Age-related water use characteristics of *Robinia pseudoacacia* on the Loess Plateau

Jian Wang[a, b], Bojie Fu[b, c*], Lei Jiao[d], Nan Lu[b], Jianye Li[e], Weiliang Chen[b, c], Lixin Wang[f]

[a] *College of Resources and Environment, Huazhong Agricultural University, Wuhan*

430070, China

[b] *State Key Laboratory of Urban and Regional Ecology, Research Center for*

Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

[c] *College of Resources and Environment, University of Chinese Academy of Sciences,*

Beijing, China

[d] *School of Geography and Tourism, Shaanxi Normal University, Xi'an 710119, China*

[e] *Key laboratory of Mollisols Agroecology, Northeast Institute of Geography and*

Agroecology, Chinese Academy of Sciences, Harbin 150081, China

[f] *Department of Earth Sciences, Indiana University Purdue University Indianapolis*

(IUPUI), 723 W. Michigan Street, SL 118M, Indianapolis, IN 46202, USA

* Corresponding author: Bojie Fu

State Key Laboratory of Urban and Regional Ecology, Research Center for

Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

E-mail: bfu@rcees.ac.cn

Abstract

Understanding water use characteristics of revegetation species is crucial for evaluating plant adaptability and guiding the sustainability of vegetation restoration in semiarid regions. Ecological restoration projects have been implemented for decades in degraded ecosystems, achieving significant changes in vegetation cover. However, water use characteristics of the main tree species at different ages remain poorly understood in such systems. We investigated water use characteristics of *Robinia pseudoacacia* in plantations of different stand-age (18 and 30 years). The species is the most widely planted tree in revegetation efforts on the Loess Plateau. The δ^2H and $\delta^{18}O$ of xylem and soil water within 500 cm of the soil surface and the $\delta^{13}C$ values of plant leaves were measured during two consecutive hydrological years. The results showed that that water uptake proportions from across the soil columns changed in 18-yr *R. pseudoacacia* between a drier (2016) and wetter year (2017). In contrast, shallow soil water was largely comparable in a stand of 30-yr *R. pseudoacacia* in 2016 and 2017, and similarly the pattern of water uptake by roots from the middle and deep soil column was comparable. However, leaf-level water use efficiency (WUE_i) of trees in the older plantation was higher during the wetter year, thereby partly alleviating a low infiltration to precipitation ratio. These findings suggest that different stand-age plantation trees have distinct water use characteristics and display different responses to variations in precipitation. Older plantation trees respond to increased water availability by increasing WUE_i instead of switching water sources. This means that stand-age is an essential factor to be considered in ecological

45 restoration management, which can enhance the effectiveness of vegetation

46 restoration strategies. The study indicates useful input from research to management

47 throughout the continuity of restoration effort.

48

51

1. Introduction

53   Drylands are subjected to different forms of land degradation and future climate

54 change will accelerate the expansion of drylands (Huang et al., 2017). Land

55 degradation leads to the loss of biological or economic productivity and directly

56 affected the development of 250 million people. Ecological restoration represents the

57 main strategy for intervention to recover ecosystem services in degraded drylands

58 (Atkinson and Bonser, 2020). Healthy ecosystems are critical to promoting food and

59 water security, biodiversity conservation, poverty eradication, and achieving the

60 sustainable development goals (Blicharska et al., 2019). Water is the most important

61 limiting factor that affects plant survival, growth, and the sustainability of

62 revegetation in semiarid ecosystems (Austin et al., 2004; Wang et al., 2012).

63 Moreover, both climate models and long-term observations show the increasing air

64 temperatures and decreasing precipitation in most arid and semiarid regions (Huang et

65 al., 2017; IPCC, 2019). As current climate change is likely increasing the frequency of

66 severe soil droughts, detailed scrutiny of the water use characteristics of plants

67 becomes especially important regarding the species selected for revegetation

68 programs (Harrison et al., 2020; Grossiord et al., 2017).

69   Numerous physiological and physical characteristics influence water use

70 characteristics of plants in different ecosystems (Volkmann et al., 2016), such as soil

71 water availability (Gow et al., 2020), the distribution and functioning of fine roots

72 (Wang et al., 2017b), and water demands of trees (Song et al., 2018). Specifically,

73 plants adjust water sources depending on soil water availability (Lanning et al., 2020).

