil water δ^{18}O and δD calculation.

To be noticed, although the δ^{18}O and δD values of soil water was more positive at middle (30-100 cm) than in shallow (0-30 cm) soil layer after 15.4 mm as in red cycle in Figure S7 as follows, the averaged δ^{18}O and δD after 5 rainfall events were more negative in middle than in shallow soil layer during the study period (Table S3).

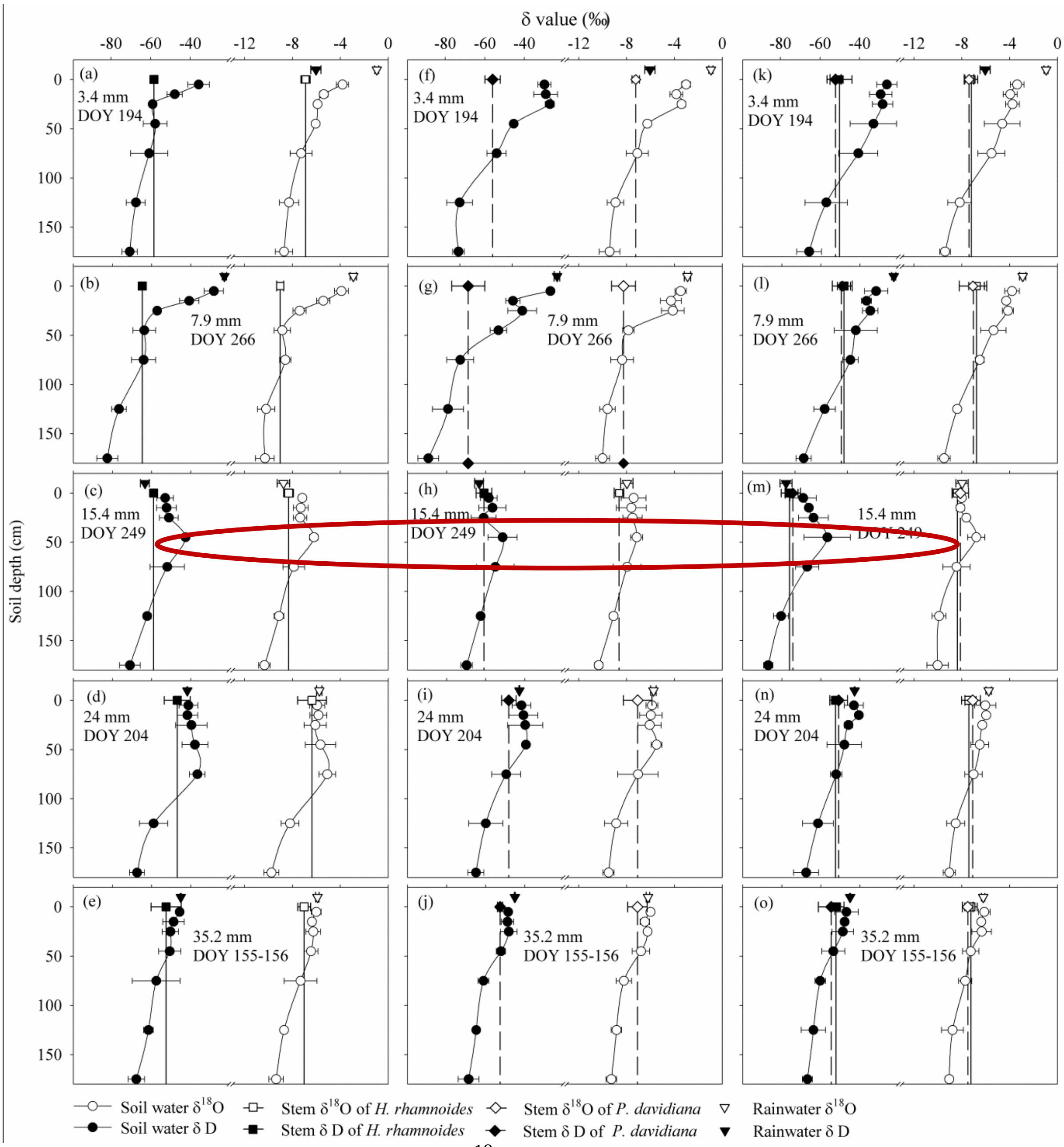


Figure S7. Variation in average (mean ± SD) δ^{18}O and δD of rainwater, stem water, and soil water at seven soil depths for *H. rhamnoides* in (a–e) pure and (k–o) mixed plantations and for *P. tomentosa* in (f–j) pure and (k–o) mixed plantations after 5 rainfall events. Error bars indicate the standard deviation (n = 3). The date of each 5 selected rainfall events is followed the corresponding rainfall amount value. The average rainwater δ^{18}O and δD for each rainfall event is calculated with 3 rainwater subsamples, which was divided from one rainwater sample.

References:

Cheng, X. L., An, S. Q., Li, B., Chen, J. Q., Lin, G. H., Liu, Y. H., Luo, Y. Q., and Liu, S. R.: Summer rain pulse size and rainwater uptake by three dominant desert plants in a desertified grassland ecosystem in northwestern China, Plant Ecol, 184, 1-12, 2006.

Gebauer, R. L. E., and Ehleringer, J. R.: Water and nitrogen uptake patterns following moisture pulses in a cold desert community, Ecology, 81, 1415-1424, 2000.
Phillips, D. L., Newsome, S. D., and Gregg, J. W.: Combining sources in stable isotope mixing models: alternative methods, Oecologia, 144, 520-527, 2005.

4. Where are the plantations where you conducted the measurements located? It would be good if you could provide a map to illustrate this. Also, what is the slope? Are there any terraces or other soil and water conservation measures? Are soil properties and land-use history similar across all nine plots included in the study? Do you have any information on the physical characteristics of the soils?

Response: Added. Thanks for these meaningful plot basic information suggestions, the detailed information have been added in the revised manuscript.

Firstly, for plots location, the plantation sites on the Loess Plateau of China has been added in “2.1 Study site” subsection in “**2 Materials and methods**” as follows: “The study was conducted in the Ansai Ecological Station in the semiarid Loess Plateau (36.55 °N, 109.16 °E), Northern China (Fig. S1).” (Page 5 Lines 110-111)

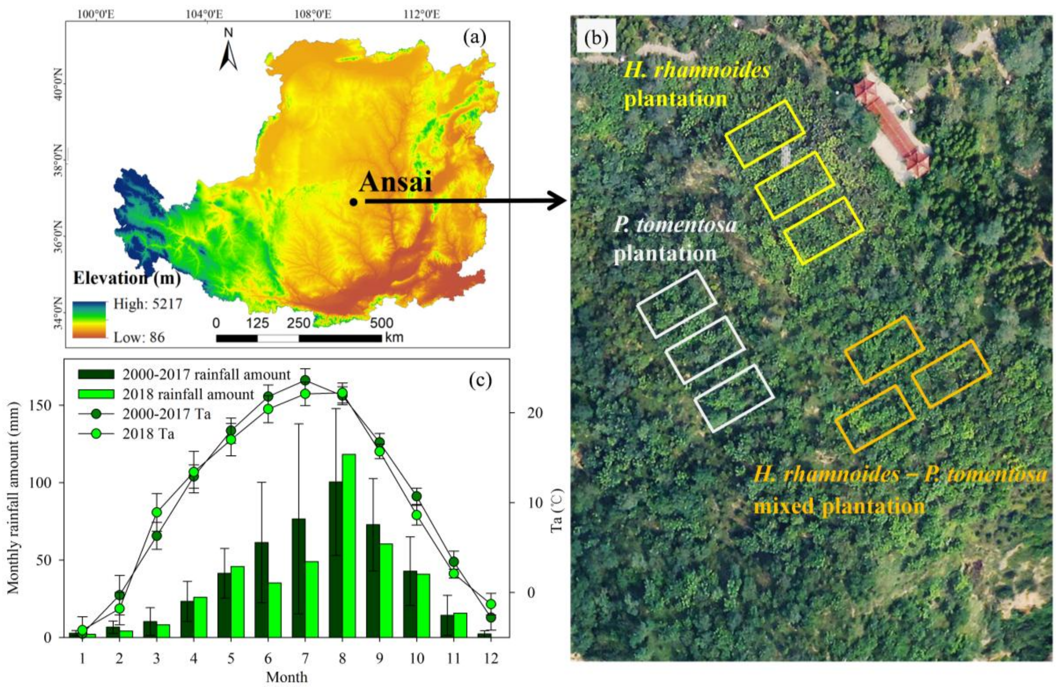
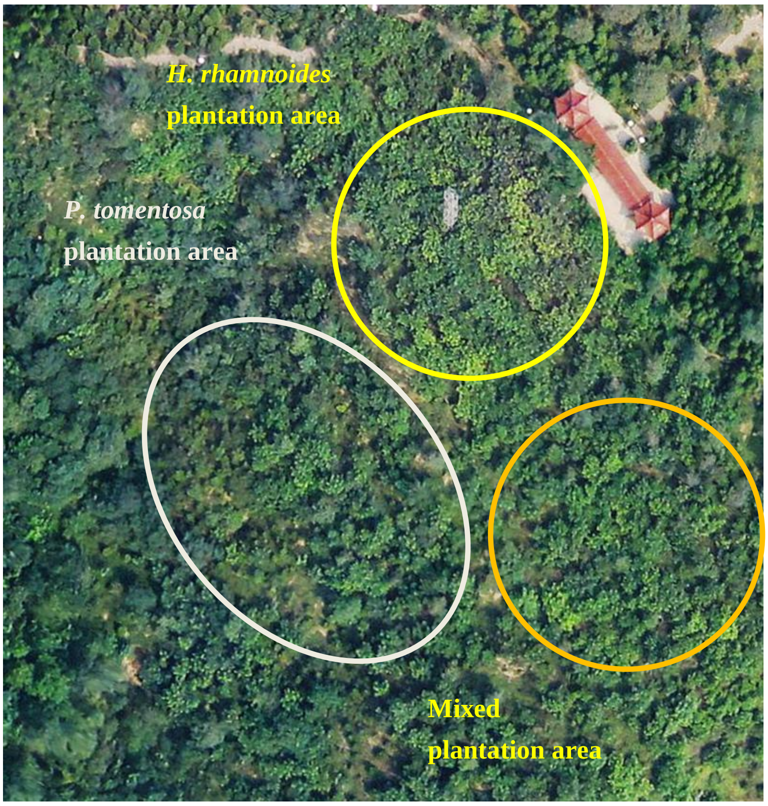


Figure S1. The geographic location of (a) study area and (b) plantation site in the Loess Plateau of China, and (c) monthly average (mean ± SD) rainfall amount and air temperature (Ta) during 2000-2017, and monthly rainfall amount and average Ta in 2018**.** Plantation types including *H. rhamnoides* pure plantation, *P. tomentosa* pure plantation, and Mixed plantation. Three adjacent plots were selected (16 m × 10 m) for each plantation type, and the schematic diagram of these plantation types is in (b). The

China basic map can be obtained from
http://map.geoq.cn/arcgis/rest/services/ChinaOnlineCommunityENG/MapServer.

In addition, the (b) in Fig S1 is the clearest picture that we can get, and the size of each three adjacent plots (16 m × 10 m) is the schematic diagram. Indeed, the plantation areas of these types are larger than the plot in Fig S1. The relative areas can be observed as follows:



Secondly, for plantation slope, land-use history, and soil and water conservation measures, the relative sentences have been added in "2.1 Study site" subsection in "**2 Materials and methods**" as follows: "Three adjacent plantations were chosen for the study: pure *H. rhamnoides* plantation, pure *P. tomentosa* plantation, and *H. rhamnoides*–*P. tomentosa* mixed plantation (Fig. S1), with corresponding plantation slope of 5.2, 4.5, and 5.5°. All plantations were planted on abandoned grassland in 2004, where *Bothriochloa ischaemum* was the dominant herbaceous species at that time. Three adjacent plots were selected (16 m × 10 m) for each plantation type, and no soil and water conservation measure was conducted in the plantations." (Page 5 Lines 118-123)

Thirdly, for soil physical properties, the relative sentences have been added in "2.1 Study site" subsection in "**2 Materials and methods**" section as follows: "The soil is characterized as a silt loam soil according to United States Department of Agriculture soil taxonomy, with 24.2% sand (2–0.05 mm), 62.5% silt (0.05–0.002 mm), and 13.3% clay (<0.002 mm) determined by Mastersize 2000 (Malvern Instruments Ltd., UK).” (Page 5 Lines 114-117).

“Based on an experiment conducted in July 2017 through cutting ring method, the soil bulk density, filtration property, total porosity, and capillary porosity at 0–50 cm soil depth were similar in three plantations. The average soil bulk density was 1.34 ± 0.04, 1.31 ± 0.05, and 1.31 ± 0.05 g cm^{-3} for pure *H. rhamnoides*, pure *P. tomentosa*, and mixed plantations, respectively, and corresponding soil saturated hydraulic conductivity was 0.97 ± 0.15, 0.96 ± 0.13, and 0.99 ± 0.11 mm min^{-1}. The average soil total porosity was 48.25 ± 0.52, 48.17 ± 0.48, and 48.03 ± 0.63% for pure *H. rhamnoides*, pure *P. tomentosa*, and mixed plantations, respectively, and corresponding soil capillary porosity was 38.89 ± 1.57, 39.02 ± 1.26, and 38.95 ± 1.87%.” (Pages 5-6 Lines 133-140).

The detailed criterion to determine the soil texture can be observed in **Figure explain 2** as follows:

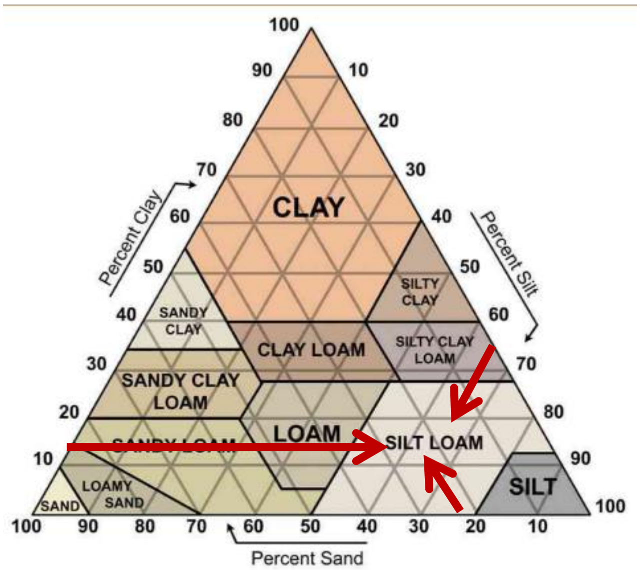


Figure explain 2 The soil texture criterion based on the percent of sand (2-0.05 mm), silt (0.05-0.002 mm), and clay (<0.002 mm) in United States Department of Agriculture soil taxonomy. The red arrow lines represent the percent of sand, silt, and clay of our studied soil.

5. The authors selected 5 distinct rainfall events of varying magnitude (ranging from 3.4 mm to 35.2 mm) to study the response of the tree species (in both pure and mixed stands) and how this varies according to the magnitude of the event. As stated in L. 168-169, ‘These rainfall events were selected with an interpulse period longer than 7 days to eliminate the potential influence of the previous rainfall event.’.

However, I have serious doubts about this approach and the validity of the results from this specific analysis (e.g., L. 478-482: 'The increasing rainfall amount significantly decreased water source proportion from deep soil layer (P<0.05) for H. 480 rhamnoides and P. tomentosa in the mixed plantation (Table S3), with the corresponding values decreasing from 43.13 ±13.74% and 47.07 ±5.39% (both after 3.4 mm), respectively, to 21.54 ±8.9% (after 35.2 mm) and 28.66 ±12.26% (after 24 mm) (Fig 4)'). Unfortunately, the selected rainfall events not only differ in magnitude, but also in terms of antecedent conditions. For example, the 3.5 mm event (DOY 194) is the lowest rainfall event but also that following the most prolonged dry period (>30 days dry period from DOY 157 to 194). It is evident that when topsoil moisture content is low following a dry period, plants will tap into deeper, more reliable water sources. This is not so much related to a single rainfall event and its magnitude, but mostly to the antecedent conditions (prolonged dry period).

Response: Deleted and Rewritten. In response to this meaningful and valuable question, these sentences in previous version has been deleted, and relative sentences have been rewritten in the revised manuscript in "4.2 RRS uptake enhances plant transpiration for coexisting species in mixed plantation" subsection in "**4 Discussion**" section as follows: "Furthermore, consistent with the second adaptation type, mixed afforestation significantly decreased the water uptake proportion from the deep soil layer for these species (Table S5). Similar to other studies in the Loess Plateau (Wang et al., 2020; Wu et al., 2021), the deep soil layer exhibited lower SW than other soil layers in all plantation types in the present study (Fig. 1, Table S3). Jia et al. (2017) and Wang et al. (2020) attributed the lower SW in deep soil layers to the imbalance between rainwater replenishment and plant uptake of water from this layer. In addition, plants may expend more energy to uptake water from deep compared to shallow soil layers (Schenk, 2008), especially when the deep soil layer exhibits lower SW. Thus, both increased rainwater-recharged soil water uptake and decreased water source competition from the deep soil layer were adopted by these species in the mixed plantation to minimize water sources competition under water limited conditions." (Page 22 Lines 495-504)

Indeed, the water sources from deep soil layer for these plant species may mainly influenced by antecedent soil water conditions. Thus, we rewrote these sentences mainly to illustrate the second adaptation type of these plant species, that is "minimized competition interactions"—mixed afforestation significantly decreased the water uptake proportion from the deep soil layer. The lower SW in deep soil layer than in other soil layers is the similar soil water conditions to other studies in the Loess Plateau, and Jia et al. (2017) and Wang et al. (2020) attribute the lower SW in deep soil layer to the imbalance between rainwater replenishment and plant uptake water from this soil layer. In addition, more energy should be expend by plant for water uptake from deep than from shallow soil layer (Schenk, 2008). These sentences illustrated the second adaptation type "minimized competition interactions".

References:

Jia, X. X., Shao, M. A., Zhu, Y. J., and Luo, Y.: Soil moisture decline due to afforestation across the Loess Plateau, China, J Hydrol, 546, 113-122, 2017.

Wang, J., Fu, B. J., Wang, L. X., Lu, N., and Li, J. Y.: Water use characteristics of the common tree species in different plantation types in the Loess Plateau of China, Agr Forest Meteorol, 288, ARTN 108020, 10.1016/j.agrformet.2020.108020, 2020.

Wu, W. J., Li, H. J., Feng, H., Si, B. C., Chen, G. J., Meng, T. F., Li, Y., and Siddique, K. H. M.: Precipitation dominates the transpiration of both the economic forest (Malus pumila) and ecological forest (Robinia pseudoacacia) on the Loess Plateau after about 15 years of water depletion in deep soil, Agr Forest Meteorol, 297, ARTN 108244, 10.1016/j.agrformet.2020.108244, 2021.

Schenk, H. J.: Soil depth, plant rooting strategies and species' niches, New Phytol, 178, 223-225, 2008.

6. I would strongly recommend that the authors include a plot of the local meteoric water line (LMWL). This should be relatively straightforward as they have analyzed the 19 collected rainfall samples for both δ18O and δH. On top of the LMWL I would then plot the signatures of the soil water at different depths. This would provide additional insights into the data and ease data interpretation (and can also be used to double-check that rainfall samples have not undergone evaporation). For instance, the rainfall signatures in Figure S5 could be visualized and interpreted much better in a dual-isotope plot.

Response: Added. In response to this meaningful and useful suggestion, the Figure S3 including the local meteoric water line (LMWL) and the regression between $\delta^{18}O$ and δD at three different soil layers (0-30, 30-100, and 100-200cm) has been added in the revised manuscript. Meanwhile, the relative sentences have also been added in "2.6 Statistical analysis" subsection in "**2 Materials and methods**" section as follows: "The shallow soil layer (0–30 cm) was vulnerable to rainfall, and exhibited higher soil water δ^{18}O and δD values and larger water isotope and SW variations (Table S3, Fig. S3). The middle soil layer (30–100 cm) was less vulnerable to rainfall, with high soil water isotope values and large water isotope and SW variations. The deep soil layer (100–200 cm) was relative stable, with low soil water isotope values and small water isotope and SW variation compared with shallow and middle soil layers." (Page 11 Lines 273-278).

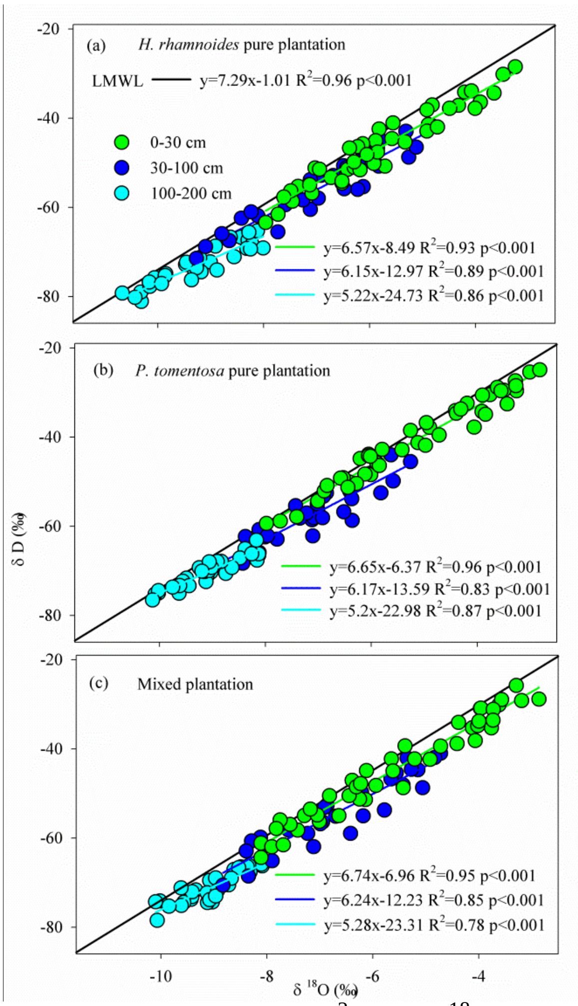


Figure S3. The linear regression relationship between δ^{2}H and δ^{18}O for soil water at three layers (0–30, 30–100, and 100–200cm) in (a) *H. rhamnoides* pure plantation, (b) *P. tomentosa* pure plantation, and (c) Mixed plantation. The local meteoric water line (LMWL) is plotted in each panel for reference.