74 Some plants shift to derive water sources from deep soil layers or groundwater when

75 shallow soil water is unavailable in the dry season (Wang et al., 2019a). The

76 distribution of fine roots affects the ability of plants to obtain water resources.

77 Deep-rooted species can obtain more steady water sources (e.g., deep soil water,

78 groundwater) than shallow-rooted species (McCole and Stern, 2007). Trees may

79 survive prolonged droughts by shift water uptake among existing roots rather than

80 growing new roots (Mackay et al., 2020). Fine roots are the first to be sacrificed under

81 extreme soil drought, thus reducing specific root length (Brunner et al. 2015). In

82 addition, plants at different growth stages have various water use characteristics due

83 to different water demands (Huo et al., 2018; Liu et al., 2015), which are associated

84 with factors such as biomass, leaf area index, and transpiration. One strategy is to

85 switch water sources depending on different life stages. For example, mature plants

86 may have deep roots and derive water from deeper sources than young plants, thereby

87 avoiding or minimizing the effects of drought during the dry season (Huo et al., 2018;

88 Kerhoulas et al., 2013). Another strategy is to avoid the effect of drought by leaf

89   shedding and remaining dormant during the dry season (Ellsworth and Sternberg,

90   2015). Therefore, understanding plant water use characteristics is critical to improve

91   the knowledge of ecological adaptability and soil-water-plant interactions in arid and

92   semiarid ecosystems.

93   Plant water use patterns and water use efficiency (WUE_i) are the two crucial

94   issues that reflect plant water use characteristics. Stable hydrogen and oxygen isotope

95   technique is a powerful and effective approach for identifying the water uptake

96   patterns of plants in semiarid ecosystems (Ding et al., 2020; Wang et al., 2020a). Plant

97   leaf $\delta^{13}C$ is widely used to indicate leaf-level WUE_i (Farquhar et al., 1989; Saugier et

98   al., 2012). Previous studies investigated water use characteristics of plants at different

99   stand-age in various semiarid ecosystems using the stable isotope technique (Zhou et

100 al., 2017; Song et al., 2018). For example, Zhou et al. (2017) found that young shrubs

101 (*Haloxylon ammodendron*) obtained water sources mainly from shallow soil, and

102 older shrubs obtained water mainly from permanent groundwater in a desert-oasis

103 ecotone. Song et al. (2018) explored seasonal variations in water sources used by

104 Mongolian pine trees of different ages, and found that different-aged trees obtained

105 soil water from the same depth. However, most of these studies focused on plant

106 water use patterns, and insufficient attention had been paid to WUE_i. There is limited

107 understanding of water use patterns and how WUE_i varies synergistically with

108 stand-age. In addition, little is known about the response of plant water use

109 characteristics to the variation of precipitation considering the future climate change

110 in semiarid regions.

111   The Loess Plateau is the largest and deepest loess deposit in the world with an

112 area of 640,000 km^2. The widespread ecosystem degradation and desertification

113 occurred due to the Millenia of land use and more recent population pressure. Massive

114 eco-restoration efforts were undertaken to decelerate the ecosystem degradation (Fu et

115 al., 2017). Large vegetation changes have occurred on the Loess Plateau in recent

116 decades since the 'Grain for Green Project' was implemented in 1999 (Fu et al., 2017).

117 Soil water resources are the only water source for plants, and water availability affects

118 the sustainability of revegetation on the semiarid Loess Plateau (Wang et al., 2017a;

119 Yu et al., 2020). The SWC of deep soil layers gradually decreased due to the depletion

120 by the trees with an increase in stand-ages. Soil desiccation formed in the deep layers

121 due to the utilization by revegetation species (Wang et al., 2011). Long-term soil

122 water deficit by revegetation species and soil desiccation led to the decline in the rate

123 of plant growth and forest degradation, causing dieback or mortality of the planted

124 trees. *Robinia pseudoacacia*, a main non-native planted tree species, is the most

125 widely planted for revegetation on the Loess Plateau (Zhang et al., 2015). Previous

126 studies explored seasonal variation in transpiration (Jiao et al., 2019) and the response

127 of soil water to rainfall events in *R. pseudoacacia* plantations (Chen et al., 2020).

128 However, these studies were limited to a specific stand age. Only few studies explored

129 the water uptake patterns of *R. pseudoacacia* (Zhao et al., 2020; Wang et al., 2020a),

130 and water use characteristics of *R. pseudoacacia* at different stand ages remain poorly

131 understood.