Indeed, the slope of LMWL is 7.29 based on 19 collected rainfall (**Figure explain 3**), which is slightly lower than the global meter water line (the slope is 8.0), but similar to the LMWL (the slope ranges from 7.47 to 7.76) results near the present study region in the semiarid Loess Plateau (Figure **explains 4 and 5**). The slopes between δD and δ^{18}O for three soil layers were smaller than LMWL and slightly decreased with soil layer increased. The slightly lower slope for each of 3 soil layer compared with LMWL, may mainly attribute to the mixture of soil water before rainfall event and rainwater, and the soil water before rainfall generally undergo evaporation. The lower soil water δD and δ^{18}O slope compared with LMWL can be observed previous studies such as in **Figures explain 4 and 5** in the semiarid Loess Plateau as follows**.**

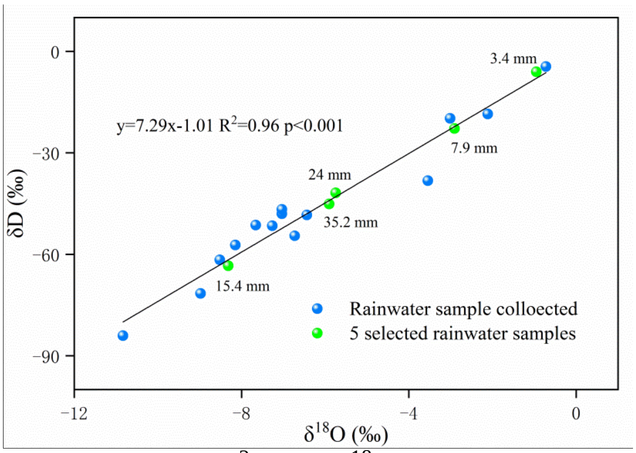


Figure explain 3 Linear regression between δ^2H and δ^{18}O in rainwater. There are 19 collected rainwater samples and 5 selected rainwater samples in the present study. The rainfall amount of each of 5 selected rainwater samples was added.

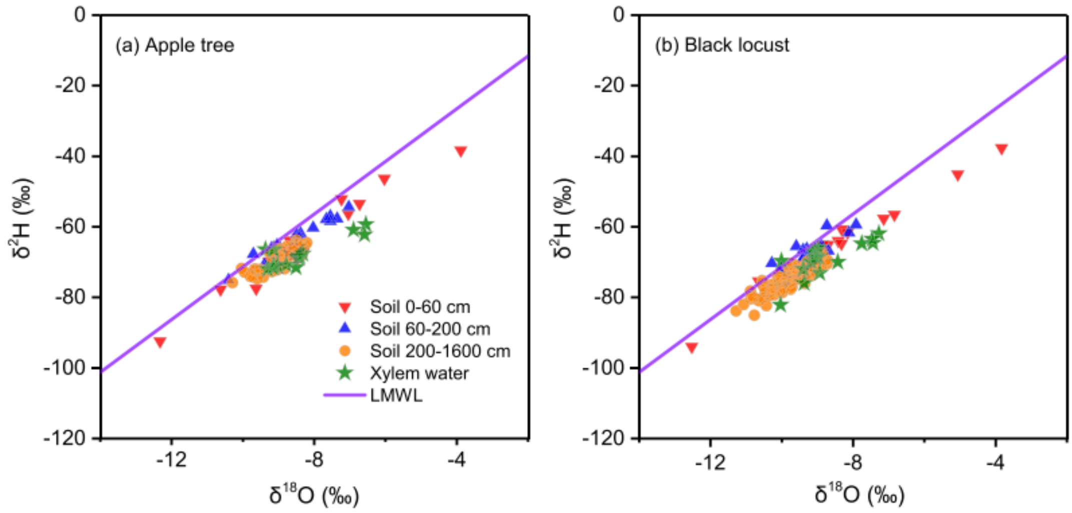


Figure explain 4 Linear regression between δ^2H and δ^{18}O in soil water for an (a) apple orchard and (b) black locust forest. LMWL represents the local meteoric water line (y = 7.47x + 3.29, R2 = 0.95, P < 0.01). The isotopic composition values of xylem water from both species are also shown. This plot is from Wu et al. (2016).

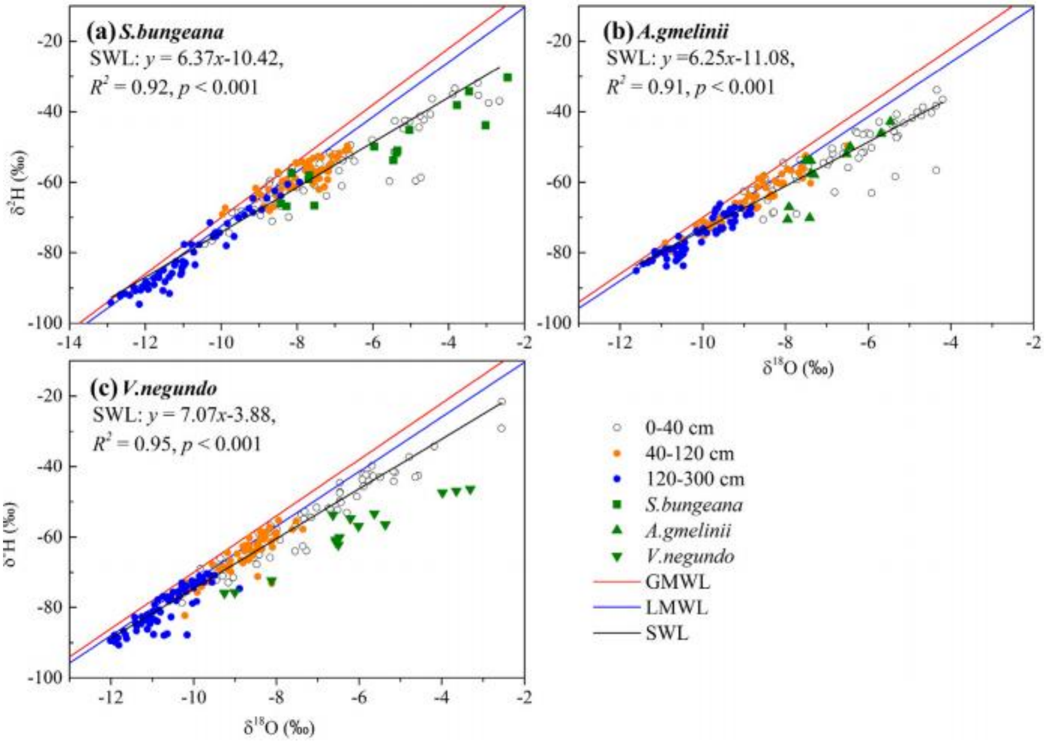


Figure explain 5 The linear regression relationship between δ^2H and δ^{18}O in soil water from three species (a) S. bungeana, (b) A. gmelinii, (c) V. negundo during the sampling periods. SWL represents soil water line based on isotopic data of soil water. LMWL represents the local meteoric water line (y = 7.76x + 5.14, R^2 = 0.91, p < 0.01). This plot is from Wang et al. (2017).

References:

Wu, W. J., Li, H. J., Feng, H., Si, B. C., Chen, G. J., Meng, T. F., Li, Y., and Siddique, K. H. M.: Precipitation dominates the transpiration of both the economic forest (Malus pumila) and ecological forest (Robinia pseudoacacia) on the Loess Plateau after about 15 years of water depletion in deep soil, Agr Forest Meteorol, 297, 2021.

Wang, J., Fu, B. J., Lu, N., and Zhang, L.: Seasonal variation in water uptake patterns of three plant species based on stable isotopes in the semi-arid Loess Plateau, Sci Total Environ, 609, 27-37, 2017.

Minor Comments:

1. In the study site description (section 2.1), it would be good if the authors could include a graph with the mean monthly rainfall throughout the year to get an overview of the rainfall seasonality in the study area. Right now, only the mean +- SD annual rainfall is provided, but there is no information on rainfall seasonality.

Response: Added. In response to this meaningful suggestion, the monthly averaged (mean ± SD) rainfall amount and air temperature have been added in Figure S1 in “2.1 Study site” subsection in “**2 Materials and methods**” section as follows: “The annual average (mean ± SD) rainfall amount and air temperature are 454.8 ± 105.2 mm and 10.6 ± 0.4 ℃ (2000–2017), respectively, with higher monthly rainfall amount and air temperature generally occurring during June–September and lower values during the other months (Fig. S1).” (Page 5 Lines 111-114)

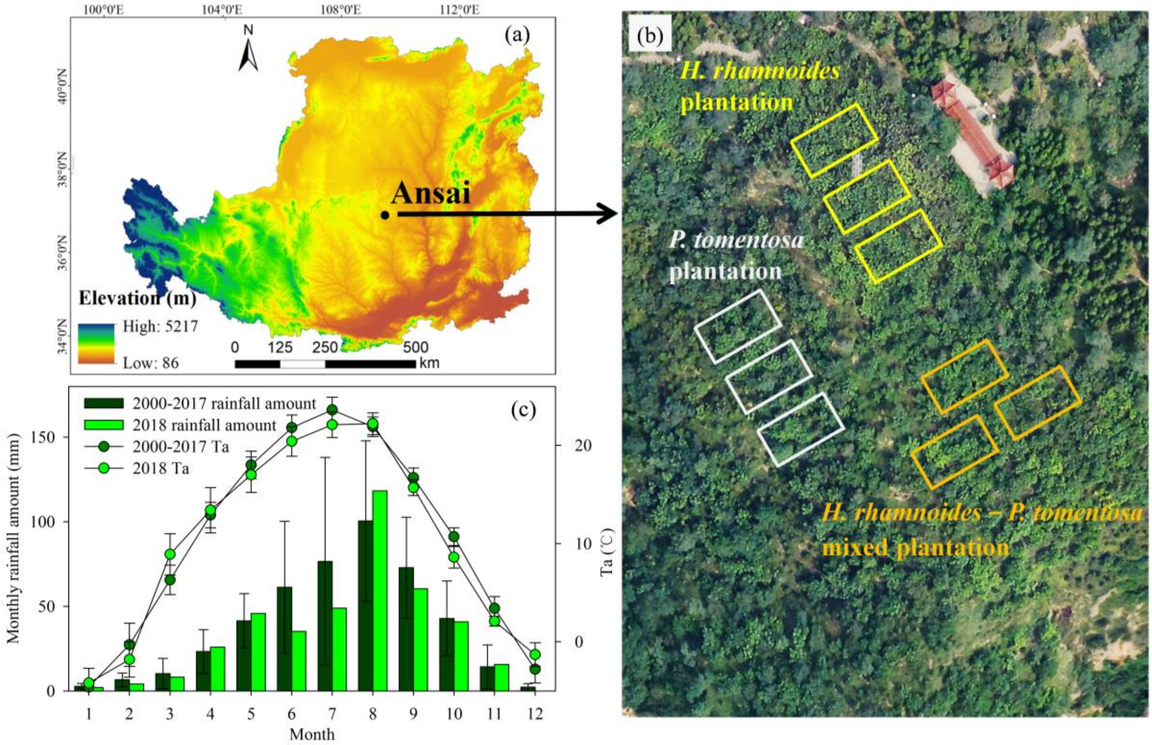


Figure S1. The geographic location of (a) study area and (b) plantation site in the Loess Plateau of China, and (c) monthly average (mean ± SD) rainfall amount and air temperature (Ta) during 2000-2017, and monthly rainfall amount and average Ta in 2018**.** Plantation types including *H. rhamnoides* pure plantation, *P. tomentosa* pure plantation, and Mixed plantation. Three adjacent plots were selected (16 m × 10 m) for each plantation type, and the schematic diagram of these plantation types is in (b). The China basic map can be obtained from http://map.geoq.cn/arcgis/rest/services/ChinaOnlineCommunityENG/MapServer.

2. When Describing the soil texture (L.105) please indicate it is the texture you refer to and add the correct source (USDA). Besides the soil texture, kindly provide the soil class.

Response: Corrected and Added. Thanks for this meaning suggestion, the texture, correct source (USDA), and the soil class has been written in “2.1 Study site” subsection in “**2 Materials and methods**” section as follows: “The soil is characterized as a silt loam soil according to United States Department of Agriculture soil taxonomy, with 24.2% sand (2–0.05 mm), 62.5% silt (0.05–0.002 mm), and 13.3% clay (<0.002 mm) determined by Mastersize 2000 (Malvern Instruments Ltd., UK).” (Page 5

Lines 114-117).

Because the "United States Department of Agriculture" occurred only once in the present study, thus the abbreviation named "USDA" of it was not used. The detailed criterion to determine the soil texture can be observed in **Figure explain 2** as follows:

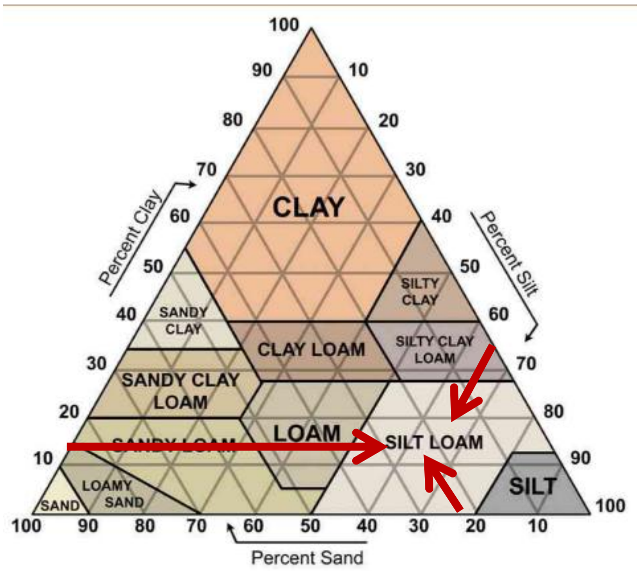


Figure explain 2 The soil texture criterion based on the percent of sand (2-0.05 mm), silt (0.05-0.002 mm), and clay (<0.002 mm). The red arrow lines represent the percent of sand, silt, and clay of our studied soil.

3. L.131: Explain what VPD stands for after equation 1 and give its units (as you have done for the other variable sin equation 1).

Response: Added. Thanks for this suggestion, the VPD explanation has been added in the revised manuscript in "2.2 Environmental parameter measurements and ET_0 calculation" subsection in "**2 Materials and methods**" section as follows: "where *γ*, *s*, and *VPD* are the psychrometric constant (kPa K^{-1}), the slope between saturation vapor pressure and air temperature (kPa K^{-1}), and vapor pressure deficit (kPa), respectively." (Page 6 Lines 155-156)

4. L.145: What does the abbreviation TDPs mean?

Response: Added. In response to this meaningful suggestion, the TDPs has been added at its first appearance sentence in "2.3 Sap flow observation" subsection in "**2 Materials and methods**" section as follows: "The sap flow was monitored by a pair of Granier-type thermal dissipation probes (TDPs) 10 mm in length and 2 mm in diameter in 36 selected individuals." (Page 7 Lines 163-165).

5. L.189, Formula 4: what is PAP?

Response: Corrected. Thanks for this suggestion. It should be RUP but not PAP, and this equation has been revised in "2.6.2 Calculation of RRS uptake proportion and water sources from different soil layers" subsection in "**2 Materials and methods**" section as follows:

"The RRS uptake proportion (RUP, %) after a recent rainfall pulse for plant was calculated as the proportion of rainwater in plant stem as follows (Cheng et al., 2006):

$$\delta^{18}\text{O (D)}_{\text{P}} = RUP \times \delta^{18}\text{O (D)}_{\text{rain}} + (1 - RUP) \times \delta^{18}\text{O (D)}_{\text{swb}} \quad (5)$$

$$RUP = (\delta^{18}\text{O(D)}_{\text{p}} - \delta^{18}\text{O(D)}_{\text{swb}})/(\delta^{18}\text{O(D)}_{\text{swa}} - \delta^{18}\text{O(D)}_{\text{swb}}) \times 100\% \quad (6)$$

" (Page 10 Lines 247-250)

6. L.208-209: Kindly provide a reference that supports this assumption ('no fractionation was considered during water source uptake by plant roots')

Response: Rewritten. Thanks for this meaningful suggestion, this sentence has been rewritten in "**2 Materials and methods**" section as follows: "No fractionation was considered during water source uptake by these plant roots because none of the plants exhibited xerophytic or halophytic characteristics. Ellsworth and Williams (2007) and Moore and Semmens (2008) suggested that a water stable isotope fractionation generally occurred during root uptake by xerophytic or halophytic plants." (Page 11 Lines 284-288).

References:

Ellsworth, P. Z., and Williams, D. G.: Hydrogen isotope fractionation during water uptake by woody xerophytes, Plant Soil, 291, 93-107, 10.1007/s11104-006-9177-1, 2007.

Moore, J. W., and Semmens, B. X.: Incorporating uncertainty and prior information into stable isotope mixing models, Ecol Lett, 11, 470-480, 10.1111/j.1461-0248.2008.01163.x, 2008.

7. Figure 1: it would be helpful if the X axes could start earlier (about 20 days if possible) to be able to see if the first two rainfall events that are shown in panel a) are following a dry period or not.

Response: Added and Clarified. In response to this meaningful suggestion, the X axes of Figure 1 have extent 20 days earlier, from DOY152 in previous manuscript to DOY132 at revised manuscript. The revised Figure 1 can be observed as follows (Page 13 Lines 325-330):

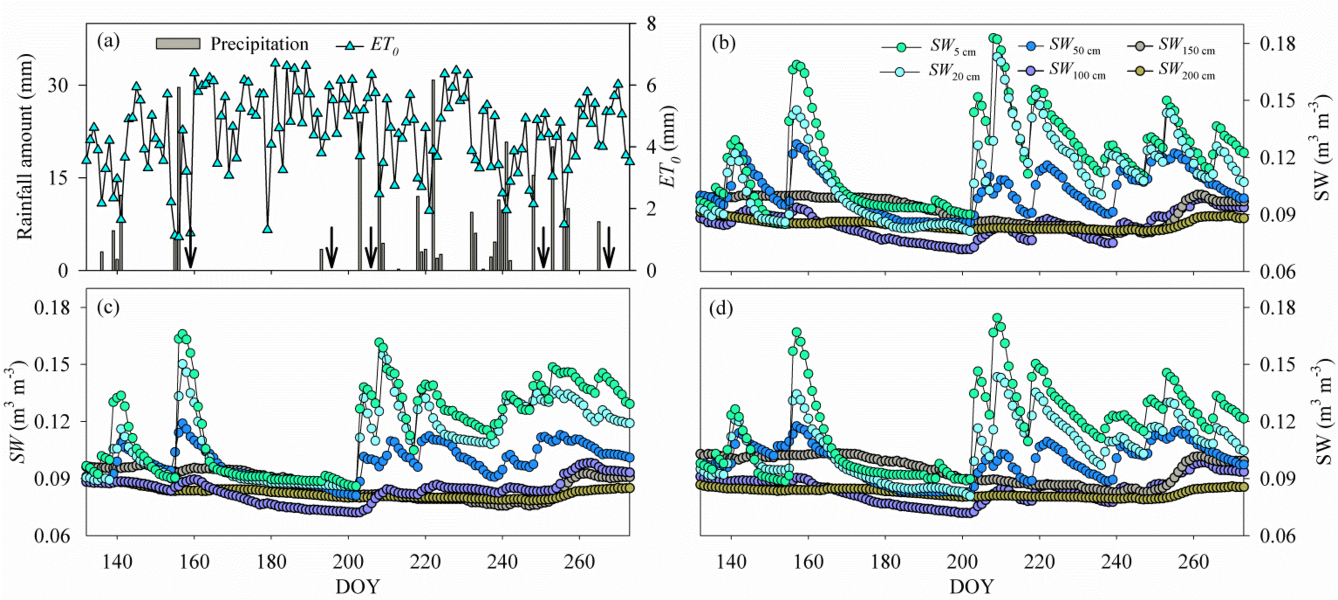


Figure 1. Variation in (a) rainfall amount, reference evapotranspiration (ET_0), and average (mean ± SD) soil water content (SW) in (b) *H. rhamnoides* pure plantation, (c) *P. tomentosa* pure plantation, and (d) mixed plantation from DOY 152 to 273 (1 June to 30 September) (n = 3). Standard deviation bars for SW at each soil layers are not shown to allow clear display of variation of SW for each plantation. Arrows in (a) indicate dates of sample collection at the first day after rainfall events: DOY 157 (6 June), DOY 194 (12 July), DOY 204 (23 July), DOY 249 (6 September), and DOY 265 (22 September).

In addition, the first selected rainfall amount is 35.2 mm, occurred in DOY 155-156, can be observed in the red box in **Figure 1** as follows. The reason that we choose the rainfall amount during DOY 155-156, is mainly because the 35.2mm was continues occurred during these two successive days. DOY 155 only received 5.6 mm rainfall from 23:00-24:00, and DOY156 received 29.6mm. Therefore, the rainfall amount (5.6mm+29.6mm=35.2mm) received during DOY 155-156 was considered as one rainfall event in our present study. The half-hourly rainfall distribution during DOY 155-156 can be observed in **Figure explain 6** as follows:

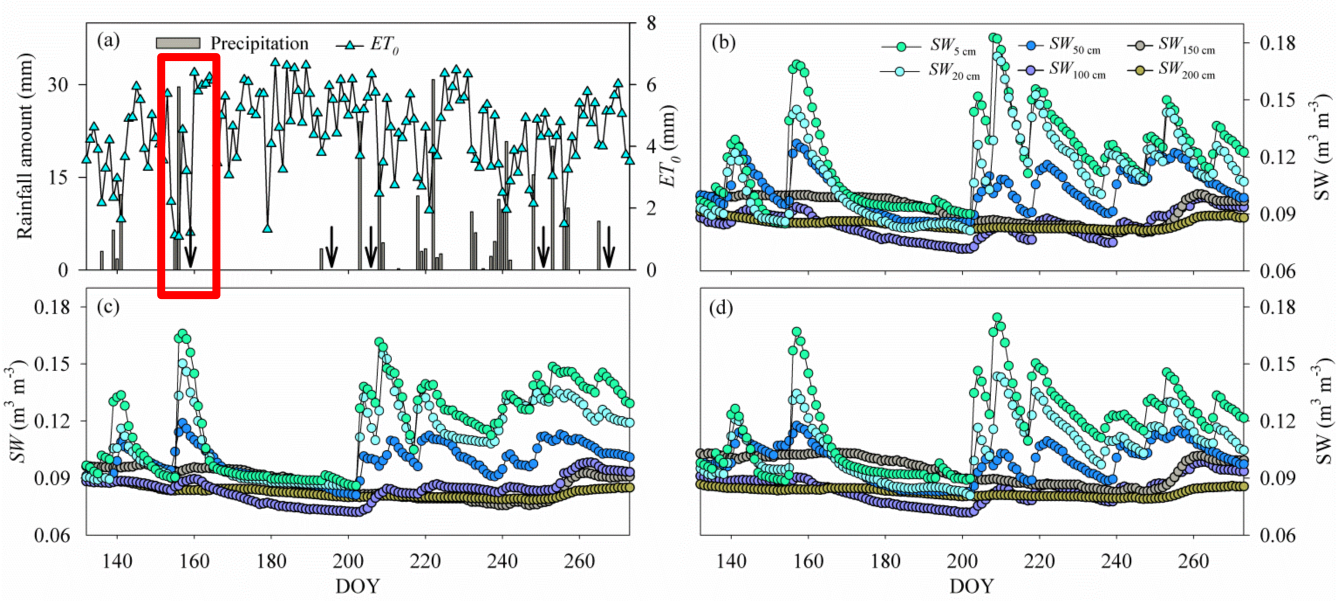


Figure 1. Variation of (a) rainfall amount, reference evapotranspiration (ET_0), and averaged soil water content (SW) in (b) *H. rhamnoides* pure plantation, (c) *P. tomentosa* pure plantation, and (d) mixed plantation from DOY 152 to 273 (1 June to 30 September). Standard deviation bars for SW at each soil layers are not shown to allow clear display of variation of SW for each plot. Arrows in (a) indicate dates of sample collection: DOY 157–159 (6–8 June), DOY 194–196 (12 –14 July), DOY 204–206 (23–25 July), DOY 249–251 (6–8 September), and DOY 265–267 (22–24 September).