132   To fill the above knowledge gaps, this study investigated water use

133   characteristics of *R. pseudoacacia* at different stand ages using stable isotope

134   techniques (δ^2H, δ^{18}O and δ^{13}C) with monthly sampling during two consecutive

135   growing seasons on the semiarid Loess Plateau. The specific objectives of this study

136   were to (i) investigate water use characteristics of *R. pseudoacacia* at different

137   stand-ages and (ii) identify the sensitivity to the variation of precipitation in water use

138   characteristics of *R. pseudoacacia* at different stand ages. The two hypotheses were

139   that trees of young and mature plantations differed in (1) their water use

140   characteristics, and (2) their sensitivities to changes in precipitation.

141

2. Materials and methods

2.1 Study area and experimental sites

144   The Yangjuangou catchment is located in the central region of the Chinese Loss

145   Plateau (36°42'45″ N, 109°31'45″ E). This catchment is a typical loess hilly gully

146   region with an area of 2.02 km^2. The soil is primary loessial soil derived from loess.

147   The soil depth is 50–200 m depending on topography. The bulk density of the surface

148   soil was 1.04–1.30 g cm^{-3}. This area has a semiarid continental climate, with a mean

149   air temperature of 10 °C and a mean precipitation of 539 mm (1960 –2017). Rainfall

150   has large interannual variability, and most of the precipitation is concentrated from

151   May to September. The original natural vegetation in the catchment was destroyed

152   due to the long-term disturbance caused by human activities. The current vegetation

153   of the catchment derives of near-to nature restoration including trees and shrubs, and

154   natural recovery of grass growth.

155   The forest species in this catchment is dominated by *R. pseudoacacia*, which was

156   planted in the later 1980s and 1999. *R. pseudoacacia* is a deciduous broad-leaved,

157   nitrogen-fixing tree species, and widely planted in the semi-arid Loess Plateau. Three

158   sample plots (10 m × 10 m) dominated by *R. pseudoacacia* were selected in each of

159   two plantations of different stand age (18- and 30-yr). These plantations had a

160   southeast aspect, middle-slope position, and similar slope gradients (~22°). The

161   different stand-age plantation had similar plantation densities (~1300 tree ha^{-1}). The

162   average heights of the 18- and 30-yr *R. pseudoacacia* plantations were 8.94 m and

163   9.28 m, respectively. The mean diameter at breast height (DBH) of 18- and 30-yr *R.*

164   *pseudoacacia* plantations was 11.43 cm and 12.36 cm, respectively. The understory

165   vegetation was mainly composed of *Artemisia sacrorum* and *Periploca sepium.*

166   *2.2 Sample collection and isotope analysis*

167   Samples of soil and plants were collected monthly from May to September

168   during two consecutive growing seasons in 2016 and 2017. Three individual plants

169   were randomly selected for sampling in the different stand-age *R. pseudoacacia*

170   plantations on each sampling date. Three leaf and plant xylem samples from every

171   selected plant were collected in each stand-age tree per month. The fully sun-exposed,

172   mature and healthy leaves in the upper canopy from each selected plant were

173   collected in different directions on each sampling date. The leaves were mixed and

174   packed into craft paper bags and brought them back to the laboratory for measuring

175   the plant leaves δ^{13}C.   Plant xylem samples were obtained by cutting suberized twigs

176   from different canopy directions at the same height. Then, the outer bark and phloem

177 tissue were removed from these twigs, and immediately placed into glass vials, sealed

178 with parafilm, and kept frozen (–20 °C). We collected a total of 60 xylem samples and

179 60 plant leaf samples during the study period.

180 In each stand-age plantation, three soil cores to a 500 cm depth were sampled

181 using a power auger at the same time as plant sampling for each stand-age plantation.

182 Soil samples from these cores were collected at 15 different depths: 0–10, 10–20, 20–

183 40, 40–60, 60–80, 80–100, 100–120, 120–150, 150–200, 200–250, 250–300, 300–350,

184 350–400, 400–450 and 450–500 cm. We collected a total of 900 soil samples during

185 the study period. The gravimetric soil water content (SWC, %) was determined by

186 drying soil samples for 24 h at 105 °C. Moreover, we collected 85 rainwater samples

187 with a polyethylene bottle and funnel in 2016 and 2017. The soil and rainwater

188 samples were stored frozen (–20 °C) before isotopic analysis.