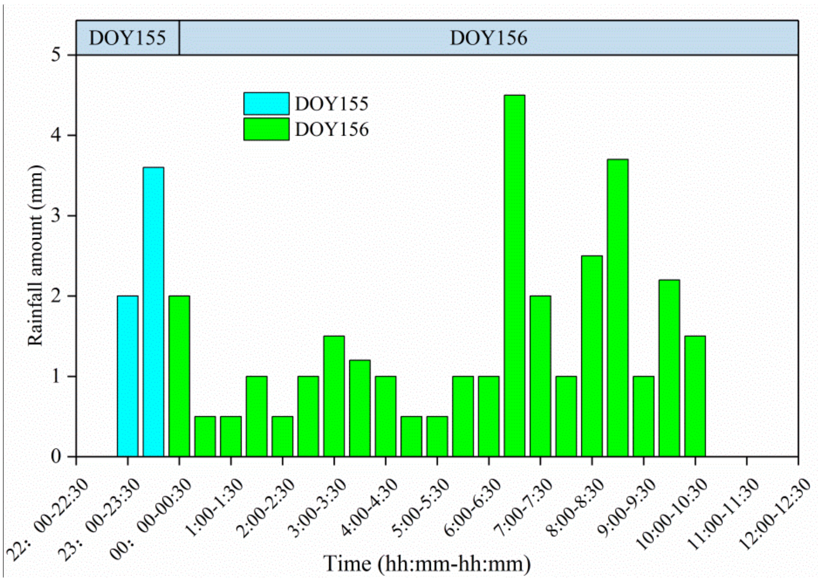


Figure explain 6 The half-hour rainfall amount during DOY155-156. The rainfall during DOY 155-156 was considered as one rainfall event in the present study.

8. Figure 2: It would be good to show the precipitation bars in this plot too.

Response: Added. Both the precipitation amount and arrows indicate dates of sample collection have been added in the revised **Figure 2 (a)** in the revised manuscript as follows (Page 14 Lines 349-352):

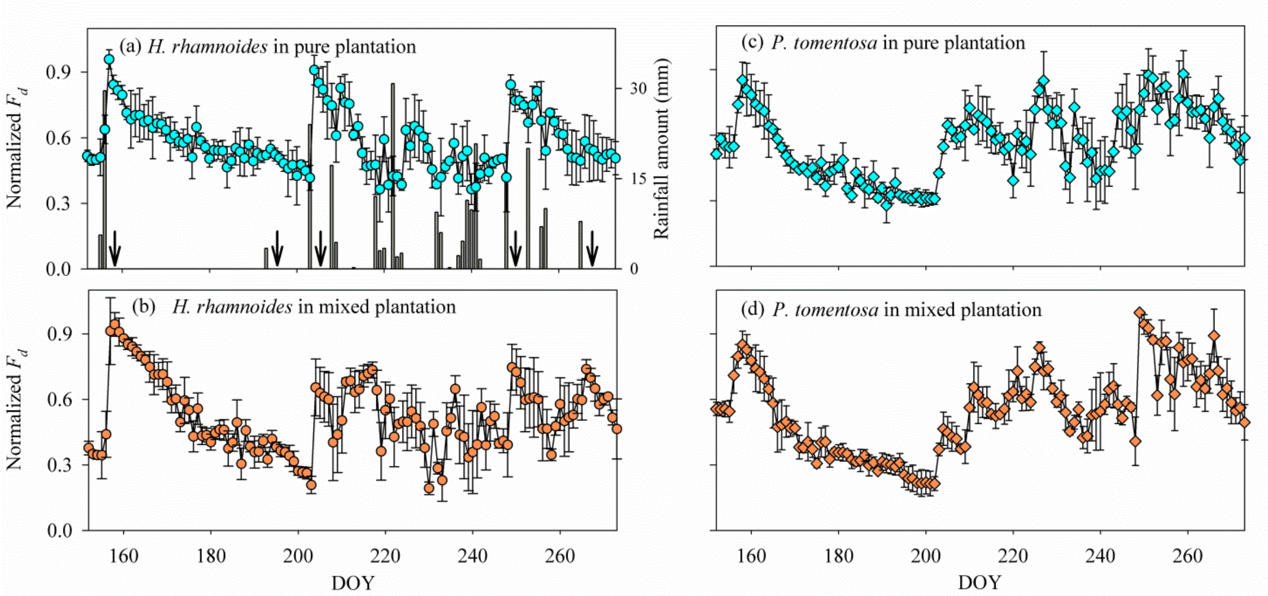


Figure 2. Variation in (a) rainfall amount, and average daily normalized F_d for *H. rhamnoides* in (a) pure and (b) mixed plantations and for *P. tomentosa* in (c) pure and (d) mixed plantations (n = 3). Arrows in (a) indicate dates of sample collection at the first day after rainfall events: DOY 157 (6 June), DOY 194 (12 July), DOY 204 (23 July), DOY 249 (6 September), and DOY 265 (22 September).

9. L.321: in figure S5, kindly add the date of rainfall events. Moreover, the dD signature of rainwater for the 3.4 and 7.9 mm events is very enriched. Could it be that there has been some evaporation of the sample going on? In any case, as I mentioned earlier, it would be really good if the authors could provide a plot of the LMWL.

Response: Added and Clarified.

Firstly, the date of 5 selected rainfall events have been added in Figure S7 in the revised manuscript as follows:

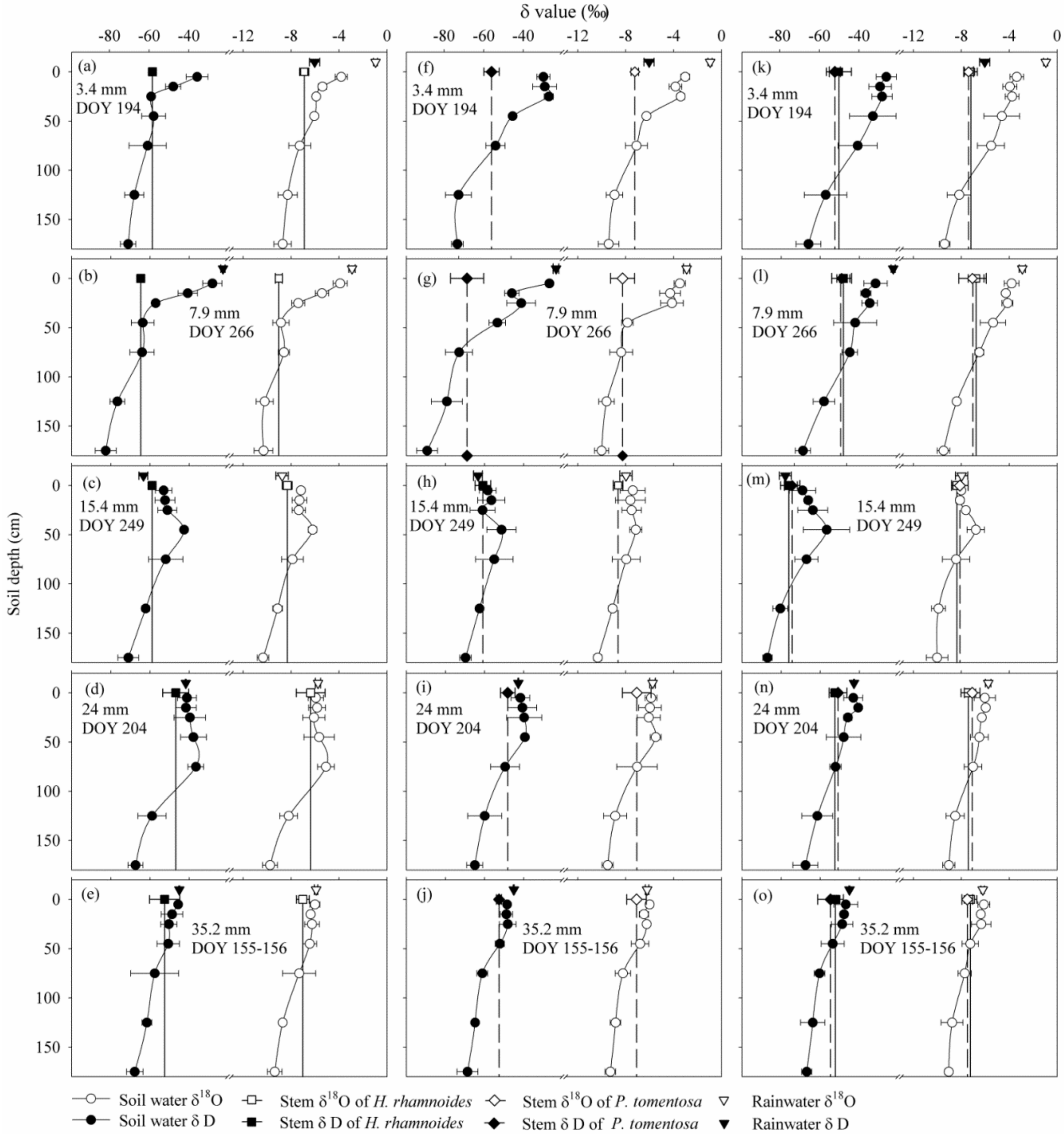


Figure S7. Variation in average (mean ± SD) $\delta^{18}O$ and δD of rainwater, stem water, and soil water at seven soil depths for *H. rhamnoides* in (a–e) pure and (k–o) mixed plantations and for *P. tomentosa* in (f–j) pure and (k–o) mixed plantations after 5 rainfall events. Error bars indicate the standard deviation (n = 3). The date of each 5 selected rainfall events is followed the corresponding rainfall amount value. The average rainwater $\delta^{18}O$ and δD for each rainfall event is calculated with 3 rainwater subsamples, which was divided from one rainwater sample.

Secondly, a plot including the local meteoric water line (LMWL) and the regression between $\delta^{18}O$ and δD at three different soil layers (0-30, 30-100, and 100-200cm) has been added in **Figure S3** as follows. Maybe there are two reasons that can illustrate the enriched $\delta^{18}O$ and δD values for 3.4 and 7.9

mm.

1), This may mainly attribute to the rainfall amount effect (Liu et al., 2014), that is the rainfall event with small rainfall amount generally had positive $\delta^{18}O$ and δD values than those for large rainfall amount (**Figures explain 3 and 7**).

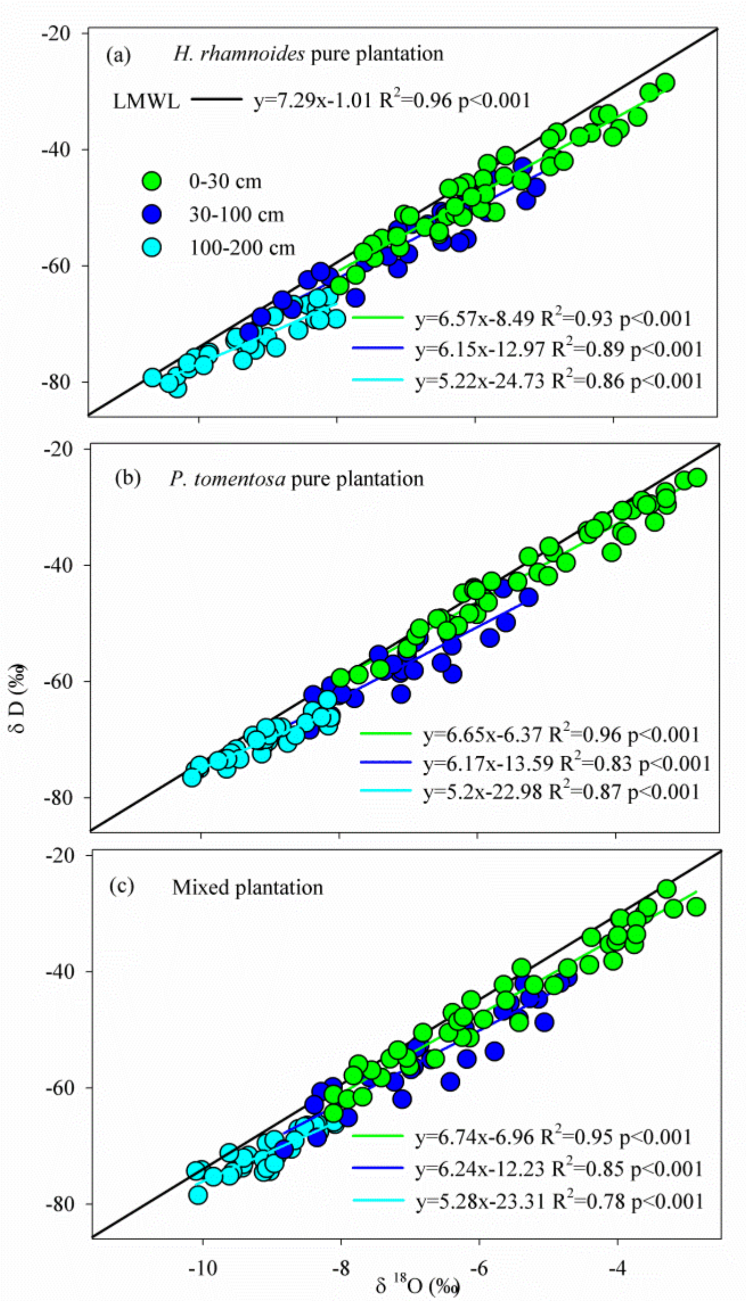


Figure S3. The linear regression relationship between δ^2H and $\delta^{18}O$ for soil water at three layers (0–30, 30–100, and 100–200cm) in (a) *H. rhamnoides* pure plantation, (b) *P. tomentosa* pure plantation, and (c) Mixed plantation. The local meteoric water line (LMWL) is plotted in each panel for reference.

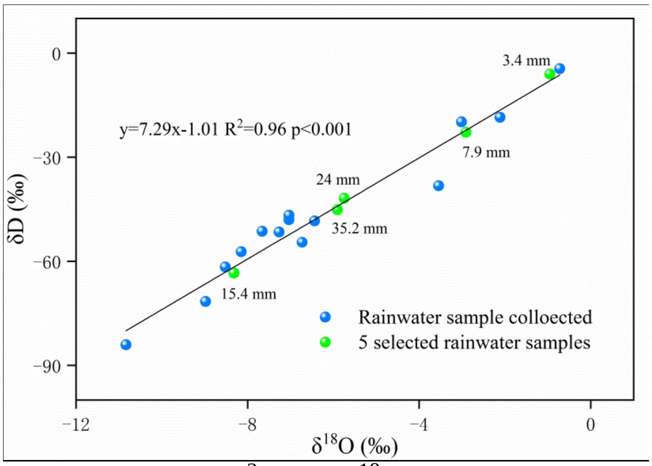


Figure explain 3 Linear regression between δ^2H and δ^{18}O in rainwater. There are 19 collected rainwater samples and 5 selected rainwater samples in the present study. The rainfall amount of each of 5 selected rainwater samples was added.

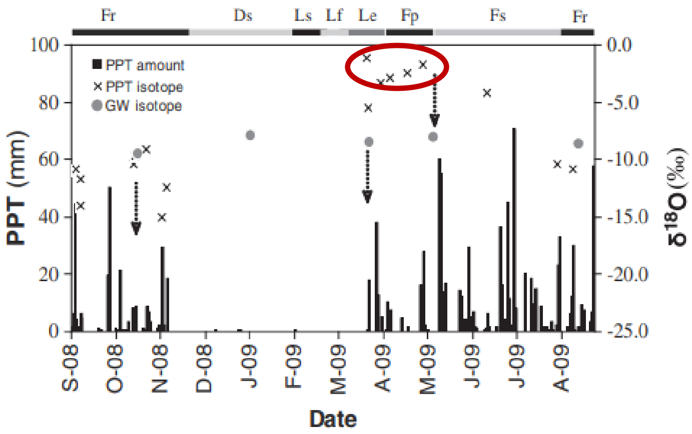


Figure explain 7 Distribution of daily precipitation (PPT) and variation of δ^{18}O values for event rainwater and groundwater (GW) during the rainy/dry season cycle (2008–2009). The stippled bars at the top of the panel are phenophases for rubber trees, i.e. Fr representing fruit ripening, Ds dormant stage, Ls leaf shedding, Lf leaf flushing, Le leaf expansion, Fp flowering phase and Fs fruit setting. Vertical arrows indicate sampling dates. This plot is from Liu et al. (2014).

2), Salamalikis et al. (2016) suggested that the positive δ^{18}O and δD values for small rainfall amount may partially attribute to the sub-cloud evaporation effect in rainfall in dry conditions (**Figure explain 8**). In the present study, the 3.4 and 7.9 mm occurred with high ET_0 period, which reflects the dry condition (**red cycles in Fig 1 as follows**).

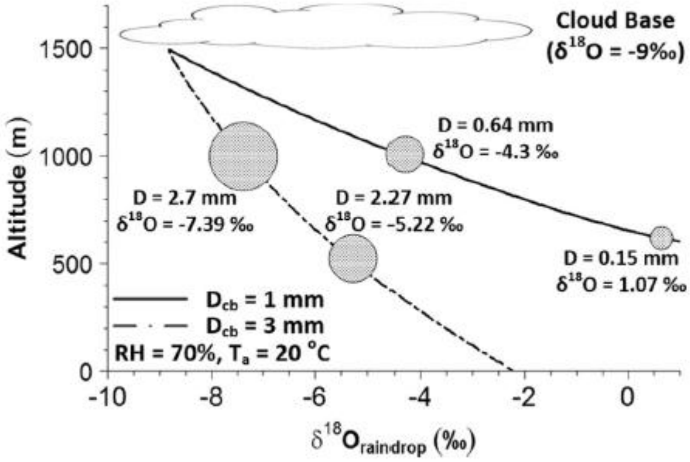


Figure explain 8 Schematic of sub-cloud evaporation effect on rainwater. This plot is from Salamalikis et al. (2016).

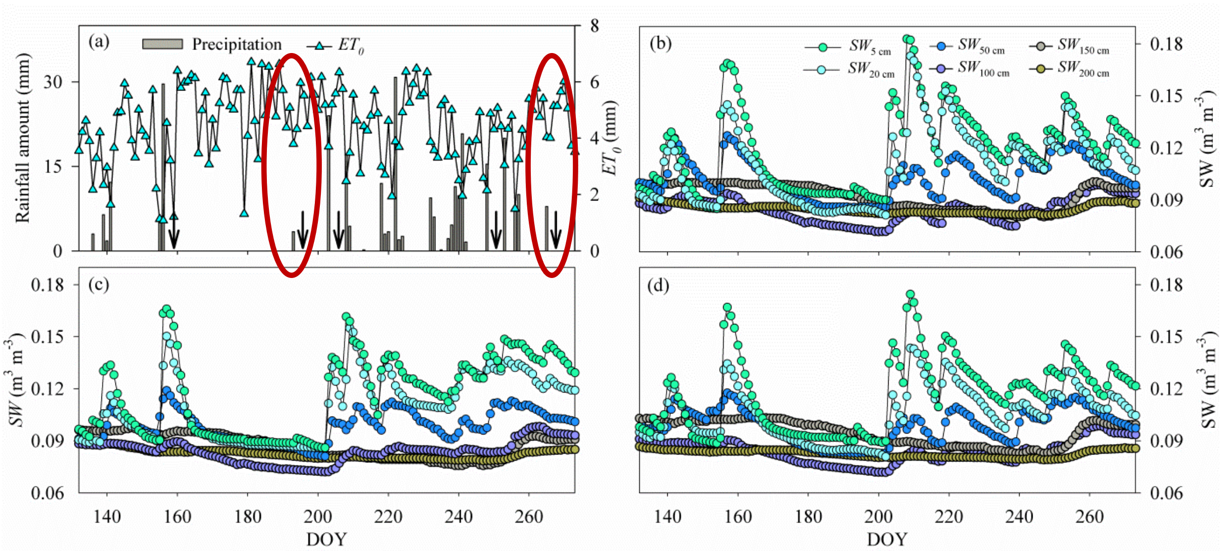


Figure 1. Variation in (a) rainfall amount, reference evapotranspiration (ET_0), and average (mean ± SD) soil water content (SW) in (b) *H. rhamnoides* pure plantation, (c) *P. tomentosa* pure plantation, and (d) mixed plantation from DOY 152 to 273 (1 June to 30 September) (n = 3). Standard deviation bars for SW at each soil layers are not shown to allow clear display of variation of SW for each plantation. Arrows in (a) indicate dates of sample collection at the first day after rainfall events: DOY 157 (6 June), DOY 194 (12 July), DOY 204 (23 July), DOY 249 (6 September), and DOY 265 (22 September).

References:

Salamalikis, V., Argiriou, A. A., and Dotsika, E.: Isotopic modeling of the sub-cloud evaporation effect in precipitation, Sci Total Environ, 544, 1059-1072, 2016.

Liu, W. J., Li, J. T., Lu, H. J., Wang, P. Y., Luo, Q. P., Liu, W. Y., and Li, H. M.: Vertical patterns of soil water acquisition by non-native rubber trees (*Hevea brasiliensis*) in Xishuangbanna, southwest China, Ecohydrology, 7,

1234-1244, 2014.
Yang, B., Wen, X. F., and Sun, X. M.: 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, 10.1016/j.agrformet.2014.11.020, 2015.

10. L.395-396: have you measured the depth of the groundwater level?

Response: Rewritten and Clarified. In response to this meaningful suggestion, the sentence has been rewritten in “4.1 RRS uptake enhances plant transpiration for H. rhamnoides but not P. tomentosa in pure plantations” subsection in “**4 Discussion**” section as follows: “Rainwater is the only replenished soil water source in the studied region (Shao et al., 2018), because plants cannot uptake ground water of approximately 150 m depth below the surface, which was determined through well observation (unpublished data).” (Page 18 Lines 409-411).

Indeed, the approximately 100 m depth of groundwater though well observation has been published in previous studies in Loess Plateau, such as in Shao et al. (2018) and Xie et al. (2018). The diagram illustrating the groundwater observation can be observed in Shao et al. (2018) as follows:

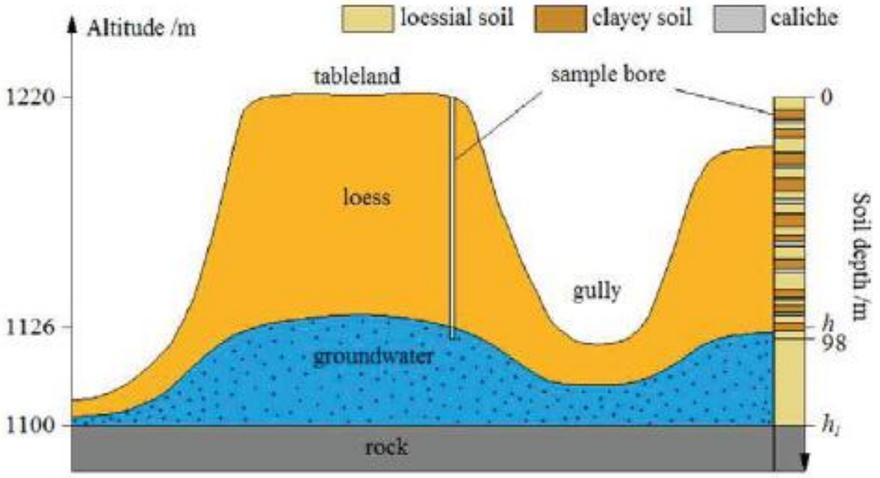


Figure explain 9 A diagram illustrating a cross section of the sampling site in the Loess Plateau of China; *h* and h_l are the depth of water table (m) and lower boundary of virtual soil layer (m) that was set as the bottom of the phreatic aquifer, respectively. This plot is from Shao et al. (2018).

In the present study, the observed groundwater was observed through well observation. The studied plantations were in tableland. The groundwater depth from the surface soil was approximately 150 m, the groundwater depth during June-September in 2018 can be observed in **Figure explain 10** as follows. These groundwater depth values have not been published. Thus, this sentence has been rewritten as

“Rainwater is the only replenished soil water source in the studied region (Shao et al., 2018), because plants cannot uptake ground water of approximately 150 m depth below the surface, which was determined through well observation (unpublished data).”

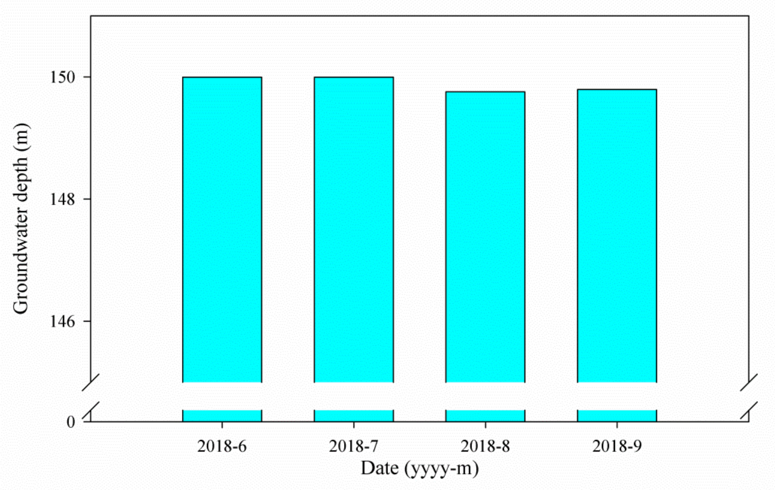


Figure explain 10 The groundwater depth from surface soil near the studied plantation.

References:

Shao, J., Si, B. C., and Jin, J. M.: Extreme Precipitation Years and Their Occurrence Frequency Regulate Long-Term Groundwater Recharge and Transit Time, Vadose Zone J, 17, 2018.

Xie, X. W., Xu, C. J., Wen, Y. M., and Li, W.: Monitoring Groundwater Storage Changes in the Loess Plateau Using GRACE Satellite Gravity Data, Hydrological Models and Coal Mining Data, Remote Sens-Basel, 10, 2018.

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Differential response of plant transpiration to uptake of rainwater-recharged soil water for dominant tree species in the semiarid Loess Plateau

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Abstract Whether uptake of rainwater-recharged soil water (RRS) can increase plant transpiration in response to rainfall pulses requires investigation to evaluate the plant adaptability, especially in water limited regions where rainwater is the only replenishable soil water source. In this study, the water sources from RRS and three soil layers, predawn (Ψ_{pd}), midday (Ψ_m) and gradient (Ψ_{pd}–Ψ_m) of leaf water potential, and plant transpiration in response to rainfall pulses were analyzed for two dominant tree species, *Hippophae rhamnoides* subsp. *sinensis* and *Populus tomentosa*, in pure and mixed plantations during the growing period (June–September). In pure plantations, the relative response of daily normalized sap flow (SF_R) was significantly affected by RRS uptake proportion (RUP) and Ψ_{pd}–Ψ_m for *H. rhamnoides*, and was significantly influenced by Ψ_{pd}–Ψ_m for *P. tomentosa* ($P < 0.05$). Meanwhile, the large Ψ_{pd}–Ψ_m was consistent with high SF_R for *H. rhamnoides*, and the small Ψ_{pd}–Ψ_m was consistent with the low SF_R for *P. tomentosa*, in response to rainfall pulses. Therefore, *H. rhamnoides* and *P. tomentosa* exhibited sensitive and insensitive responses to rainfall pulses, respectively. Furthermore, mixed afforestation significantly enhanced RUP, SF_R, and reduced the water source proportion from the deep soil layer (100–200 cm) for both species ($P < 0.05$). The SF_R was significantly influenced by RUP and Ψ_{pd}–Ψ_m for both species in the mixed plantation. Lower Ψ_m and higher Ψ_{pd} were adopted by *H. rhamnoides* and *P. tomentosa* in mixed plantation, respectively, to enlarge Ψ_{pd}–Ψ_m and enhance RRS uptake. These results indicate that mixed afforestation enhanced the influence of RRS uptake to plant transpiration for these different rainfall pulse sensitive plants. This study provides insights into suitable plantation species selection and management considering the link between RRS uptake and plant transpiration in water limited regions.

Keywords: Leaf water potential; Loess Plateau; Plant transpiration; Rainwater-recharged soil water; Water stable isotope

1 Introduction

Rainwater-recharged soil water (RRS) uptake by plants and plant transpiration in response to rainfall pulses drive the survival of plant species and ecosystem ecohydrological processes, especially in arid and semiarid regions where rainwater is the only replenishable soil water source (Berkelhammer et al., 2020; Gebauer and Ehleringer, 2000; West et al., 2012). Generally, RRS uptake after a rainfall pulse refers to the root uptake of soil water that was recharged by recent rainwater, and can be quantified through water stable isotopes (Cheng et al., 2006; Meier et al., 2018). The variability and intermittency of rainfall, which plays an important role in plant water uptake and transpiration (Swaffer et al., 2014; Wang et al., 2020), have been predicted to increase in water limited regions (Mendham et al., 2011). Clarifying the influence of RRS uptake on plant transpiration after rainfall pulses is essential to understand the process of plant species adaptation in water limited regions (Meier et al., 2018; Tfwala et al., 2019).

The RRS uptake by plant is expected to increase plant transpiration after a rainfall pulse (Cheng et al., 2006; Liu et al., 2019). However, the uptake of RRS may also be mainly used to reduce the water uptake from deep soil layers or decrease the risk of cavitation in stems for some plant species (Plaut et al., 2013; Tfwala et al., 2019). The controversial rainfall pulse response between RRS uptake and plant transpiration may be mainly attributed to an inconsistent influence of plant leaf physiological characteristics (West et al., 2007), root morphology adjustment (Wang et al., 2020), or environmental conditions (Tfwala et al., 2019) on these two water processes. Generally, plant transpiration is observed to increase after rainfall pulses for plants with shallow (Liu et al., 2019) or dimorphic root systems (Swaffer et al., 2014); meanwhile, no increase or a decrease in plant transpiration is observed for plants with deep rooting systems (West et al., 2012). However, regardless of the root distribution, the plant leaf water potential gradient (the difference between predawn (Ψ_{pd}) and midday (Ψ_{m}) leaf water potential) has been observed to regulate plant transpiration after rainfall pulses (Kumagai and Porporato, 2012; Liu et al., 2019). Thus, taking into consideration plant leaf physiological or root morphological parameters could help in understanding the mechanisms underlying the influence of RRS uptake on plant transpiration in response to rainfall pulses.

Uptake of contrasting water sources between coexisting species usually shows water source separation and can minimize water source competition (Munoz-Villers et al., 2020; Silvertown et al., 2015); however, overlapping water sources among plant species may lead to competition in arid and semiarid regions (Tang et al., 2019; Yang et al., 2020). Rainfall pulses have been observed to relieve or eliminate water competition among coexisting species and thus maintain or increase plant transpiration in some water limited regions (Wang et al., 2020; Tfwala et al., 2019). Meanwhile, plant species with strong RRS uptake ability generally exhibit more competitiveness than coexisting weak RRS uptake ability species (Stahl et al., 2013; West et al., 2012). However, Liu et al. (2019) attribute opposite RRS uptake ability to the stable coexistence of species in mixed plantations in semiarid regions, where the rainfall events are variable and less RRS taken up by one of the coexisting plant species. In addition, coexisting species may also cope with or minimize water resource competition through plant leaf water potential or root distribution adjustment (Chen et al., 2015; Silvertown et al., 2015). It is still unclear whether these adjustments could influence the RRS uptake and plant transpiration for coexisting species in water limited regions.

The "Grain for Green project" has increased vegetation coverage by 25% in the Loess Plateau through afforestation activities since the 1990s, to deal with vegetation degradation and water and soil loss (Tang et al., 2019; Wu et al., 2021). *Hippophae rhamnoides* subsp. *sinensis* and *Populus tomentosa* are typical deciduous broadleaved tree species, with similar leaf expansion (April) and falling (November) periods, and occupy nearly 30% of the plantation area in this region (Liu et al., 2017; Tang et al., 2019). Our previous study indicated that *H. rhamnoides* generally took up soil water from 0−40 cm or > 100 cm soil depths and adopted large leaf water potential variation to cope with varied soil water conditions in this region (Tang et al., 2019). Meanwhile, *P. tomentosa* generally took up soil water from > 100 cm soil depth throughout the growing season in varied soil water conditions (Xi et al., 2018). In addition, mixed plantations of these two species were widely promoted by local government due to the higher soil and water conservation capacity than pure plantations in the original afforestation stage (Tang et al., 2019; Wang et al., 2020). Tang et al. (2019) also suggested that mixed afforestation with *Ulmus pumila*, a deciduous broadleaved tree species with similar leaf growth phenology to *H. rhamnoides*, increased the water source from 0−40 cm soil depth and the leaf water potential variation for *H. rhamnoides* compared with these values for this species in pure plantation. Furthermore, rainfall events have obvious seasonal variability and the rainfall amount is generally lower than the reference evapotranspiration (ET_0) during the plant growth period in this semiarid region (Zhang et al., 2017). The imbalance between rainwater input and plant water demand may weaken the sustainability of plantations with further plant growth (Jia et al., 2020; Wu et al., 2021). To understand the adaptation of plantation species in this study, the plant transpiration, water sources from RRS and different soil layers, and plant leaf water potential for *H. rhamnoides* and *P. tomentosa* in pure and mixed plantations were analyzed. The specific objectives were as follow: (1) to investigate the influence of RRS uptake and leaf water potential on plant transpiration after rainfall events in pure plantation, and (2) to assess the mixed afforestation effect on these influences. Based on variations of plant water uptake from soil layers and/or leaf water potential for these species in Xi et al. (2018) and Tang et al. (2019), we hypothesize that (1) the influence of RRS uptake and leaf water potential on plant transpiration may differ for these species in pure plantations, and (2) these influences may differ for specific species in pure and mixed plantations.

2 Materials and methods

2.1 Study site

The study was conducted in the Ansai Ecological Station in the semiarid Loess Plateau (36.55 °N, 109.16 °E), Northern China (Fig. S1). The study area has a semiarid continental climate. The annual average (mean ± SD) rainfall amount and air temperature are 454.8 ± 105.2 mm and 10.6 ± 0.4 °C (2000–2017), respectively, with higher monthly rainfall amount and air temperature generally occurring during June–September and lower values during the other months (Fig. S1). The soil is characterized as a silt loam soil according to United States Department of Agriculture soil taxonomy, with 24.2% sand (2–0.05 mm), 62.5% silt (0.05–0.002 mm), and 13.3% clay (<0.002 mm) determined by Mastersize 2000 (Malvern Instruments Ltd., UK).

Three adjacent plantations were chosen for the study: pure *H. rhamnoides* plantation, pure *P. tomentosa* plantation, and *H. rhamnoides–P. tomentosa* mixed plantation (Fig. S1), with corresponding plantation slope of 5.2, 4.5, and 5.5 °. All plantations were planted on abandoned grassland in 2004, where *Bothriochloa ischaemum* was the dominant herbaceous species at that time. Three adjacent plots were selected (16 m × 10 m) for each plantation type, and no soil and water conservation measure was conducted in the plantations. In pure plantations, the original planted spacing for each individual plant was 2.0 m × 2.0 m. In the mixed plantation, *P. tomentosa* was originally planted between the 4.0 m gaps in rows of *H. rhamnoides*, each individual plant was also spaced 2.0 m × 2.0 m. Based on a survey performed in July 2018, in pure plantations, the average tree trunk diameter (at 1.2 m height above the ground) and height were 50.5 ± 3.6 mm and 4.11 ± 0.81 m for *H. rhamnoides*, respectively, and the corresponding values were 52 ± 4.6 mm and 4.05 ± 0.63 m for *P. tomentosa*. Meanwhile, in mixed plantations, the average trunk diameter and tree height were 51.3 ± 2.9 mm and 4.49 ± 0.7 m for *H. rhamnoides*, respectively, and the corresponding values were 56.3 ± 3.8 mm and 4.23 ± 0.79 m for *P. tomentosa*. *B. ischaemum* and *Glycyrrhiza uralensis* were the dominant herbaceous species in *H. rhamnoides* and *P. tomentosa* pure plantations, respectively; meanwhile, *B. ischaemum* was dominant in the mixed plantation. Based on an experiment conducted in July 2017 through cutting ring method, the soil bulk density, filtration property, total porosity, and capillary porosity at 0–50 cm soil depth were similar in three plantations. The average soil bulk density was 1.34 ± 0.04, 1.31 ± 0.05, and 1.31 ± 0.05

g cm^{-3} for pure *H. rhamnoides*, pure *P. tomentosa*, and mixed plantations, respectively, and corresponding soil saturated hydraulic conductivity was 0.97 ± 0.15, 0.96 ± 0.13, and 0.99 ± 0.11 mm min^{-1}. The average soil total porosity was 48.25 ± 0.52, 48.17 ± 0.48, and 48.03 ± 0.63% for pure *H. rhamnoides*, pure *P. tomentosa*, and mixed plantations, respectively, and corresponding soil capillary porosity was 38.89 ± 1.57, 39.02 ± 1.26, and 38.95 ± 1.87%.

2.2 Environmental parameter measurements and ET_0 calculation

Net radiation (R_n, CNR4, Kipp &Zone Inc., Netherlands), atmospheric pressure (CS105, Vaisala Inc., Finland), air temperature (T_a) and relative humidity (HMP45D, Vaisala Inc.), and wind velocity (Ws, A100R, Vector Inc., UK) were measured using a weather station nearly 500 m from the research plots. Soil heat flux (G) and rainfall amount were measured at 5 cm below ground using two HFT-3 plates (Campbell Scientific Inc., USA) and a TE525 rain gauge (Campbell Scientific Inc.), respectively. At each plot, soil water content (SW) was measured at 5, 30, 50, 100, 150, and 200 cm below ground (SW_{5cm}, SW_{30cm}, SW_{50cm}, SW_{100cm}, SW_{150cm}, and SW_{200cm}) by CS615 TDR probes (Campbell Scientific Inc.). All these parameters were measured and stored at 30 min interval by a CR3000 datalogger (Campbell Scientific Inc.).

ET_0, considering both aerodynamic characteristics and energy balance, was used to indicate atmospheric evaporative demand (Allen et al., 1998):

$$ET_0=(0.408\times s\times(R_n-G)+\gamma\times\frac{900}{T_a+273}\times W_s\times VPD)/(s+\gamma\times(1+0.34\times W_s)) \quad (1)$$

where *γ*, *s*, and *VPD* are the psychrometric constant (kPa K^{-1}), the slope between saturation vapor pressure and air temperature (kPa K^{-1}), and vapor pressure deficit (kPa), respectively. The units of R_n and *G* are W m^{-2}, and of W_s is m s^{-1}.

2.3 Sap flow observation

Three standard individuals, with approximately mean height and trunk diameter, for specific species were chosen in each of the nine plots (Table S1). In each plot in the mixed plantation, three individuals of *H. rhamnoides* were chosen firstly, then a neighboring *P. tomentosa* individual was selected at approximately 2 m distance from each chosen *H. rhamnoides* individual. The sap flow was monitored by a pair of Granier-type thermal dissipation probes (TDPs) 10 mm in length and 2 mm in diameter in 36 selected individuals. During the plant growing season and ranging from 1 June (DOY 152) to 30 September (DOY 273) in 2018, the 30 s original and 30 min average sap flow values were monitored using a CR3000 data logger (Campbell Scientific Inc.). Waterproof silicone and aluminum foil were used to avoid the impact of the external environment on and physical damage to TDPs (Du et al., 2011). The standard sap flow density (F_d, ml m^{-2} s^{-1}) was calculated as follows (Granier, 1987):

$$F_d = 119((\Delta t_{\max} - \Delta t)/\Delta t)^{1.231} \quad (2)$$

where Δt and Δt_{max} are the temperature difference of heated and unheated probes at 30 min intervals and the maximum Δt in each day, respectively.

Steppe et al. (2010) suggested that F_d should have a species-specific calibration to validate Eq. (2). Meanwhile, the possibility of underestimating the F_d value with the Granier-type thermal dissipation method (Du et al., 2011) should be considered when the whole tree transpiration is calculated. However, with the lack of species-specific calibration for Eq. (2) in the present study, the daily normalized F_d for each replicate individual was calculated as the index of plant transpiration, through dividing F_d by the maximum value from DOY 152 to DOY 273. Thus, each monitored individual had a maximum daily normalized F_d of 1. In each plantation type, the average daily normalized F_d for specific species was calculated in each plot to determine the plant transpiration characteristics rather than the absolute transpiration amount (Du et al., 2011).

2.4 Rainwater, plant stem, soil water, and leaf sample collection and measurement

From April to October 2018, at the end of each rainfall event, 19 rainwater samples were collected immediately using a polyethylene rain gauge cylinder placed in the weather station, and stored at 4 ℃. A funnel containing a ping-pang ball was connected at the top of rain gauge cylinder to avoid rainwater evaporation (Yang et al., 2015). To avoid the influence of sample collection on sap flow observation, one standard individual for the specific species nearby each sap flow monitored individual was selected for plant stem and soil water collection. In the mixed plantation, the distance was approximately 2 m between the selected *H. rhamnoides* and *P. tomentosa* standard individuals in each plot for sample collection. For plant stem and soil water collection, 5 rainfall events were selected: 3.4 mm (DOY 194), 7.9 mm (DOY 266), 15.4 mm (DOY 249), 24 mm (DOY 204), and 35.2 mm (DOY 155–156). These rainfall events were selected with an interpulse period longer than 7 days to eliminate the potential influence of the previous rainfall event. At each of successive three days after every selected rainfall event, one suberized stem after removing the bark was collected at midday (11:30–13:30) for each standard individual. Meanwhile, approximately 0.5 m around the stem of each standard individual in the pure plantations and at the middle between two species in the mixed plantation, one soil core at seven depths (0–10, 10–20, 20–30, 30–50, 50–100, 100–150, and 150–200 cm) was collected through soil drilling. The suberized stem and collected soil samples were placed into glass bottles. These bottles were sealed with parafilm and stored at –15 ℃.

On the same day as plant stem and soil sample collections, one leaf was selected from each sap flow monitored individual for leaf water potential measurement. The Ψ_{pd} and Ψ_m were measured by a PMS1515D analyzer (PMS Instrument, Corvallis Inc., OR, USA) at predawn (4:30–5:30) and midday (11:20–12:40), respectively.

All the plant stem, soil, and leaf samples collected on the first day after a rainfall pulse were used for analysis, with the detailed given in section “2.6 Statistical analysis”. There were 180 stem and 945 soil samples for water extraction, and 180 leaf samples for Ψ_{pd} and Ψ_m measurement, respectively.

A vacuum line (LI-2100, LICA Inc., China) was used to extract water from soil samples and plant stems. The water isotopic values of rainwater, soil samples, and plant stems were determined using a DLT-100 water isotope analyzer (LGR Inc., USA), with accuracy of ± 0.1 ($\delta^{18}O$) and ± 0.3 ‰ (δD). The potential influence of organic matter on water isotopic values produced during water extraction from stems was eliminated using the method of Yang et al. (2015). The isotopic values (‰) were calculated as follows:

$$\delta^{18}O(D) = (R_{sample} - R_{standard}) / R_{standard} \times 1000\,‰ \tag{3}$$

where $R_{standard}$ and R_{sample} indicate the $^{18}O/^{16}O$ (D/H) molar ratios of water sample relative to the Vienna

Standard Mean Ocean Water, respectively. The average water $\delta^{18}O$ and δD of plant stems for specific species and corresponding soil samples was calculated in each plot for further analysis.

2.5 Plant fine root investigation

In August 2018, 4 soil cores were dug around each selected standard individual for plant stem and soil water collection, through a soil drill with diameter 20 cm to investigate plant fine roots. The collected soil depths were 0–10, 10–20, 20–30, 30–50, 50–70, 70–100, 100–130, 130–150, 150–200 cm, with approximately 0.5 m around the stem of each species standard individual. The sum of root samples for 4 soil cores at each soil depth for each selected standard individual was used for fine root distribution analysis, giving 324 fine root samples. WinRHIZO (Regent Instruments Inc., Quebec, Canada) was used to determine the fine root (diameter < 2 mm) surface area at each soil depth. The average fine root surface area for specific species at each soil depth was calculated in each plot for further analysis.

2.6 Statistical analysis

2.6.1 Plant transpiration and leaf water potential in response to rainfall pulse calculation

In the present study, the first day after rainfall was the maximum normalized F_d within 3 days for *H. rhamnoides* and *P. tomentosa* in both plantation types, except that the second day after 24 and 35.2 mm was the maximum normalized F_d for *P. tomentosa* in pure plantation. However, for *P. tomentosa* in pure plantation, there was no significant difference ($P > 0.05$) in diurnal sap flow between the first and second day after each of these two rainfall events based on independent-sample *t*-test (Fig. S2). Therefore, the normalized F_d on the first day after each selected rainfall amount was used in Eq. (4) to calculate the relative response of daily normalized F_d (SF_R, %) to rainfall pulses:

$$SF_R = ((X_{after} - X_{before}) / X_{before}) \times 100\% \tag{4}$$

where X_{after} and X_{before} are the normalized F_d on the first day after and on the day before the rainfall event, respectively.

Meanwhile, none of Ψ_{pd}, Ψ_m nor $\Psi_{pd}-\Psi_m$ showed significant differences between the first and second day after each rainfall event ($P > 0.05$) for these two species in both plantation types (Table S2). On the first day after each rainfall event, the average Ψ_{pd}, Ψ_m, and $\Psi_{pd}-\Psi_m$ for specific plant species in each plot were used in the following analysis to illustrate the influence of leaf water potential on SF_R in response to rainfall pulses.

2.6.2 Calculation of RRS uptake proportion and water sources from different soil layers

The RRS uptake proportion (RUP, %) after a recent rainfall pulse for plant was calculated as the proportion of rainwater in plant stem as follows (Cheng et al., 2006):

$$\delta^{18}O\ (D)_p = RUP \times \delta^{18}O\ (D)_{rain} + (1-RUP) \times \delta^{18}O\ (D)_{swb} \quad (5)$$

$$RUP = (\delta^{18}O(D)_p - \delta^{18}O(D)_{swb})/(\delta^{18}O(D)_{swa} - \delta^{18}O(D)_{swb}) \times 100\% \quad (6)$$

where $\delta^{18}O(D)_{rain}$ and $\delta^{18}O(D)_p$ are the isotopic values for rainwater and plant stem after rainfall, respectively; $\delta^{18}O(D)_{swb}$ and $\delta^{18}O(D)_{swa}$ are the isotopic values of soil water immediately before and after rainfall, respectively. The Eq. (6) is derived through the linear mixing model for water isotopic value in plant stem after rainfall in Eq. (5). The RUP was the average value calculated in Eq. (6) based on $\delta^{18}O$ and δD, respectively, for specific plant species in each plot.