189 The xylem water and soil water were extracted by a cryogenic vacuum

190 distillation method described by Wang et al. (2019a). The δ^2H and $\delta^{18}O$ in soil water

191 and rainwater were measured using isotopic ratio infrared spectroscopy (IRIS)

192 (DLT-100, Los Gatos Research, Mountain View, USA) with an analytical accuracy of

193 ± 1.2‰ for δ^2H and ± 0.3‰ for $\delta^{18}O$. No contamination of organic matter was found

194 in soil water after quantifying applying the spectral contamination identifier

195 post-processing software. The δ^2H and $\delta^{18}O$ in xylem water and the $\delta^{13}C$ in the plant

196 leaves were analysed using an isotope ratio mass spectrometer (IRMS) (MAT253,

197 Thermo Fisher Scientific, Bremen, Germany). The $^{18}O/^{16}O$ ratios in the xylem water

198 samples were measured using an automated equilibration unit (Gasbench II; Thermo

199 Fisher Scientific, Bremen, Germany) coupled to a MAT-253 mass spectrometer

200 (Thermo Fisher Scientific, Bremen, Germany). The xylem water samples were

201 reduced to H_2 gas using a fully automated chromium reduction system at 800 °C

202 (H/Device, Thermo Fisher Scientific) and the $^2H/H$ ratios of this gas were then

203 measured with a MAT-253 mass spectrometer (Thermo Fisher Scientific, Bremen,

204 Germany). The isotopic analyses of carbon in the plant leaf were conducted with a

205 MAT-253 mass spectrometer (Thermo Fisher Scientific, Bremen, Germany) coupled

206 to an automatic, online elemental analyzer (Flash EA1112, Thermo Electron, Milan,

207 Italy). The precision of the xylem water isotope using IRMS was $\pm 1‰$ for δ^2H and $\pm$

208 $0.2‰$ for $\delta^{18}O$, and $\pm 0.15‰$ for $\delta^{13}C$. The isotopic ratios in the water samples were

209 calculated as:

210 $$\delta X = R_{sample} / R_{standard} - 1 \qquad (1)$$

211 where X represents ^2H, ^{18}O, or ^{13}C. R_{sample} and $R_{standard}$ are the $^2H/^1H$, $^{18}O/^{16}O$ or

212 $^{13}C/^{12}C$ ratios in the sample and standard, respectively. The standard material for ^2H

213 and ^{18}O is Vienna Standard Mean Ocean Water. Vienna Pee Dee Belemnite is the

214 standard material for ^{13}C.

215 *2.3 Data analysis*

216 Soil water from different layers is considered to be the main water source for

217 plant species on the Chinese Loess Plateau because the plants have difficulty reaching

218 the groundwater (deeper than 60 m), and there was no irrigation during the study

219 period (Wang et al., 2017b). The depth of water uptake by the plants was estimated

220 using the graphical inference method. The relative proportional contributions of

221   different soil water sources to the xylem water were determined by the Bayesian

222   isotope mixing model MixSIAR (version 3.1.7) (Stock and Semmens, 2013). The

223   model used the raw isotopic values of xylem water of each plant as the 'mixture data'.

224   The means and standard deviations of the isotopic values of different soil layers were

225   used as the 'source data'. The potential fractionation was set to 0. More details about

226   the model settings can be found in a previous study (Wang et al., 2017b). For

227   subsequent analysis and comparison, the potential plant water sources were identified

228   as soil water from shallow (0–80 cm), middle (80–200 cm) and deep (200–500 cm)

229   soil depths according to the variability in SWC and the isotopic values of the soil

230   water.

231   We used mixed linear, random intercept models to test the differences in the

232   isotopic values of xylem water, soil water, and plant leaf, SWC between different

233   stand ages and sampling times. Soil depth and sampling times were set as fixed

234   effects and plot was a random effect. Differences in the $\delta^{13}C$ values of the plant leaves

235   and water source partitioning between different stand ages were analysed using

236   analysis of variance (ANOVA). Post hoc comparisons were based on Tukey's HSD.

237   The critical value of $p < 0.05$ was applied to determine statistical significance. All

238   statistical analyses were performed in R software (v.3.4.4, R Core Team, 2018).