Equations (5) and (6) are based on the assumption that little or no soil water is lost through evaporation. Thus, in this study, only the values of plant stem and soil water collected on the first day immediately after rainfall were used, and only the RUP on the first day after each rainfall event was calculated.

In this study, the $\delta^{18}O(D)_{swb}$ could not be directly and accurately determined through soil water sample collection, due to unpredictable natural rainfall events. A linear mixed model can be used to calculate the $\delta^{18}O(D)_{swb}$, based on the isotopic values for rainwater and soil water after rainfall, and soil depth interval weighted SW before (sw_b, $m^3\ m^{-3}$) and after (sw_a, $m^3\ m^{-3}$) rainfall:

$$\delta^{18}O(D)_{swb} = sw_b/sw_a \times \delta^{18}O(D)_{swa} + (1-sw_b/sw_a) \times \delta^{18}O(D)_{rain} \quad (7)$$

In addition to RUP, the water uptake proportions from different soil layers were calculated on the first day after a rainfall event using the MixSIR program, to complement the analysis of plant water source variations in response to rainfall pulses. The RUP method only calculated the proportion of recent rainwater in the plant stem and did not include soil water before the recent rainfall event (Gebauer and Ehleringer, 2000; Cheng et al., 2006). The water taken up from different soil layers by the plant is a mixture of soil water before the recent rainfall event and the recent rainwater.

Firstly, the 7 soil depths (0–10, 10–20, 20–30, 30–50, 50–100, 100–150, and 150–200 cm) were combined into three soil layers (shallow, middle, and deep) based on the variation of soil water $\delta^{18}O$ and δD and SW, to facilitate water source comparisons. The shallow soil layer (0–30 cm) was vulnerable to rainfall, and exhibited higher soil water $\delta^{18}O$ and δD values and larger water isotope and SW variations (Table S3, Fig. S3). The middle soil layer (30–100 cm) was less vulnerable to rainfall, with high soil water isotope values and large water isotope and SW variations. The deep soil layer (100–200 cm) was relative stable, with low soil water isotope values and small water isotope and SW variation compared with shallow and middle soil layers. In addition, based on independent-sample *t*-test, no significant difference ($P > 0.05$) in soil water $\delta^{18}O$ and δD between different soil depths in the same soil layer in each plot ensured the feasibility of the combination of the three soil layers (Phillips et al., 2005). Then, the water uptake proportions from three soil layers were calculated using the MixSIR program (Moore and Semmens, 2008), with model input parameters being the average $\delta^{18}O$ and δD values in plant stem water and soil water at each soil layer in each plot. The SD for $\delta^{18}O$ and δD at each soil layer was also used to accommodate the uncertainties of these values. No fractionation was considered during water source uptake by these plant roots because none of the plants exhibited xerophytic or halophytic characteristics. Ellsworth and Williams (2007) and Moore and Semmens (2008) suggested that a water stable isotope fractionation generally occurred during root uptake by xerophytic or halophytic plants.

2.6.3 Statistical analysis for plant transpiration, water sources, and leaf water potential in response to rainfall pulse

A repeated ANOVA (ANOVAR) was used to analyze the differences in plant transpiration, water sources, and plant physiological parameters between these species in pure and mixed plantations, respectively. This analysis was conducted with SF_R, RUP, relative water uptake proportions from three soil depths, and $\Psi_{pd} - \Psi_m$ as response variables, and “species” and “rainfall” as between-subject and within-subject factors, respectively. The same analysis was used to detect mixed afforestation effect on response variables for each plant species, with "plantation type" and "rainfall" as between-subject and within-subject factors, respectively. Furthermore, significant differences in fine root proportion for each soil layer (shallow, middle, and deep) for specific species between pure and mixed plantations were detected through independent-sample *t*-test. All of these analyses were calculated with SPSS 18 (IBM Inc., New York, US), after data normal distribution and homogeneity of variance analysis were tested.

3 Results

3.1 Variation in environmental parameters and plant fine root vertical distribution

The rainfall amount during the study period (262.7 mm, DOY 152–273) was 15.56% lower than the average value during 2000–2017. Rainfall varied seasonally with 36 consecutive days having no rainfall event (DOY 157–192) and 5 days having successive rainfall events (DOY 237–241) (Fig. 1). The ET_0 (554.7 mm) was approximately twice the rainfall amount during the study period, with the higher and lower values during the low and high rainfall event periods, respectively (Fig. 1). The SW increased and subsequently decreased by different degrees following rainfall events, with shallow soil layer (0–30 cm) exhibited higher variation than the corresponding value below 30 cm in the three plantations (Fig. 1, Table S3). The coefficients of variation (CVs, SD/mean) in the shallow soil layer were 19.23%, 20%, and 17.5% in *H. rhamnoides* and *P. tomentosa* pure plantations and the mixed plantation, respectively. The SW for shallow and middle (30–100 cm) soil layers exhibited lower values than some deep soil layers (100–200 cm) during the less rainfall event period (such as DOY 157–192) in three plantations. In addition, compared with shallow and middle soil layers, the deep soil layer SW exhibited a time lag response to rainfall events.

The *H. rhamnoides* and *P. tomentosa* in pure plantations exhibited different fine root vertical distributions, with more than 40% of fine roots observed in shallow and deep soil layers, respectively (Fig. S4). In the mixed plantation, approximately 40% of *H. rhamnoides* fine roots were in the shallow soil layer. Meanwhile, no significant differences in fine root proportion were observed for *H. rhamnoides* for each soil layer in pure and mixed plantations ($P > 0.05$). The fine root proportion of *P.*

tomentosa in the shallow soil layer was significantly increased from 21.94% in pure plantation to 31.28% in the mixed plantation ($P < 0.05$).

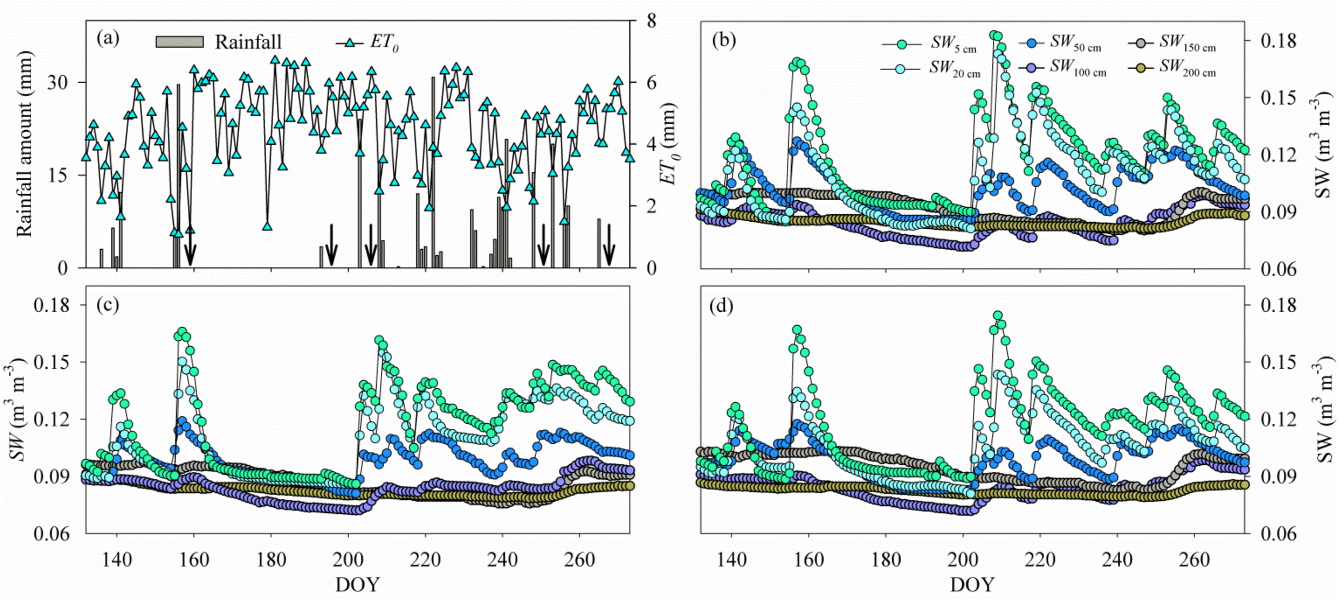

Figure 1. Variation in (a) rainfall amount, reference evapotranspiration (ET_0), and average (mean ± SD) soil water content (SW) in (b) *H. rhamnoides* pure plantation, (c) *P. tomentosa* pure plantation, and (d) mixed plantation from DOY 152 to 273 (1 June to 30 September) (n = 3). Standard deviation bars for SW at each soil layers are not shown to allow clear display of variation of SW for each plantation. Arrows in (a) indicate dates of sample collection at the first day after rainfall events: DOY 157 (6 June), DOY 194 (12 July), DOY 204 (23 July), DOY 249 (6 September), and DOY 265 (22 September).

3.2 Variations in sap flow

Daily normalized F_d for *H. rhamnoides* and *P. tomentosa* fluctuated with rainfall events in pure and mixed plantations (Fig. 2). The variation of normalized F_d for *H. rhamnoides* and *P. tomentosa* in mixed plantation was higher than the specific species in pure plantations, with corresponding CVs of 30.99% and 34.88% in the mixed plantation, and 24.64% and 27.44% in pure plantations (Fig. 2). The SF_R after rainfall pulses was significantly influenced by both rainfall amount and plant species ($P < 0.001$) (Fig. 2, Table S4). Following large rainfall amounts (≥15.4 mm), the diurnal variation of sap flow was significantly higher than the value before rainfall ($P < 0.05$) for *H. rhamnoides* in pure plantation and for *P. tomentosa* in both plantation types (Figs. S5 and S6). The lowest rainfall amount (7.9 mm) that significantly increased the diurnal variation of sap flow was observed for *H. rhamnoides* in the mixed plantation (Fig. S5). Furthermore, in response to rainfall pulses, the SF_R for *H. rhamnoides* in pure (range 6.69 ± 1.22% to 106.34 ± 4.7%) and mixed (range 2.23 ± 0.54% to 190.89 ± 15.49%) plantations was significantly higher ($P < 0.001$) than corresponding values for *P. tomentosa*: ranges 4.24 ± 0.52% to 60.28 ± 5.72% and 3.14 ± 0.53% to 83.04 ± 14.23% (Table S4). Mixed afforestation significantly enhanced SF_R for both species ($P < 0.001$) (Table S4).

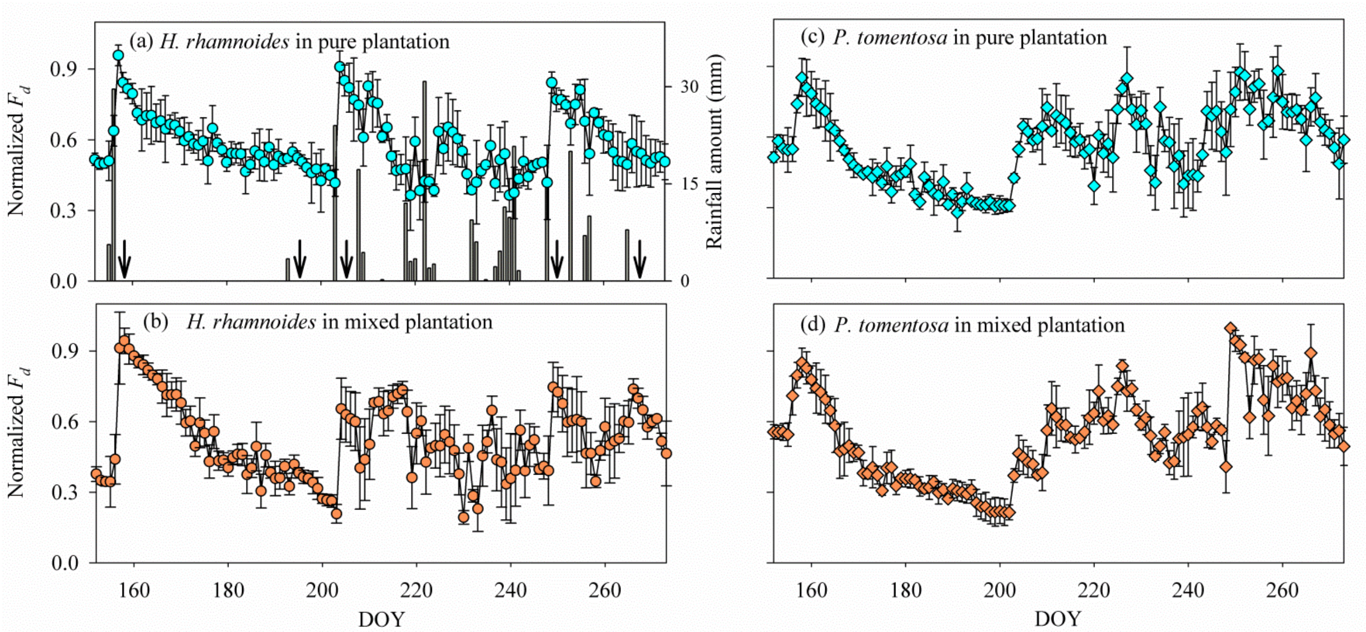

Figure 2. Variation in (a) rainfall amount, and average daily normalized F_d for *H. rhamnoides* in (a) pure and (b) mixed plantations and for *P. tomentosa* in (c) pure and (d) mixed plantations (n = 3). Arrows in (a) indicate dates of sample collection at the first day after rainfall events: DOY 157 (6 June), DOY 194 (12 July), DOY 204 (23 July), DOY 249 (6 September), and DOY 265 (22 September).

3.3 Variations in plant water sources

The soil water $\delta^{18}O$ and δD for pure *H. rhamnoides*, pure *P. tomentosa*, and mixed plantations showed large vertical variation following small rainfall events (≤7.9 mm), and exhibited relatively small vertical variations following large rainfall events (≥15.4 mm) (Fig. S7). Generally, the isotopic values of soil water depleted from shallow to deep soil layers, and water isotopic values in shallow and middle soil layer were close to rainwater in the three plantations following large rainfall events.

Although no significant difference in RUP was observed between *H. rhamnoides* (14.2 ± 7.81%) and *P. tomentosa* (12.43 ± 7.33%) in pure plantations (Fig. 3, Table S4), the RUP was significantly higher for *H. rhamnoides* (19.17 ± 8.6%) than *P. tomentosa* (14.59 ± 5.86%) in the mixed plantation (P < 0.05) (Table S4). In addition, *H. rhamnoides* mainly uptake water from the middle soil layer in pure and mixed plantations based on the MixSIR result, with corresponding average values of 36.27 ± 2.43% and 44.14 ± 3.06% (Fig. 4). The water source for *P. tomentosa* in pure and mixed plantations was mainly from the deep and middle soil layers, respectively, with corresponding average values of 41.4 ± 15.18% and 40.17 ± 5.9%. In pure plantation, the water source from shallow and middle soil layers for *H. rhamnoides* was significantly higher than *P. tomentosa*; however, the water source from the deep soil layer was significantly lower for the former species (P < 0.05) (Table S5). No significant differences in water sources from each soil layer were observed between these species in the mixed plantation (Table S5). In addition, mixed afforestation significantly enhanced RUP and decreased the deep soil water uptake proportion for *H. rhamnoides* and *P. tomentosa* (P < 0.05) (Table S4, Figs. 3 and 4).

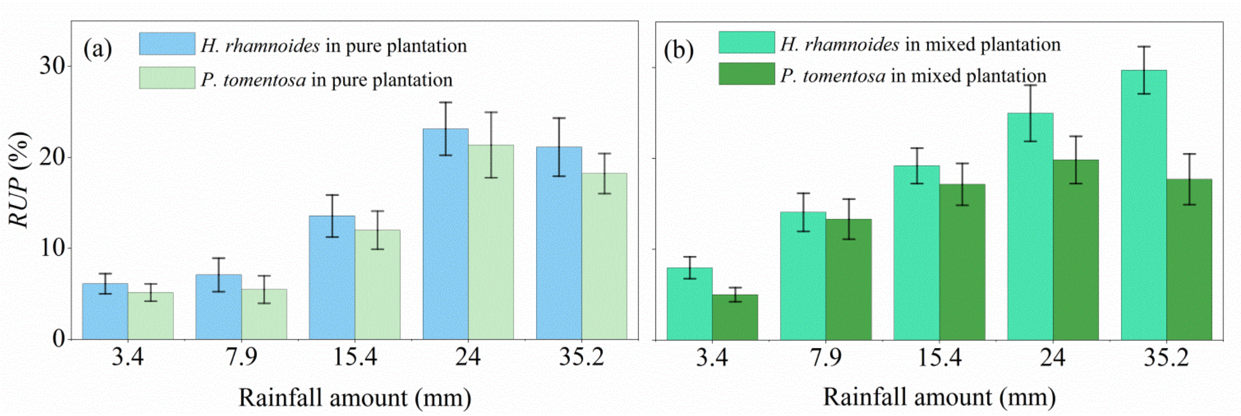

Figure 3. Variation in average rainwater-recharged soil water uptake proportion (RUP) for *H. rhamnoides* and *P. tomentosa* in (a) pure and (b) mixed plantations after five rainfall events (n = 3).

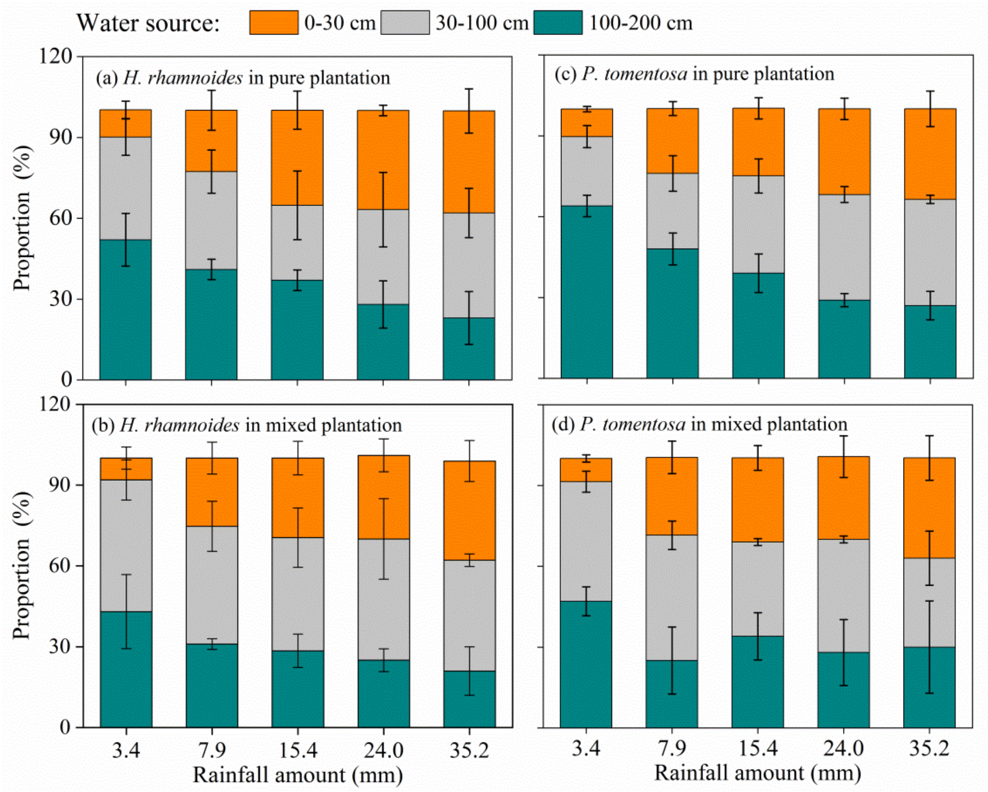

Figure 4. Variation in average plant water sources from three soil layers (0–30, 30–100, and 100–200 cm) for *H. rhamnoides* in (a) pure and (b) mixed plantations, and for *P. tomentosa* in (c) pure and (d) mixed plantations after five rainfall events (n = 3).

3.4 Variations in plant leaf water potential

In response to rainfall pulses, *H. rhamnoides* exhibited higher CVs for Ψ_{pd}, Ψ_m, and Ψ_{pd}–Ψ_m than corresponding values for *P. tomentosa* in both plantation types, except that *H. rhamnoides* exhibited lower CVs for Ψ_{pd} than *P. tomentosa* (12.99% and 18.33%, respectively) in the mixed plantation (Fig. 5). Compared with *P. tomentosa*, *H. rhamnoides* exhibited significantly positive Ψ_{pd} in the pure plantation, negative Ψ_m in the mixed plantation, and larger Ψ_{pd}–Ψ_m in both plantation types ($P < 0.05$) (Table S6). Meanwhile, mixed afforestation significantly reduced the Ψ_m and increased the Ψ_{pd} for *H. rhamnoides* and *P. tomentosa* ($P < 0.05$), respectively, and significantly increased Ψ_{pd}–Ψ_m for both species (Table S6).

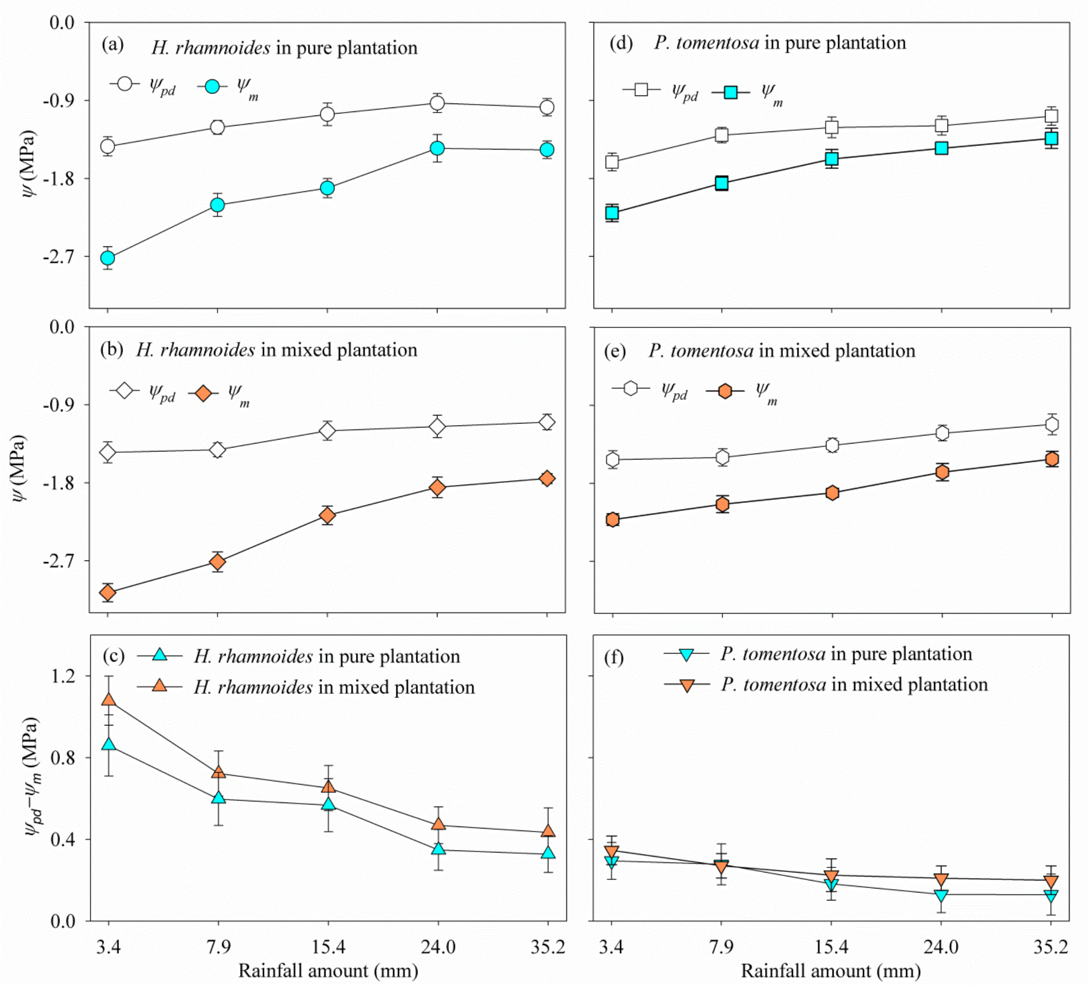

Figure 5. Variation in average plant predawn (Ψ_{pd}), midday leaf water potential (Ψ_m), and leaf water potential gradient (Ψ_{pd}–Ψ_m) for (a–c) *H. rhamnoides* and (d–f) *P. tomentosa* in both plantation types after five rainfall events (n = 3).