239

240   ## 3. Results

241   ### 3.1 Meteorological factors and isotopic composition of precipitation

242   The total precipitation in 2016 and 2017 was 473.6 and 689.7 mm, respectively.

243   Most of the precipitation was concentrated in the growing season (Fig. 1). The total

244   precipitation in 2016 was 12.14% lower than the multiyear mean (1961−2017)

245   precipitation (539.9 mm) and the growing season precipitation amount was 432.6 mm.

246   However, the total precipitation in 2017 was 27.83% higher than the average annual

247   precipitation and 69.71% of the precipitation (480.8 mm) occurred during the growing

248   season. The growing season precipitation in 2017 was 11.14% higher than that in

249   2016. The ratio of precipitation to potential evapotranspiration in the growing season

250   was 0.46 in 2016 and 0.77 in 2017. The mean temperature in 2016 and 2017 was 10.7

251   and 10.1 °C, respectively. These values are higher than that of average annual

252   temperature (10 °C). The monthly mean temperature during the growing season was

253   19.6 °C in 2016 and 19.2 °C in 2017.

254   The isotopic compositions of the precipitation showed a large fluctuation during

255   the study period (Fig. 1). The mean $\delta^{18}O$ of the precipitation in 2016 was −5.40‰,

256   ranging from −1.37 to −12.03‰, and the mean δ^2H of the precipitation in 2016 was

257   −36.92‰, ranging from −13.06 to −90.25‰. The $\delta^{18}O$ value of the precipitation in

258   2017 ranged from −13.36 to 0.44 ‰ with an average of −7.31‰, and the average δ^2H

259   was −47.03‰, ranging from −98.19 to 5.51‰. The degree of isotopic variation in

260   precipitation was higher in 2016 than that in 2017. The average isotopic value of the

261   precipitation in 2017 was more depleted than that in 2016.
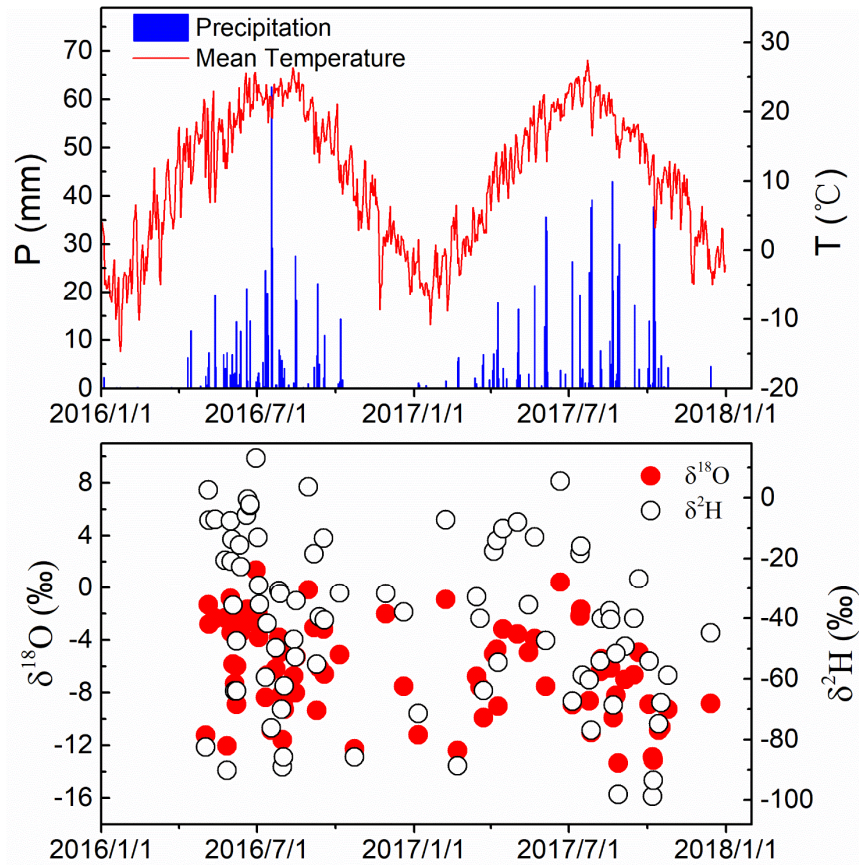
Fig. 1. Variations in precipitation, mean air temperature, and isotopic values (δ^2H, $\delta^{18}O$) in precipitation at a daily timescale from 2016 to 2017.