3.5 Influence of water sources and Ψ_{pd}–Ψ_m on plant transpiration

The SF_R significantly increased with increasing RUP and decreasing Ψ_{pd}–Ψ_m for *H. rhamnoides* ($P < 0.01$) in both plantation types (Fig. 6). Meanwhile, SF_R significantly increased with decreasing Ψ_{pd}–Ψ_m for *P. tomentosa* in both plantation types ($P < 0.05$). However, a significant relationship between SF_R and RUP was observed for *P. tomentosa* in the mixed ($P < 0.05$) but not in pure plantations (Fig. 6).

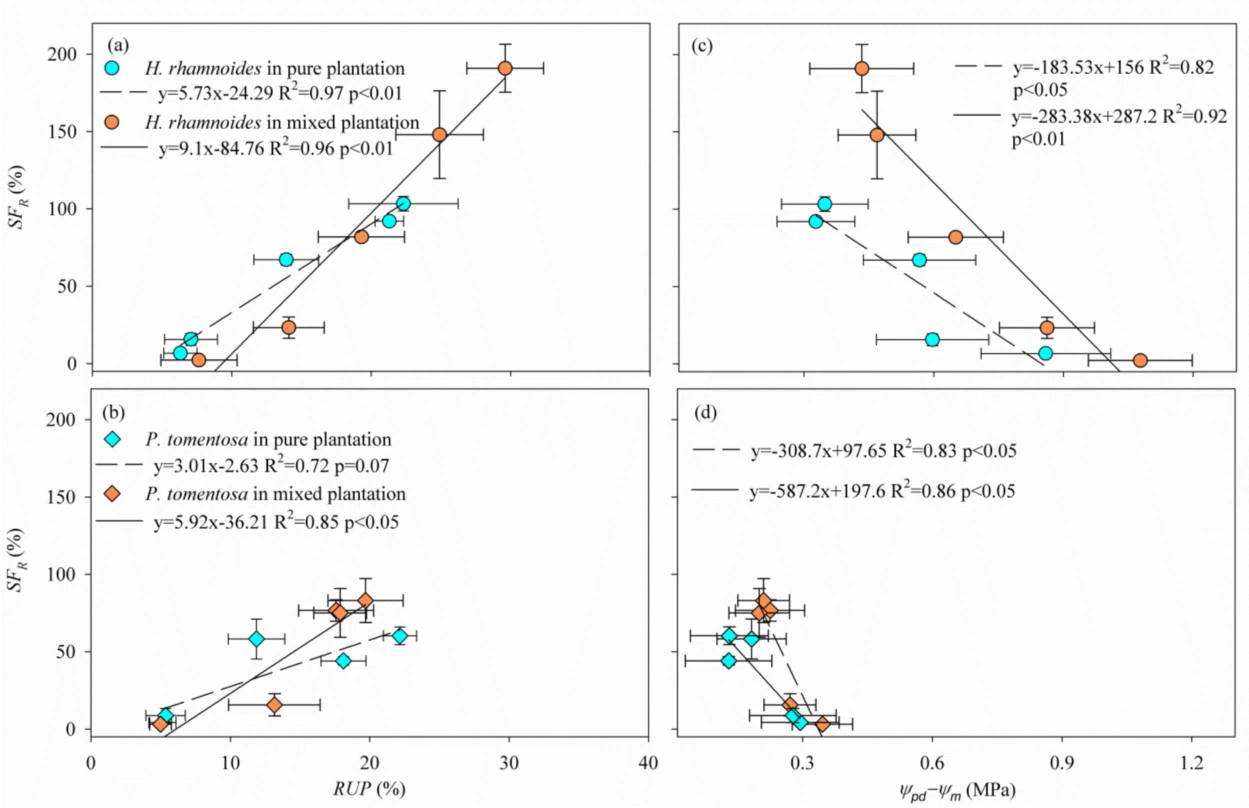

Figure 6. Relationship of average (a, b) rainwater-recharged soil water uptake proportion (RUP) and (c, d) leaf water potential gradient (Ψ_{pd}–Ψ_m) with relative response of normalized F_d (SF_R) for *H. rhamnoides* and *P. tomentosa* in both plantation types (n = 3).

4 Discussion

4.1 RRS uptake enhances plant transpiration for *H. rhamnoides* but not *P. tomentosa* in pure plantations

Rainwater is the only replenished soil water source in the studied region (Shao et al., 2018), because plants cannot uptake ground water of approximately 150 m depth below the surface, which was determined through well observation (unpublished data). Small rainfall events generally only wet the soil surface and may evaporate before plant root uptake (Gebauer and Ehleringer, 2000). However, large rainfall events are most likely recharge soil water and enhance the metabolic activity of plant fine roots (Hudson et al., 2018), thus enhancing plant water uptake. Similar to *Salix psammophila* and *Caragana korshinskii* in the studied region (Zhao et al., 2021), both *H. rhamnoides* and *P. tomentosa* exhibited plasticity in water sources in pure plantations (Fig. 4), with *H. rhamnoides* exhibiting the greater plasticity. In pure plantations, the obviously lower SWC at all soil depths (Fig. 1) and large water uptake proportion from the deep soil layer (Fig. 4) after 3.4 mm of rainfall for these two species, suggested that this rainfall amount did not relieve the drought caused by 36 days (DOY 157–192) of no rainfall. The RUP for *H. rhamnoides* but not *P. tomentosa* significantly increased following an increase in rainfall amount ($P < 0.05$) (Fig. S8), indicating that water uptake was more sensitive to rainfall pulse for *H. rhamnoides*. This may be mainly due to the greater proportions of fine root surface area distributed in the shallow soil layer for *H. rhamnoides* (40.85 ± 3.14%) compared to *P. tomentosa* (21.94 ± 2.3%) (Fig. S4).

The RRS uptake does not permit plant transpiration increase after rainfall pulses especially in semiarid and arid environments (Grossiord et al., 2017; West et al., 2007), and the influence of water potential gradient (Ψ_{pd}–Ψ_m) on plant transpiration should also be considered (Hudson et al., 2018; Kumagai and Porporato, 2012). For example, although *Juniperus osteosperma*, a deep rooted plant species, could uptake RRS after large rainfall events in the west of the United States, the plant transpiration did not increase with increasing rainfall amount (West et al., 2007). The asynchronization between RRS uptake and plant transpiration for *J. osteosperma* was mainly attributed to the uptake of RRS by plants being unable to reverse the cavitation in its roots and stems (Grossiord et al., 2017; West et al., 2007). Our previous investigations in the studied region indicated that *P. tomentosa* is relatively more vulnerable to cavitation than *H. rhamnoides*, with water potential at 50% loss of conductivity of −1.15 MPa (Zhang et al., 2013) and −1.49 MPa (Dang et al., 2017), respectively, based on stem vulnerability curves. Being less vulnerable to stem cavitation allowed *H. rhamnoides* to experience a significantly lower Ψ_m and larger Ψ_{pd}–Ψ_m compared with *P. tomentosa* in response to soil water conditions after rainfall pulses. The large Ψ_{pd}–Ψ_m for *H. rhamnoides* was consistent with the high SF_R and CVs of normalized sap flow, indicating that this species exhibited a rainfall sensitive mechanism. The relative constant Ψ_{pd}–Ψ_m for *P. tomentosa* was consistent with the relatively small SF_R and CVs of normalized sap flow, indicating that this species exhibited a rainfall insensitive mechanism. Furthermore, after rainfall events, the SF_R for *H. rhamnoides* but not for *P. tomentosa* significantly increased following rainfall amount increases ($P < 0.05$) (Fig. S8), also indicating that plant transpiration was more sensitive to rainfall pulses for *H. rhamnoides*.

Consistent with the first hypothesis, the influence of RRS uptake and physiological adjustment on plant transpiration was different for these species in pure plantations. The SF_R was significantly influenced by RUP and Ψ_{pd}–Ψ_m for *H. rhamnoides* in the pure plantation, indicating that RRS uptake and leaf physiological adjustment enhanced its plant transpiration (Figs. 6 and 7). However, the SF_R was significantly influenced by Ψ_{pd}–Ψ_m for *P. tomentosa* (Fig. 6), suggesting that its transpiration was mainly constrained by plant physiological characteristics. The ET_0 represents the atmospheric evaporative demand, and has been observed to influence plant transpiration in water limited (Li et al., 2021) and non-water limited regions (Iida et al., 2016). However, in the present study, neither ET_0 after rainfall nor relative response of ET_0 significantly influenced SF_R for either species in pure plantations (Table S7). The influence of plant physiological characteristics (i.e. Ψ_{pd}–Ψ_m) on SF_R for both species, may partially contribute to the lack of atmosphere evaporative demand effect on plant transpiration in the studied region, although these species exhibited different rainfall pulse sensitivity.

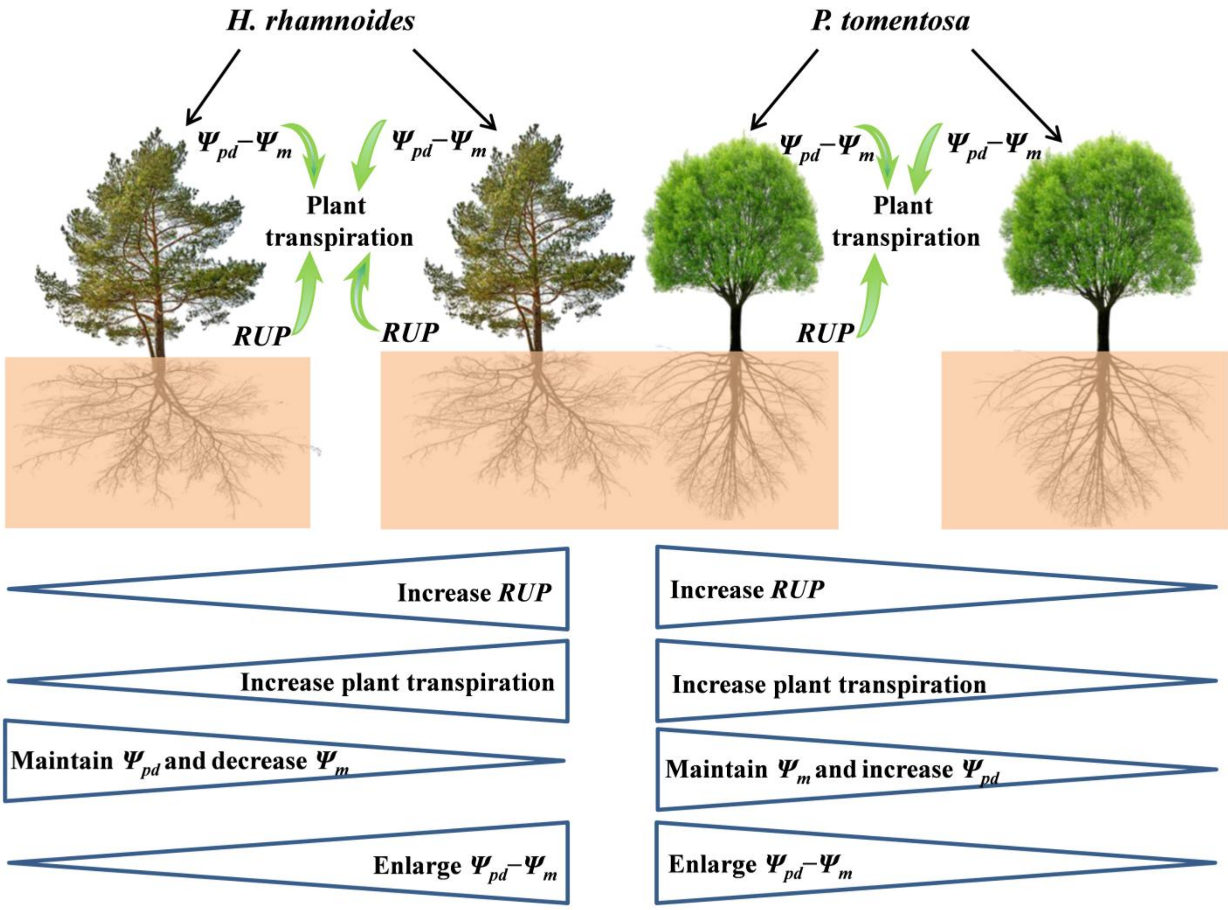

Figure 7. Schematic of rainwater-recharged soil water (RRS) uptake, leaf water potential gradient, and plant transpiration for *H. rhamnoides* and *P. tomentosa* in both plantation types. Both RRS uptake

proportion (RUP) and leaf water potential gradient (Ψ_{pd}–Ψ_m) enhanced plant transpiration after rainfall pulses for *H. rhamnoides* in pure and mixed plantations, and for *P. tomentosa* in mixed plantation. However, Ψ_{pd}–Ψ_m rather than RUP significantly influenced plant transpiration after rainfall pulses for *P. tomentosa* in the pure plantation. Mixed afforestation effect of these parameters for each species are indicated at the bottom half of the schematic, with "increase", "decrease" or "enlarge" indicating a significant difference ($P < 0.05$) for a species between pure and mixed plantations. Mixed afforestation significantly enhanced RUP and plant transpiration, decreased Ψ_m, and enlarged Ψ_{pd}–Ψ_m for *H. rhamnoides*, and also significantly enhanced the RUP and plant transpiration, increased Ψ_{pd}, and enlarged Ψ_{pd}–Ψ_m for *P. tomentosa*.

4.2 RRS uptake enhances plant transpiration for coexisting species in mixed plantation

Spatial water resource partitioning is considered one of the essential plant strategies to maintain coexistence in mixed plantations, especially in semiarid and arid regions (Munoz-Villers et al., 2020; Silvertown et al., 2015; Yang et al., 2020). However, water source competition has widely been observed among coexisting plant species according to the literature surveys by Silvertown et al. (2015) and Tang et al. (2018), in either water sufficient or limited regions. In the present study, the non-significant differences in xylem $\delta^{18}O$ and δD ($P > 0.05$) and plant water sources for the three soil layers (Fig. 4, Table S5) indicated water competition between these species in the mixed plantation, although the RUP was significantly higher for *H. rhamnoides* (Table S4).

Generally, two types of adaptation can be adopted by plants to cope with resource competition: increased competition ability or minimized competition interactions (West et al., 2007). Consistent with the first adaptation type, mixed afforestation enhanced the RUP for *H. rhamnoides* and *P. tomentosa* (Figs. 3 and 7, Table S4). Although mixed afforestation did not significantly alter the Ψ_{pd} and Ψ_m for *H. rhamnoides* and *P. tomentosa*, respectively, significantly negative Ψ_m and positive Ψ_{pd} were observed for corresponding species ($P < 0.01$) (Table S6). Mixed afforestation significant increased Ψ_{pd} for *P. tomentosa*, possibly due to the advantage of access to soil moisture recharged by rainwater through an increased root surface area in the shallow soil layer for this species in the mixed plantation (Fig. S4).

Thus, plant physiological (Ψ_m) and root morphological adjustments were adopted by *H. rhamnoides* and *P. tomentosa* in the mixed plantation, respectively, to significantly enlarge Ψ_{pd}–Ψ_m and increase RUP (Fig. 7). In addition to these adjustments for specific plant species in mixed plantation, the significant influence of RUP and Ψ_{pd}–Ψ_m on SF_R for *P. tomentosa* in mixed plantation was also consistent with the second hypothesis (Fig. 6). Similar to the result in pure plantations, no significant relationship between SF_R and ET_0 after rainfall and relative response of ET_0 was observed for these species in the mixed plantation (Table S7). This result also confirmed the influence of physiological or morphological factors on plant transpiration for these species in the mixed plantation in response to rainfall pulses.

Furthermore, consistent with the second adaptation type, mixed afforestation significantly decreased the water uptake proportion from the deep soil layer for these species (Table S5). Similar to other studies in the Loess Plateau (Wang et al., 2020; Wu et al., 2021), the deep soil layer exhibited lower SW than other soil layers in all plantation types in the present study (Fig. 1, Table S3). Jia et al. (2017) and Wang et al. (2020) attributed the lower SW in deep soil layers to the imbalance between rainwater replenishment and plant uptake of water from this layer. In addition, plants may expend more energy to uptake water from deep compared to shallow soil layers (Schenk, 2008), especially when the deep soil layer exhibits lower SW. Thus, both increased rainwater-recharged soil water uptake and decreased water source competition from the deep soil layer were adopted by these species in the mixed plantation to minimize water sources competition under water limited conditions.

4.3 Implications for plantation species and type selection based on RRS uptake and plant transpiration

The RRS uptake and plant transpiration in response to rainfall pulses may influence plant physiological process and the water cycle (Meier et al., 2018; Zhao et al., 2021). In pure plantations, *H. rhamnoides* rather than *P. tomentosa* showed an advantage in RRS uptake due to the large Ψ_{pd}–Ψ_m and high fine root surface area proportions distributed in the shallow soil layer for the former species, although both species exhibited plasticity in water sources. The excessive water uptake from the deep soil may desiccate deep soil (Wu et al., 2021), weakening plant resilience to drought stress and thus plant community sustainability in this Loess Plateau region (Song et al., 2018; Zhao et al., 2021). West et al. (2012) and Wu et al. (2021) suggested that increased RRS uptake can reduce plant water uptake from deep soil layers, and is essential for plantation adaptation in water limited regions. In the present study, physiological (e.g., Ψ_m) and morphological (fine root distribution) adjustments were observed for *H. rhamnoides* and *P. tomentosa* in the mixed plantation, respectively, to enlarge Ψ_{pd}–Ψ_m and enhance the RUP and plant transpiration (Figs. 7 and S4). The significantly increased RUP and decreased deep soil water uptake proportion for both species in mixed plantation may relieve deep soil water deficit and strengthen plantation sustainability (Tables S4 and S5). Furthermore, mixed afforestation also increased the total biomass of *H. rhamnoides* and *P. tomentosa*, calculated through the allometric equation indicated in Zhou et al. (2018) and Tang et al. (2019) (Table S8). Thus, rainfall pulse sensitive species in pure plantation, and plant species in mixed plantation that can adopt physiological or morphological adjustment to enhance rainwater-recharged soil water uptake and reduce excessive water uptake from deep soil layers, should be more often considered for use in the studied region. In addition, no runoff was generated under 0.74 mm min^{-1} rainfall intensity in silt loam soil in the Loess Plateau (Huang et al., 2014), which had no vegetation cover and similar soil saturated hydraulic conductivity (0.99 ± 0.15 g cm^{-3}) to that in the present study. Pan and Shuangguan (2005) also observed no runoff generation under 1.5 mm min^{-1} rainfall intensity for vegetation covered plots with 15° slope in the Loess Plateau. Direct observation for possible runoff after large rainfall events in further studies would be helpful for evaluating plantation species adaptability in the studied region, although Zhao et al. (2013) showed that the vegetation cover can enhance soil permeability and reduce water loss in the Loess Plateau. Furthermore, water conservation measures, such as water-fertilizer pits (60 × 60 × 40 cm) (Wang et al., 2020), that can intercept any possible runoff after large rainfall events and deliver it to deep soil layers may be appropriate for the studied region.

5 Conclusions

The influence of water sources and Ψ_{pd}–Ψ_m on plant transpiration in response to rainfall pulses was determined for *H. rhamnoides* and *P. tomentosa* in the semiarid Loess Plateau region. In pure plantations, the SF_R was significantly influenced by RUP and Ψ_{pd}–Ψ_m for *H. rhamnoides*, but the SF_R was significantly influenced by Ψ_{pd}–Ψ_m for *P. tomentosa*. Meanwhile, the lower value Ψ_{pd}–Ψ_m was consistent with the high SF_R for *H. rhamnoides*, and the higher value Ψ_{pd}–Ψ_m was consistent with the low SF_R for *P. tomentosa*, in response to rainfall pulses. Thus, *H. rhamnoides* and *P. tomentosa* exhibited sensitive and insensitive response to rainfall pulses, respectively. Furthermore, mixed afforestation enhanced the RRS uptake and plant transpiration for both species. Significantly lower plant Ψ_m and increased fine root surface area were adopted by *H. rhamnoides* and *P. tomentosa* in the mixed plantation, respectively, to enlarge Ψ_{pd}–Ψ_m and enhance RRS uptake and decrease water source competition from the deep soil layer. The SF_R was significantly influenced by RUP and Ψ_{pd}–Ψ_m for both species in the mixed plantation, and RRS uptake enhanced plant transpiration in the mixed plantation regardless of species sensitivity to rainfall pulses.

Data availability

The data that support the findings of this study are available from the corresponding author upon request.

Author contribution

YKT designed the study, performed the statistical analyses and wrote the original manuscript draft. LNW and YQY performed the experiments and collected the data. DXL collected the data.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Tables and captions

Table S1. Plant height, trunk diameter, and estimated sapwood width for *H. rhamnoides* and *P. tomentosa* in both pure and mixed plantations.