The local meteoric water line (LMWL) was fitted based on the isotopic values of the precipitation. The soil water evaporation line (SWL), which was fitted based on the isotopic values of the soil water, had a lower slope value than that of the LMWL during the study period (Fig. 2). All the SWLs during the study periods are plotted to the right of the LMWL. Moreover, the slope of the SWL in the studied *R. pseudoacacia* plantations had higher values in 2016 than that in 2017. The $\delta^{18}O$ and δ^2H values of 18- and 30-yr *R. pseudoacacia* were within the range of the soil water isotopic values (Fig. 2).
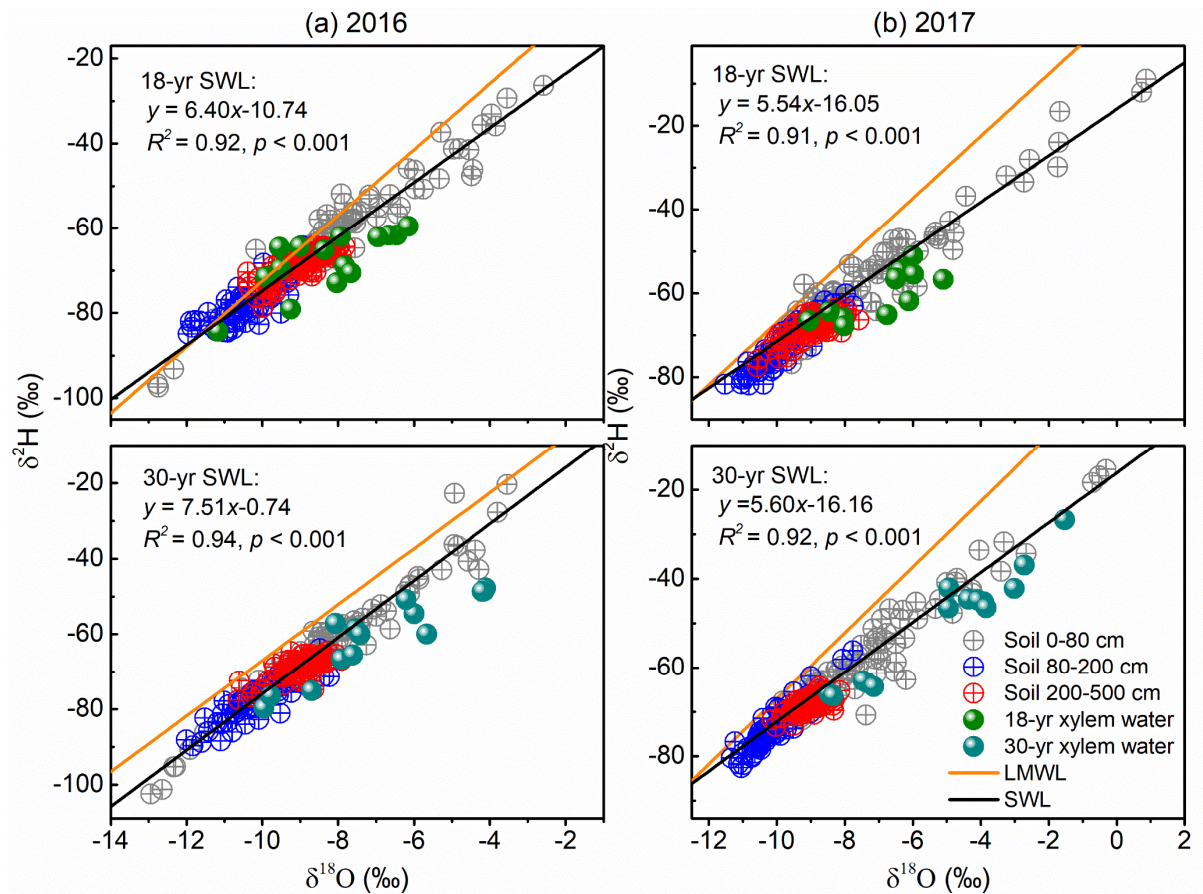
Fig. 2. The relationships of isotopic values of soil water and xylem water from 18- and 30-yr *R.*

pseudoacacia in 2016 and 2017. LMWL is the local meteoric water line (2016: $y = 7.76x + 5.14$,

$R^2 = 0.91$, $p < 0.01$; 2017: $y = 7.41x + 7.14$, $R^2 = 0.91$, $p < 0.01$). SWL is the soil water

evaporation line based on isotopic values of soil water.