Plantation type	No.	Height (m)	Trunk diameter (mm)	Sapwood width (mm)
H. rhamnoides in pure plantation	1	3.95	45	9
	2	4.26	53	11
	3	4.05	51	10
	4	4.13	49	9
	5	3.98	50	10
	6	4.1	51	11
	7	4.3	57	12
	8	3.86	44	9
	9	3.92	53	11
P. tomentosa in pure plantation	1	4.41	58	17
	2	3.9	52	9
	3	3.92	56	16
	4	4.35	56	17
	5	4.59	58	16
	6	4.2	53	13
	7	4.29	54	15
	8	3.86	51	9
	9	3.98	52	11
H. rhamnoides in mixed plantation	1	4.36	52	12
	2	3.9	49	11
	3	4.23	51	12
	4	4.5	56	13
	5	4.73	55	14
	6	3.96	49	11
	7	4	51	12
	8	4.52	53	12
	9	4.39	52	12
P. tomentosa in mixed plantation	1	4.12	53	11
	2	3.75	46	9
	3	4.5	57	13
	4	4.21	53	11
	5	4.2	53	11
	6	4.16	51	10
	7	3.8	45	9
	8	4.95	59	13
	9	4.16	51	10

The sapwood width was estimated through the equation established through 12 unmonitored individual core samples for specific species with different diameters. The core sample was obtained using an increment borer, and the colour difference between sapwood and heartwood was large. The equation between trunk diameter (mm) and sapwood width (mm) was $y=0.248x-2.296$ $R^2=0.84$ $p<0.01$ for *H. rhamnoides* in pure plantation; $y=0.348x-5.98$ $R^2=0.78$ $P<0.01$ for *H. rhamnoides* in mixed plantation; $y=1.126x-47.66$ $R^2=0.83$ $P<0.01$ for *P. tomentosa* in pure plantation; $y=0.317x-5.71$ $R^2=0.939$ $P<0.01$ for *P. tomentosa* in mixed plantation.

Table S2. Independent-sample *t*-test parameters for predawn (Ψ_{pd}), midday (Ψ_{m}), and gradient of leaf water potential ($\Psi_{pd} - \Psi_{m}$) between the first and second day after each rainfall amount.

	Rainfall amount (mm)	*df*	Ψ_{pd}		Ψ_{m}		$\Psi_{pd} - \Psi_{m}$	
			t	*p*	*t*	*p*	*t*	*p*
H. rhamnoides in pure plantation	3.4	4	0.18	0.87	1.21	0.29	-2.5	0.07
	7.9	4	0.33	0.75	0.79	0.58	-8.01	0.47
	15.4	4	0.85	0.44	0.27	0.8	0.21	0.85
	24	4	0.97	0.39	-0.67	0.54	2.13	0.1
	35.2	4	-0.09	0.93	-7.1	0.52	0.28	0.79
P. tomentosa in pure plantation	3.4	4	0.88	0.43	0.66	0.55	0.81	0.47
	7.9	4	0.34	0.08	0.75	0.49	-1.8	0.14
	15.4	4	0.23	0.83	0.73	0.51	-0.82	0.46
	24	4	-2.08	0.11	1.14	0.32	-0.85	0.45
	35.2	4	-1.67	0.17	1.15	0.31	-2.22	0.09
H. rhamnoides in mixed plantation	3.4	4	2.53	0.07	1.4	0.24	-0.6	0.58
	7.9	4	1.24	0.28	2.02	0.11	-1.87	0.14
	15.4	4	-0.9	0.42	0.96	0.39	-1.29	0.27
	24	4	1.74	0.16	2.04	0.11	-1.22	0.29
	35.2	4	1.89	0.13	2.57	0.06	-0.29	0.78
P. tomentosa in mixed plantation	3.4	4	0.07	0.95	1.9	0.13	-0.35	0.72
	7.9	4	0.81	0.46	0.96	0.39	-0.46	0.67
	15.4	4	0.7	0.52	2.12	0.1	-0.53	0.62
	24	4	1.85	0.14	0.74	0.49	0.48	0.66
	35.2	4	2.23	0.09	1.21	0.3	0.55	0.61

Table S3 The average (mean ± SD) and coefficients of variation (CVs, SD/mean) of soil water $\delta^{18}O$ and δD on the first day after 5 selected rainfall events, and daily soil water content (SW) from DOY 152 to 273 (1 June to 30 September) in *H. rhamnoides* pure plantation, *P. tomentosa* pure plantation, and *H. rhamnoides*–*P. tomentosa* mixed plantation.

	Soil depth	soil water $\delta^{18}O$ (‰)		soil water δD (‰)		SW (m^3 m^{-3})	
		average	CV	average	CV	average	CV
H. rhamnoides pure plantation	0–30 cm	-5.61 ±1.57	27.99	-41.53 ±11.68	28.12	0.13 ±0.025	19.23
	30–100 cm	-7.14 ±0.92	12.89	-52.37 ±6.47	12.35	0.1 ±0.012	12
	100–200 cm	-9.3 ±0.69	7.42	-68.66 ±3.53	5.14	0.09 ±0.006	6.67
P. tomentosa pure plantation	0–30 cm	-5.43 ±1.69	31.12	-42.08 ±11.91	28.3	0.13 ±0.026	20
	30–100 cm	-7.49 ±0.73	9.75	-51.34 ±4.56	8.88	0.09 ±0.008	8.89
	100–200 cm	-9.39 ±0.34	3.62	-67.36 ±3.79	5.63	0.08 ±0.005	6.25
Mixed plantation	0–30 cm	-5.68 ±1.73	30.46	-41.67 ±10.67	25.61	0.12 ±0.021	17.5
	30–100 cm	-6.57 ±1.08	16.44	-47.8 ±5.78	12.09	0.1 ±0.011	11
	100–200 cm	-9.07 ±0.5	5.51	-64.47 ±2.45	3.8	0.09 ±0.005	5.56

There are 45, 30, and 30 data for calculated the average water $\delta^{18}O$ and δD of shallow, middle, and deep soil layer in each plantation, respectively. The absolute value was used for CVs of soil water $\delta^{18}O$ and δD calculation.

Table S4. Repeated ANOVA (ANOVAR) parameters for the relative response of normalized sap flow (SF_R) and rainwater-recharged soil water uptake proportion (RUP) after rainfall pulses of *H. rhamnoides* and *P. tomentosa* (n = 30).

	Variation source	*df*	SF_R		RUP	
			F	*p*	*F*	*p*
Pure plantation	Rainfall	4	97.91	<0.001	385.02	<0.01
	Species	1	121.13	<0.001	21.02	<0.05
	Rainfall × Species	4	27.35	<0.001	0.83	0.52
Mixed plantation	Rainfall	4	489.9	<0.001	17696.38	<0.01
	Species	1	70.38	<0.001	4089.12	<0.01
	Rainfall × Species	4	249.17	<0.001	1776.62	<0.01
H. rhamnoides	Rainfall	4	42.63	<0.001	496.72	<0.01
	Plantation type	1	337.09	<0.001	360.16	<0.01
	Rainfall × Plantation type	4	215.43	<0.001	17.62	<0.01
P. tomentosa	Rainfall	4	10.05	<0.001	1969.3	<0.01
	Plantation type	1	32.36	<0.01	54.83	<0.01
	Rainfall × Plantation type	4	19.12	<0.001	208.06	<0.01

df = degree of freedom, Plantation type = pure and mixed plantation for each species. Pure and Mixed plantation indicate the result of SF_R and RUP for both species in different plantation types, respectively; *H. rhamnoides* and *P. tomentosa* indicate the mixed afforestation effect on SF_R and RUP for these species.

Table S5. Repeated ANOVA (ANOVAR) parameters for water uptake proportion from shallow (0–30 cm), middle (30–100 cm), and deep (100–200 cm) soil layer for *H. rhamnoides* and *P. tomentosa* (n = 30).

	Variation source	*df*	0–30cm		30–100cm		100–200cm	
			F	*p*	*F*	*p*	*F*	*p*
Pure plantation	Rainfall	4	153.45	<0.01	145.04	<0.01	176.79	<0.01
	Species	1	8.69	<0.05	10.56	<0.05	11.08	<0.05
	Rainfall × Species	4	129.89	<0.01	112.46	<0.01	4.99	<0.01
Mixed plantation	Rainfall	4	1.5	0.41	2.3	0.11	18.34	<0.01
	Species	1	2.2	0.21	1.48	0.29	3.9	0.12
	Rainfall × Species	4	0.9	0.48	2.41	0.09	1.9	0.16
H. rhamnoides	Rainfall	4	2.05	0.14	1.51	0.25	85.46	<0.01
	Plantation type	1	1.07	0.36	1.32	0.32	10.08	<0.05
	Rainfall × Plantation type	4	0.62	0.66	1.39	0.28	5.59	<0.01
P. tomentosa	Rainfall	4	14.72	<0.01	71.59	<0.01	19.46	<0.01
	Plantation type	1	4.1	0.12	5.68	0.08	123.27	<0.01
	Rainfall × Plantation type	4	9.55	<0.01	85.29	<0.01	9.35	<0.01

df = degree of freedom, Plantation type = pure and mixed plantation for each species. Pure and Mixed plantation indicate the result of water sources from different soil layers for both species in different plantation types, respectively; *H. rhamnoides* and *P. tomentosa* indicate the mixed afforestation effect on water sources from different soil layers for these species.

Table S6. Repeated ANOVA (ANOVAR) parameters for predawn (Ψ_{pd}), midday leaf water potential (Ψ_m), and leaf water potential gradient ($\Psi_{pd}-\Psi_m$) for *H. rhamnoides* and *P. tomentosa* (n = 30).

	Variation source	*df*	Ψ_{pd}		Ψ_m		$\Psi_{pd}-\Psi_m$	
			F	*p*	*F*	*p*	*F*	*p*
Pure plantation	Rainfall	4	4.02	<0.05	24.44	<0.01	47.88	<0.01
	Species	1	182.74	<0.01	4.9	<0.05	969.97	<0.01
	Rainfall × Species	4	3.24	<0.05	2.08	0.13	18.68	<0.01
Mixed plantation	Rainfall	4	0.66	0.63	25.54	<0.01	82.49	<0.01
	Species	1	0.12	0.75	127.3	<0.01	3420.1	<0.01
	Rainfall × Species	4	1.8	0.18	3.7	<0.05	35.92	<0.01
H. rhamnoides	Rainfall	4	7.14	<0.01	19.64	<0.01	3.59	<0.05
	Plantation type	1	27.05	<0.01	496.66	<0.01	1278.96	<0.01
	Rainfall × Plantation type	4	1.69	0.202	3.32	<0.05	6.66	<0.01
P. tomentosa	Rainfall	4	30.78	<0.01	12.39	<0.01	7.38	<0.01
	Plantation type	1	792.77	<0.01	2.97	0.16	634.12	<0.01
	Rainfall × Plantation type	4	3.8	<0.05	0.09	0.98	3.83	<0.05

df = degree of freedom, Plantation type = pure and mixed plantation for each species. Pure and Mixed plantation indicate the result of leaf water potential for both species in different plantation types, respectively; *H. rhamnoides* and *P. tomentosa* indicate the mixed afforestation effect on leaf water potential for these species.

Table S7. Regression of reference evapotranspiration (ET_0) and relative response of normalized sap flow (SF_R).

Independent factors	*H. rhamnoides* in pure plantation		*H. rhamnoides* in mixed plantation		*P. tomentosa* in pure plantation		*P. tomentosa* in mixed plantation	
	R^2	p	R^2	p	R^2	p	R^2	p
ET_0	0.18	0.47	0.11	0.59	0.44	0.22	0.39	0.26
Relative response of ET_0	0.35	0.32	0.61	0.12	0.12	0.56	0.25	0.4

The regression equation is y=ax+b for all equations in this Table. Relative response of ET_0 is calculated as the same SF_R in Eq. (4) in the manuscript, with before and the first day after rainfall event parameter is ET_0 instead.

Table S8. Parameters of allometric equation and average (mean ± SD) estimated biomass of leaf, branches, wood, and roots of *H. rhamnoides* and *P. tomentosa* in pure and mixed plantations (n=6).

Species		*a*	*b*	Biomass in pure plantation	Biomass in mixed plantation
H. rhamnoides	leaf	0.017	0.541	0.51 ±0.02	0.55 ±0.04
	branches	0.013	0.042	0.16 ±0.05	0.14 ±0.01
	wood	0.036	0.721	2.4 ±0.09	2.6 ±0.07
	roots	0.019	0.732	1.51 ±0.06	1.79 ±0.04
	total biomass			4.58 ±1.01	5.08 ±1.13
P. tomentosa	leaf	0.052	0.621	1.21 ±0.05	1.58 ±0.09
	branches	0.025	0.81	1.35 ±0.04	1.32 ±0.06
	wood	0.0492	0.832	4.22 ±0.11	4.73 ±0.13
	roots	0.031	0.791	2.02 ±0.06	2.75 ±0.1
	total biomass			8.8 ±1.39	10.38 ±1.55

The allometric equation is $Y=a(D^2H)^b$, Y is biomass (kg), D is trunk diameter measured at 1.3 m above the ground (cm), H is tree height (m). Six standard individuals of *H. rhamnoides* and *P. tomentosa* in pure and mixed plantations were selected for average Y calculation.

Figure Legends

Figure S1. The geographic location of (a) study area and (b) plantation site in the Loess Plateau of China, and (c) monthly average (mean ± SD) rainfall amount and air temperature (Ta) during 2000-2017, and monthly rainfall amount and average Ta in 2018**.** Plantation types including *H. rhamnoides* pure plantation, *P. tomentosa* pure plantation, and Mixed plantation. Three adjacent plots were selected (16 m × 10 m) for each plantation type, and the schematic diagram of these plantation types is in (b). The China basic map can be obtained from http://map.geoq.cn/arcgis/rest/services/ChinaOnlineCommunityENG/MapServer.

Figure S2. Independent-sample *t*-test for diurnal variation of average (mean ± SD) sap flow between the first and second day after rainfall amount of (a) 24 and (b) 35.2 mm for *P. tomentosa* in pure plantation. Error bars indicate the standard deviation (n = 3).

Figure S3. The linear regression relationship between δ^2H and $\delta^{18}O$ for soil water at three layers (0–30, 30–100, and 100–200cm) in (a) *H. rhamnoides* pure plantation, (b) *P. tomentosa* pure plantation, and (c) Mixed plantation. The local meteoric water line (LMWL) is plotted in each panel for reference.

Figure S4. Variation in average (mean ± SD) surface area of fine root at different soil depths for *H. rhamnoides* and *P. tomentosa* in pure (a) and mixed (b) plantations. Error bars indicate the standard deviation (n = 3).

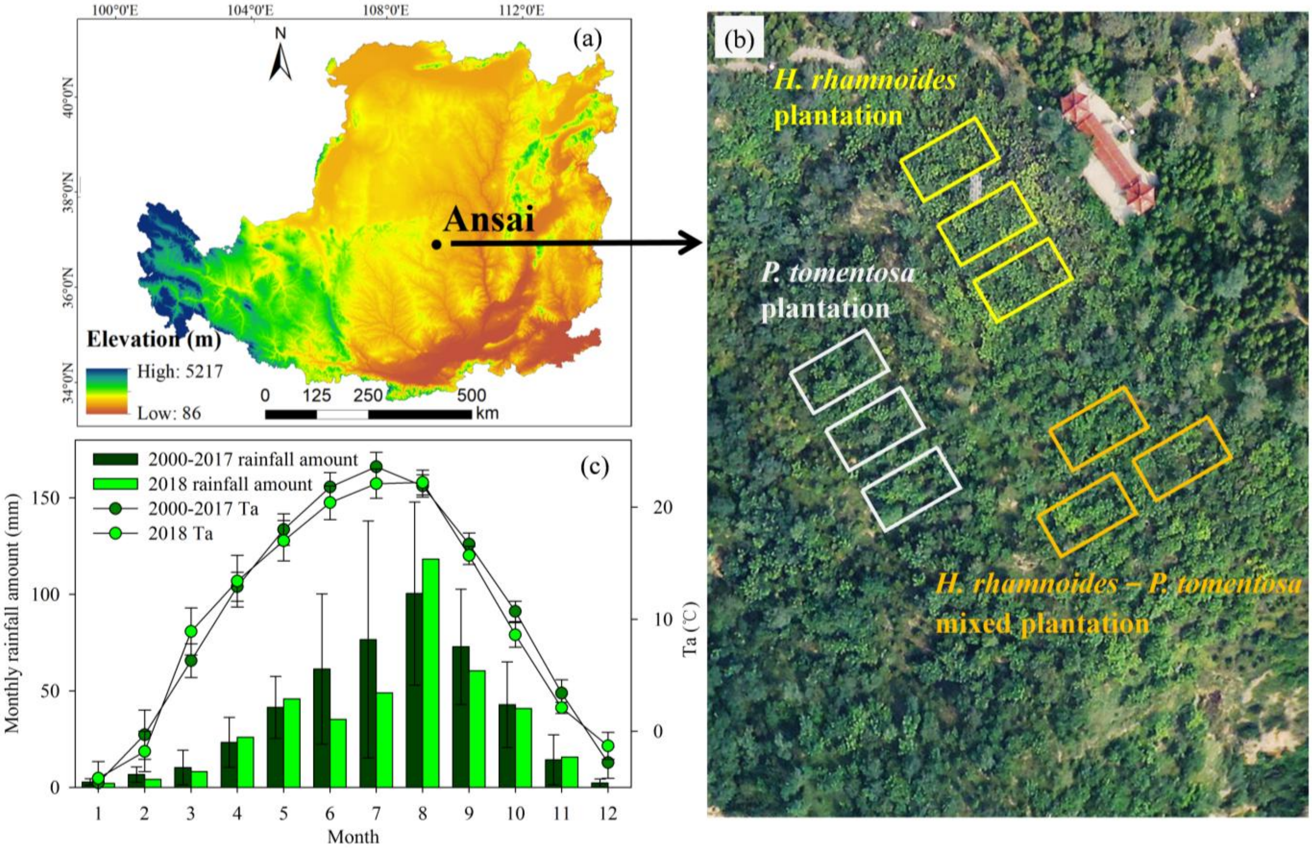
Figure S5. Independent-sample *t*-test for diurnal variation of average (mean ± SD) sap flow before and after 5 rainfall events for *H. rhamnoides* in pure (a–e) and mixed plantation (f–j). Before and after rainfall indicated the value in the day before and first day after a rainfall event. Error bars indicate the standard deviation (n = 3).

Figure S6. Independent-sample *t*-test for diurnal variation of average (mean ± SD) sap flow before and after 5 rainfall events for *P. tomentosa* in pure (a–e) and mixed plantation (f–j). Before and after rainfall indicated the value in the day before and first day after a rainfall event. Error bars indicate the standard deviation (n = 3).

Figure S7. Variation in average (mean ± SD) $\delta^{18}O$ and δD of rainwater, stem water, and soil water at seven soil depths for *H. rhamnoides* in (a–e) pure and (k–o) mixed plantations and for *P. tomentosa* in (f–j) pure and (k–o) mixed plantations after 5 rainfall events. Error bars indicate the standard deviation (n = 3). The date of each 5 selected rainfall events is followed the corresponding rainfall amount value. The average rainwater $\delta^{18}O$ and δD for each rainfall event is calculated with 3 rainwater subsamples, which was divided from one rainwater sample.

Figure S8. Relationship between rainfall amount and (a) relative response of normalized sap flow (SF_R) and (b) rainwater-recharged soil water uptake proportion (RUP) for *H. rhamnoides* in both plantation types, and these corresponding relationships for *P. tomentosa* (c–d) in both plantation types (n=3).

Figure S1.



100°0'E
104°0'E
108°0'E
112°0'E
(a)
N
40°0'N
38°0'N
36°0'N
34°0'N
Ansai
Elevation (m)
High: 5217
Low: 86
0 125 250 500
km
(b)
H. rhamnoides
plantation
P. tomentosa
plantation
H. rhamnoides – P. tomentosa
mixed plantation
(c)
2000-2017 rainfall amount
2018 rainfall amount
2000-2017 Ta
2018 Ta
Monthly rainfall amount (mm)
Ta (℃)
Month

Figure S2.

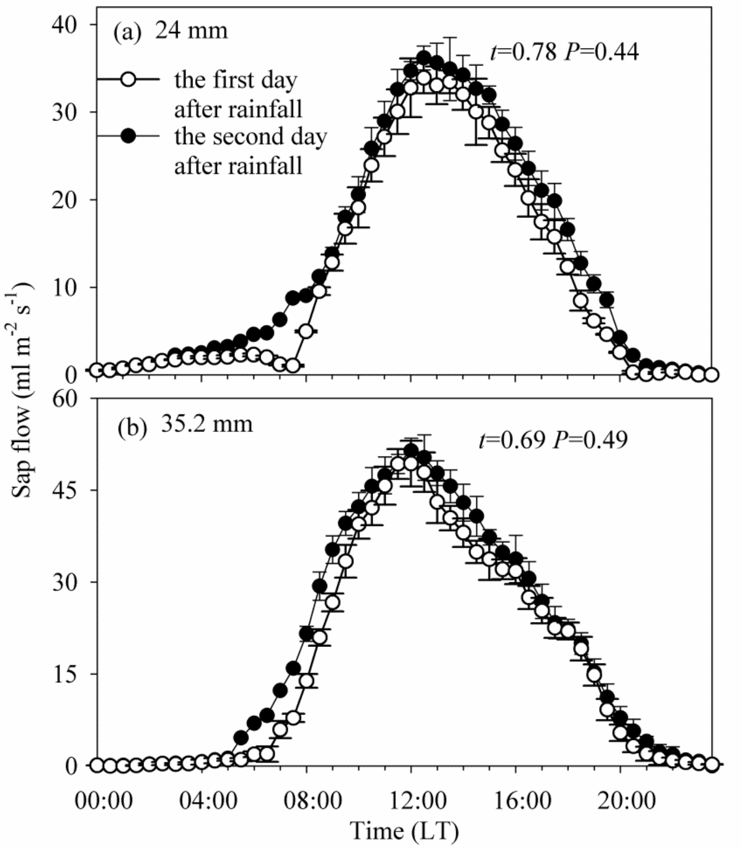

(a) 24 mm
t=0.78 P=0.44
the first day after rainfall
the second day after rainfall
(b) 35.2 mm
t=0.69 P=0.49
Sap flow (ml m-2 s-1)
Time (LT)
00:00
04:00
08:00
12:00
16:00
20:00
0
10
20
30
40
0
15
30
45
60

Figure S3.

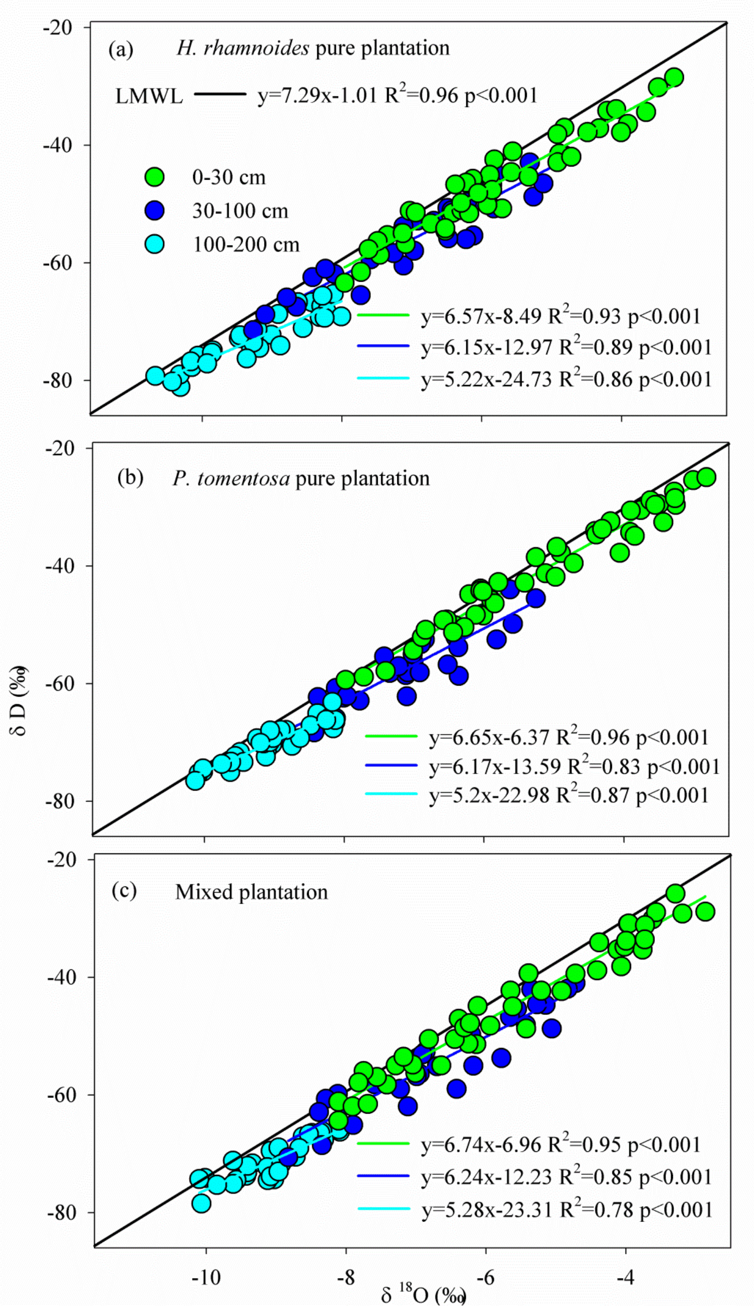
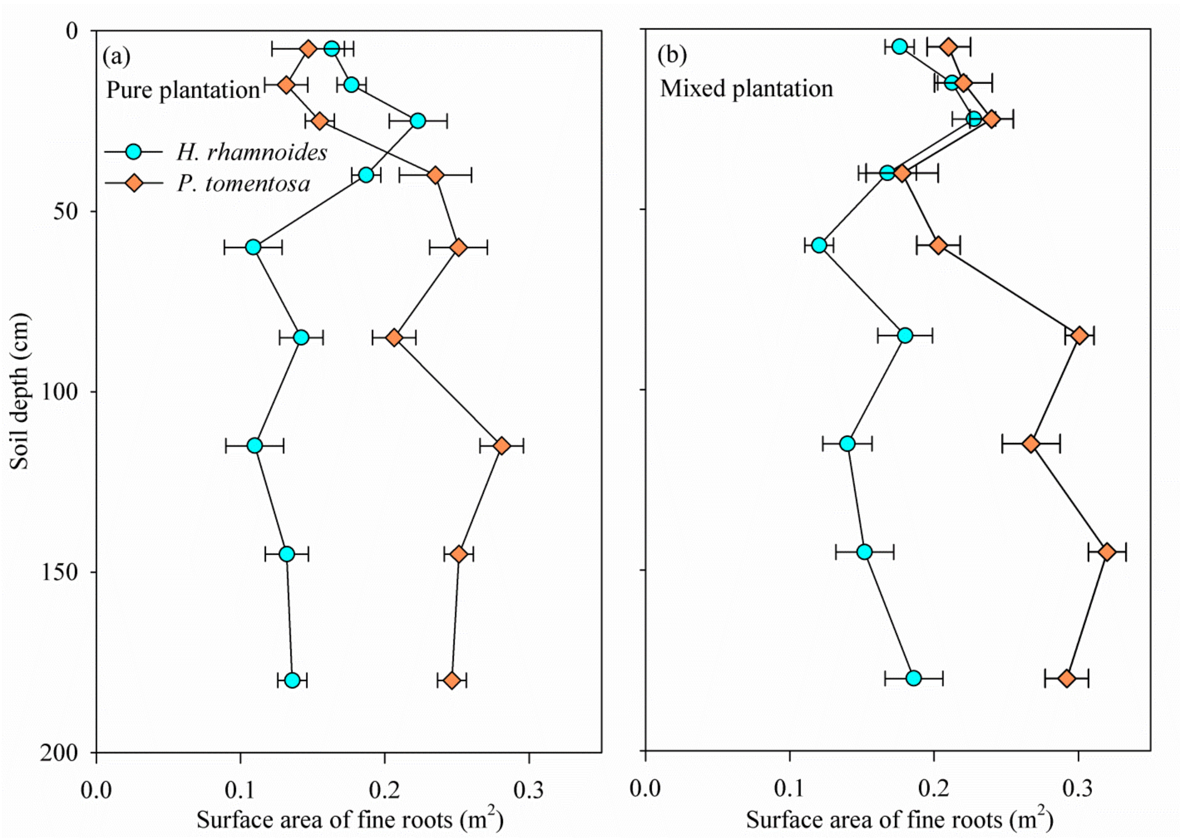

(a) H. rhamnoides pure plantation
LMWL y=7.29x-1.01 R2=0.96 p<0.001
0-30 cm
30-100 cm
100-200 cm
y=6.57x-8.49 R2=0.93 p<0.001
y=6.15x-12.97 R2=0.89 p<0.001
y=5.22x-24.73 R2=0.86 p<0.001
(b) P. tomentosa pure plantation
y=6.65x-6.37 R2=0.96 p<0.001
y=6.17x-13.59 R2=0.83 p<0.001
y=5.2x-22.98 R2=0.87 p<0.001
(c) Mixed plantation
y=6.74x-6.96 R2=0.95 p<0.001
y=6.24x-12.23 R2=0.85 p<0.001
y=5.28x-23.31 R2=0.78 p<0.001
δ D (‰)
δ 18O (‰)
-20
-40
-60
-80
-10
-8
-6
-4

Figure S4.



(a)
Pure plantation
H. rhamnoides
P. tomentosa
(b)
Mixed plantation
Soil depth (cm)
0
50
100
150
200
0.0
0.1
0.2
0.3
Surface area of fine roots (m2)
0.0
0.1
0.2
0.3
Surface area of fine roots (m2)

Figure S5.

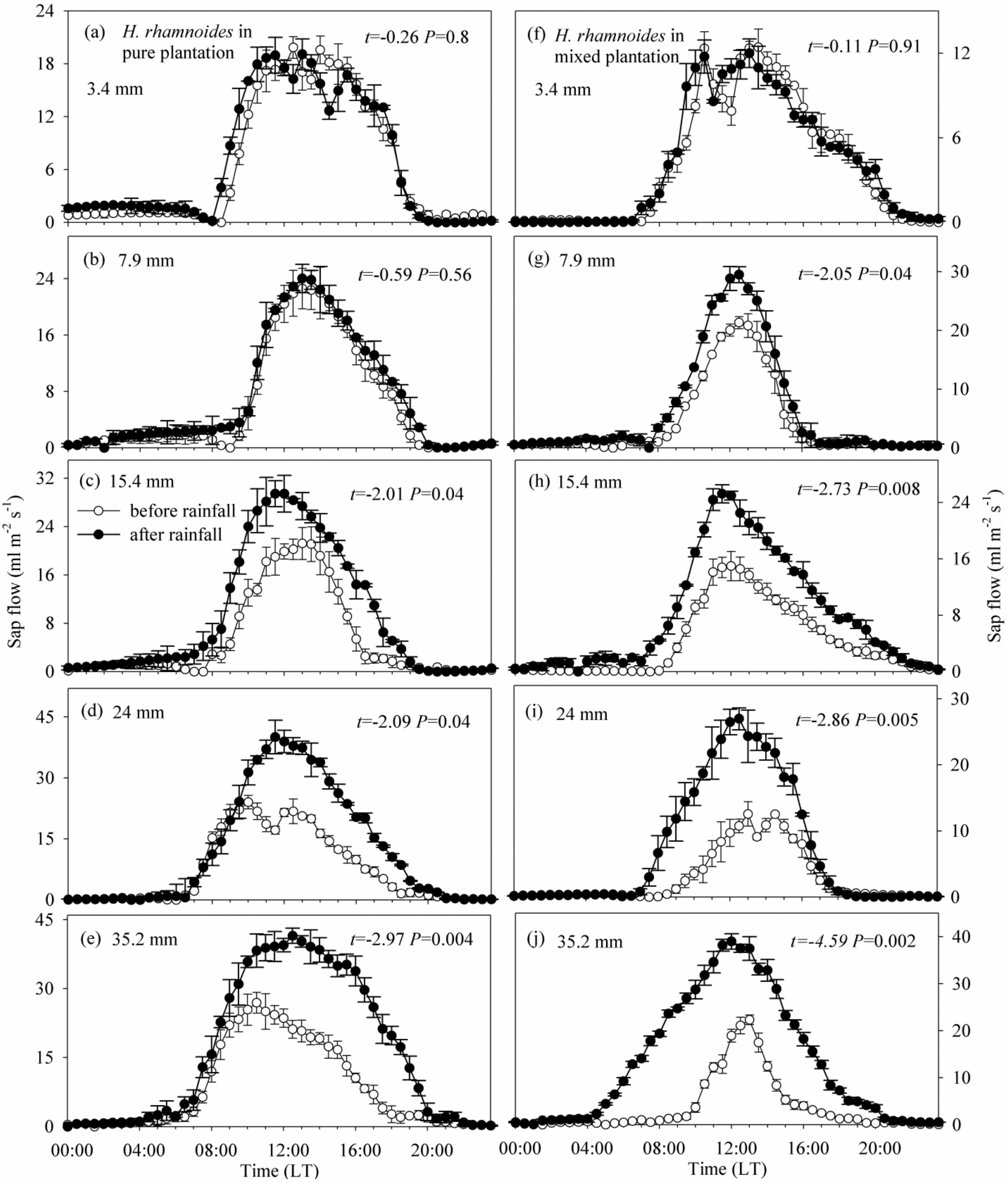
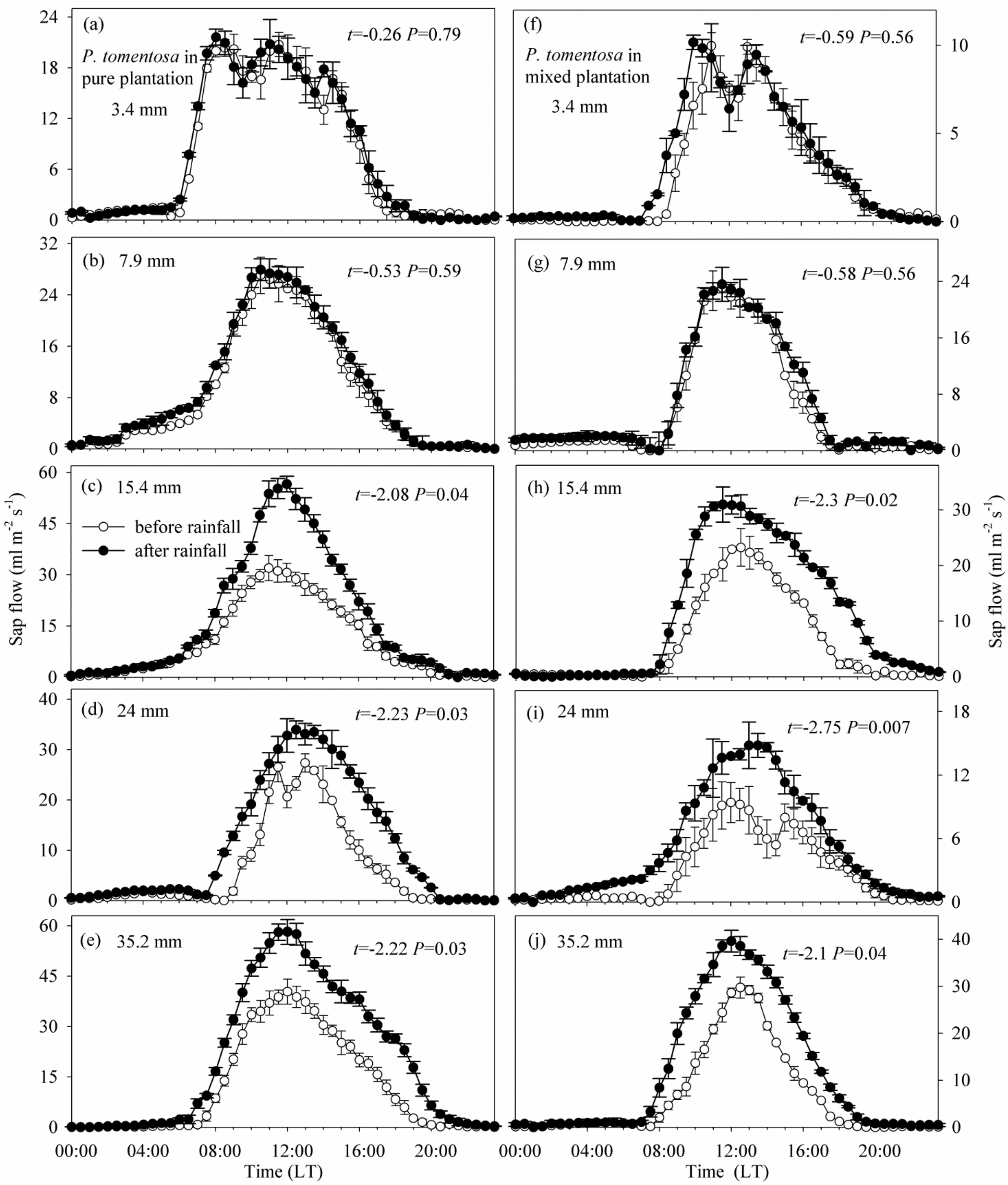

(a) H. rhamnoides in pure plantation
3.4 mm
t=-0.26 P=0.8
(f) H. rhamnoides in mixed plantation
3.4 mm
t=-0.11 P=0.91
(b) 7.9 mm
t=-0.59 P=0.56
(g) 7.9 mm
t=-2.05 P=0.04
(c) 15.4 mm
before rainfall
after rainfall
t=-2.01 P=0.04
(h) 15.4 mm
t=-2.73 P=0.008
(d) 24 mm
t=-2.09 P=0.04
(i) 24 mm
t=-2.86 P=0.005
(e) 35.2 mm
t=-2.97 P=0.004
(j) 35.2 mm
t=-4.59 P=0.002
Sap flow (ml m-2 s-1)
Time (LT)
00:00
04:00
08:00
12:00
16:00
20:00

Figure S6.



(a)
P. tomentosa in pure plantation
3.4 mm
t=-0.26 P=0.79
(b) 7.9 mm
t=-0.53 P=0.59
(c) 15.4 mm
t=-2.08 P=0.04
before rainfall
after rainfall
(d) 24 mm
t=-2.23 P=0.03
(e) 35.2 mm
t=-2.22 P=0.03
(f)
P. tomentosa in mixed plantation
3.4 mm
t=-0.59 P=0.56
(g) 7.9 mm
t=-0.58 P=0.56
(h) 15.4 mm
t=-2.3 P=0.02
(i) 24 mm
t=-2.75 P=0.007
(j) 35.2 mm
t=-2.1 P=0.04
Sap flow (ml m-2 s-1)
Time (LT)
00:00
04:00
08:00
12:00
16:00
20:00

Figure S7.

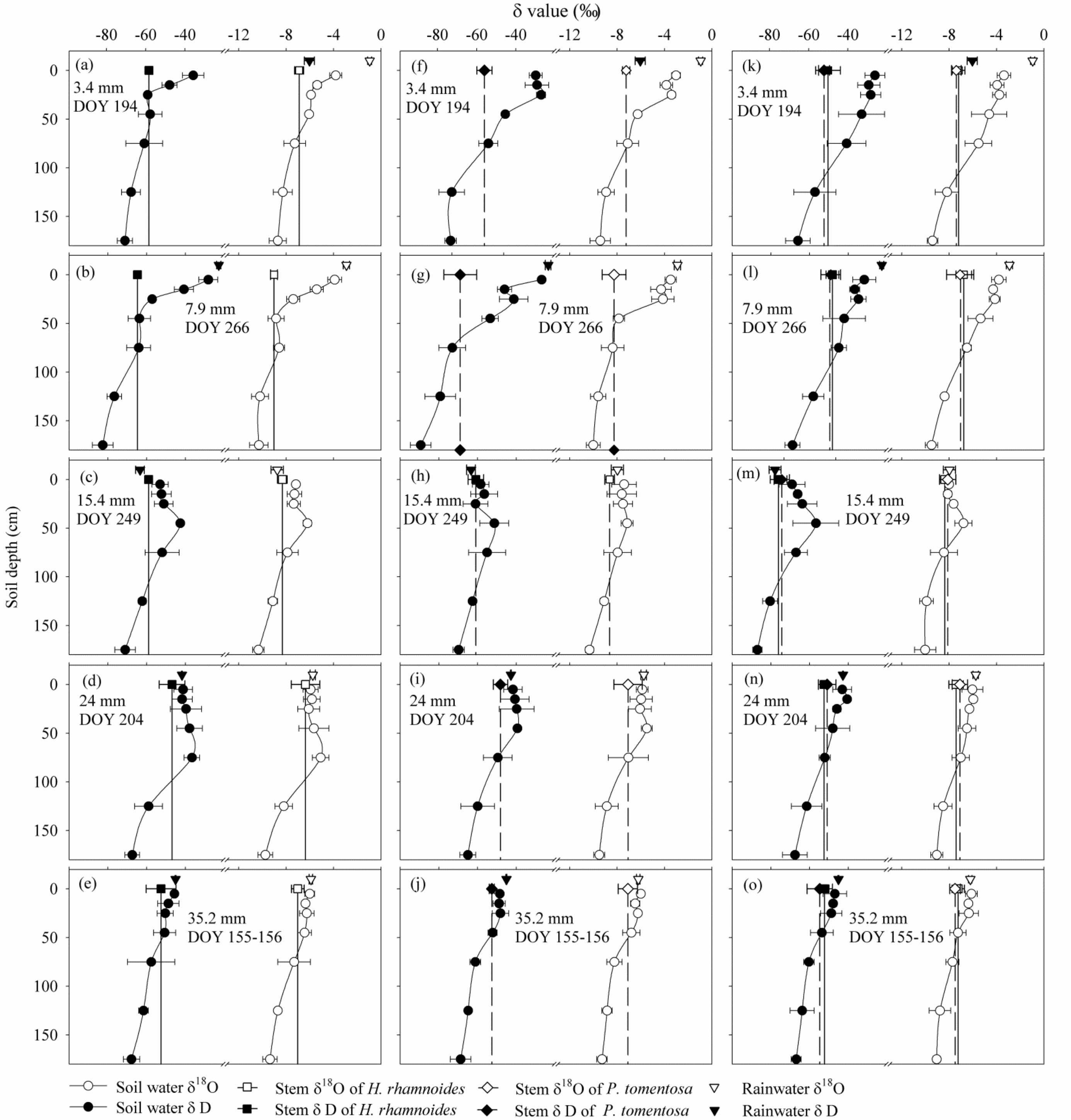
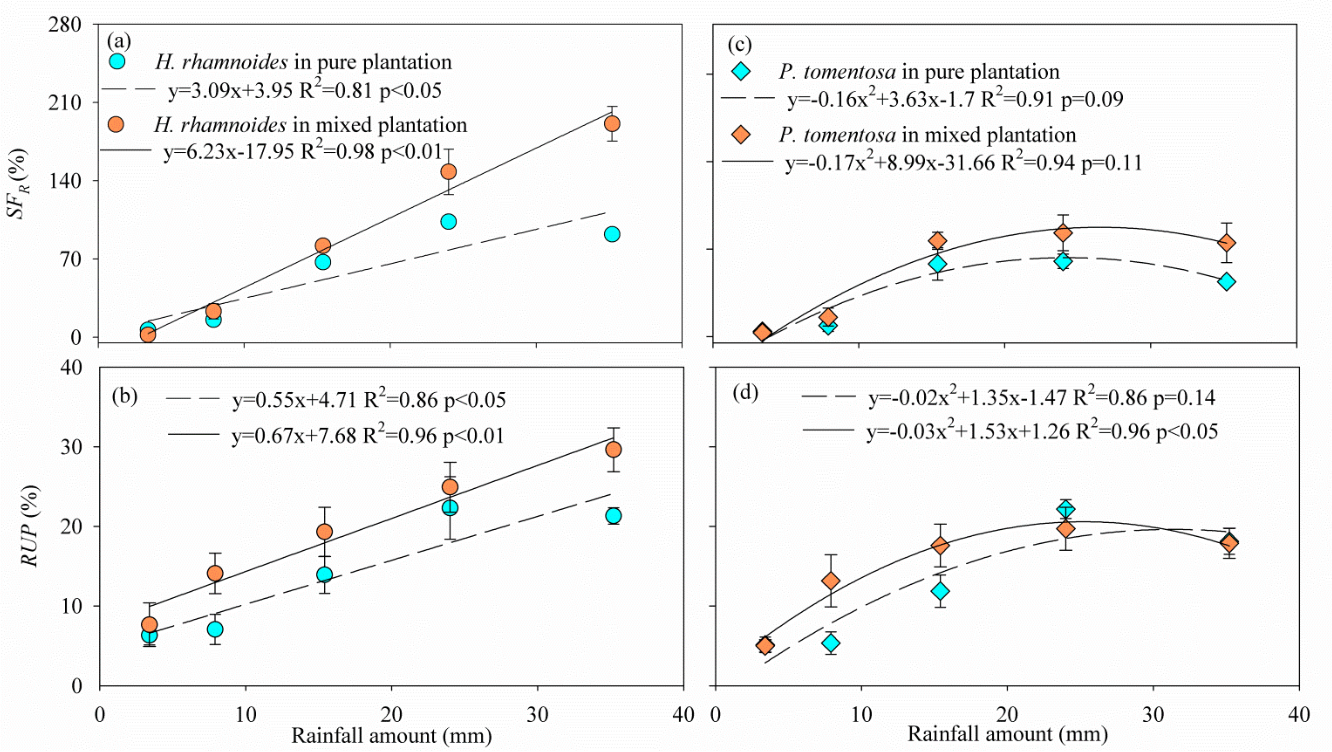

δ value (‰)
-80
-60
-40
-12
-8
-4
0
Soil depth (cm)
0
50
100
150
(a)
3.4 mm
DOY 194
(b)
7.9 mm
DOY 266
(c)
15.4 mm
DOY 249
(d)
24 mm
DOY 204
(e)
35.2 mm
DOY 155-156
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
(o)
Soil water δ18O
Soil water δ D
Stem δ18O of H. rhamnoides
Stem δ D of H. rhamnoides
Stem δ18O of P. tomentosa
Stem δ D of P. tomentosa
Rainwater δ18O
Rainwater δ D

Figure S8.



(a)
H. rhamnoides in pure plantation
y=3.09x+3.95 R2=0.81 p<0.05
H. rhamnoides in mixed plantation
y=6.23x-17.95 R2=0.98 p<0.01
(c)
P. tomentosa in pure plantation
y=-0.16x2+3.63x-1.7 R2=0.91 p=0.09
P. tomentosa in mixed plantation
y=-0.17x2+8.99x-31.66 R2=0.94 p=0.11
(b)
y=0.55x+4.71 R2=0.86 p<0.05
y=0.67x+7.68 R2=0.96 p<0.01
(d)
y=-0.02x2+1.35x-1.47 R2=0.86 p=0.14
y=-0.03x2+1.53x+1.26 R2=0.96 p<0.05
SFR (%)
RUP (%)
Rainfall amount (mm)
Rainfall amount (mm)