3.2 Isotopic compositions of soil water and xylem water

In 2016, the mean δ^2H and $\delta^{18}O$ values of soil water in 18-yr *R. pseudoacacia*

plantations were −67.66‰ and −8.90‰, respectively, compared with corresponding

values of −68.27‰ and −8.92‰ in 30-yr *R. pseudoacacia* plantations. The mean

isotopic values of soil water in 18-yr (−8.48‰ for $\delta^{18}O$, −64.72‰ for δ^2H) and 30-yr

R. pseudoacacia plantations (−8.64‰ for $\delta^{18}O$, −65.42‰ for δ^2H) were higher in

2017 than that in 2016. The isotopic composition of water in the middle soil layers

286   was more negative than that in the shallow and deep soil layers during the study

287   period (Table 1). Soil water isotopes in different stand-age *R. pseudoacacia*

288   plantations showed significant differences ($p < 0.01$) with depth and season, but there

289   was no significant difference in the soil water isotopes between the two stand ages in

290   2016. In 2017, the soil water isotopes in 18-yr *R. pseudoacacia* plantations changed

291   significantly ($p < 0.05$) with depth and season. However, there was no significant

292   difference ($p = 0.30$ for δ^2H, $p = 0.26$ for $\delta^{18}O$) in soil water isotopes among different

293   seasons, and there was a statistically significant difference ($p < 0.001$) among

294   different depths in the 30-yr *R. pseudoacacia* plantations. Only the water isotopes in

295   the middle soil layers differed significantly ($p < 0.05$) between the different-aged *R.*

296   *pseudoacacia* plantations.

297   **Table 1** Variation characteristics of $\delta^{18}O$ and δ^2H in xylem and soil water during the study period.

298   Data are shown as the mean ± 1SD.

	2016		2017	
	18-yr	30-yr	18-yr	30-yr
Xylem water $\delta^{18}O$	−8.30 ± 1.43	−7.00 ± 1.89	−7.03 ± 1.15	−5.37 ± 2.30
0−80 cm soil water $\delta^{18}O$	−7.67 ± 1.11	−8.04 ± 1.23	−6.93 ± 1.22	−6.98 ± 0.93
80−200 cm soil water $\delta^{18}O$	−10.35 ± 0.26	−10.06 ± 0.74	−9.79 ± 0.45	−10.15 ± 0.32
200−500 cm soil water	−8.96 ± 0.29	−8.91 ± 0.36	−8.90 ± 0.26	−9.02 ± 0.13
Xylem water δ^2H	−67.84 ± 7.04	−61.02 ± 10.38	−60.65 ± 5.75	−50.96 ± 12.72
0−80 cm soil water δ^2H	−58.73 ± 8.16	−61.16 ± 9.81	−54.47 ± 7.76	−55.26 ± 5.25
80−200 cm soil water δ^2H	−77.48 ± 2.09	−76.99 ± 4.51	−72.73 ± 2.24	−73.93 ± 2.72
200−500 cm soil water δ^2H	−68.56 ± 1.67	−68.39 ± 2.51	−67.91 ± 1.02	−68.22 ± 0.78

299   The isotopic composition of xylem water changed with seasons and stand-ages.

300   The isotopic values of xylem water in 18-yr *R. pseudoacacia* were lower than those of

301   30-yr *R. pseudoacacia* during the study period (Fig. 3). The δ^2H of xylem water in

18-yr *R. pseudoacacia* ranged from −77.90 to −60.92‰ (mean ± 1SD, −67.84 ±

7.04 ‰), the $\delta^{18}O$ ranged from −9.97 to −6.42‰ with an average of −8.30‰, and the

mean isotopic values of xylem water in 30-yr *R. pseudoacacia* were −61.02‰ for δ^2H

and −7.00‰ for $\delta^{18}O$ during the growing season in 2016. The respective average

isotopic compositions of 18- and 30-yr trees were −60.65 and −50.96‰ for δ^2H, and

−7.03 and −5.37‰ for $\delta^{18}O$ during the growing season in 2017 (Table 1). There were

significant differences ($p < 0.05$) in the xylem water isotopes between 18- and 30-yr

R. pseudoacacia during the study period.
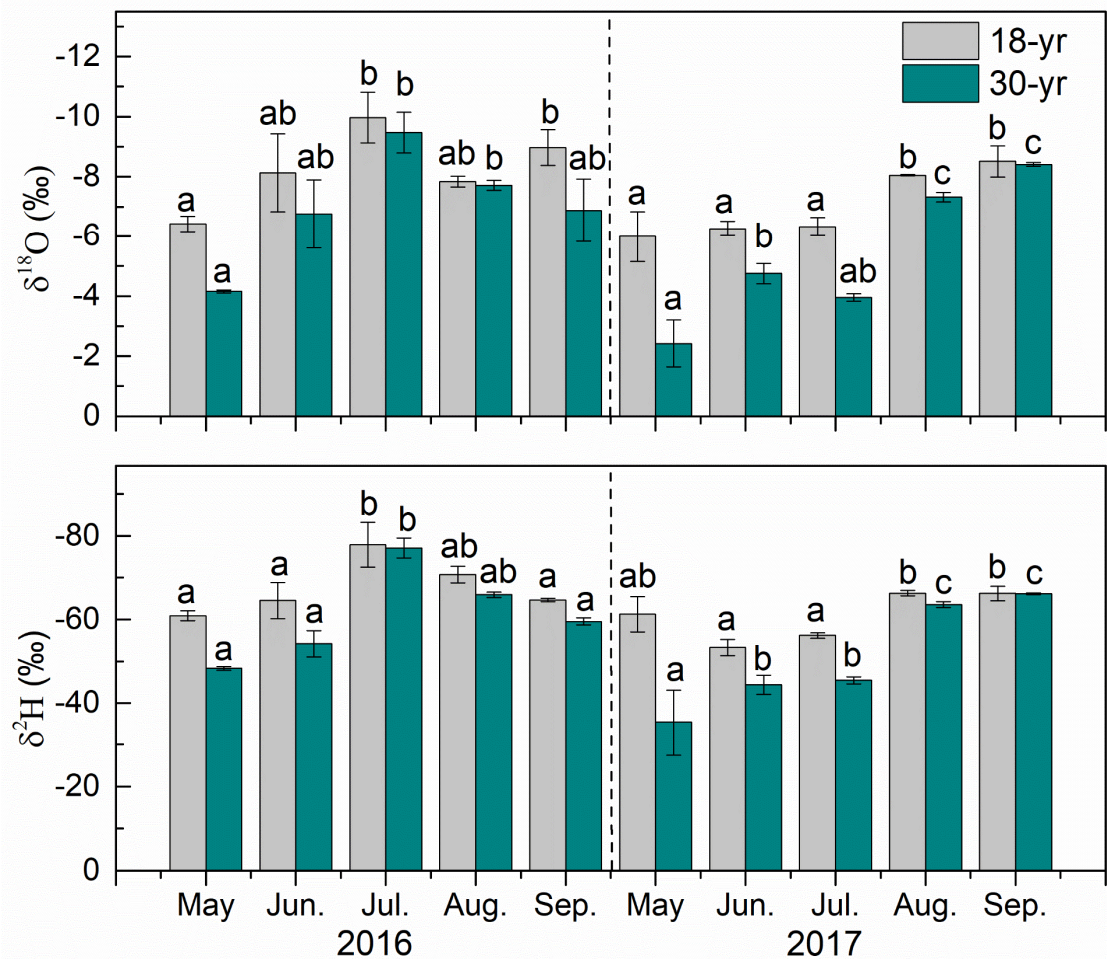
Fig. 3. Seasonal variation in isotopic compositions of xylem water in 18- and 30-yr *R.*

pseudoacacia in 2016 and 2017. Different lowercase letters represent significant differences

313   among sampling months at the $p < 0.05$ level. The error bar is the standard deviation.

3.3 Variations in SWC and water uptake patterns

315   The SWC in different stand-age *R. pseudoacacia* showed clear vertical

316   and seasonal variations during the study period (Fig. 4). The SWC in the shallow

317   soil layers (0–80 cm) had a higher degree of variation than the SWC in the 200–

318   500 cm soil layers. The SWC in the shallow soil layers showed higher variations with

319   season due to the influence of precipitation and evaporation. However, the SWC in

320   the 200–500 cm soil layer showed a lower degree of variation with sampling month

321   (Fig. 4). In the growing season of 2016, both the shallow and deep SWC differed

322   significantly ($p < 0.01$) between the 18- and 30-yr *R. pseudoacacia*

323   plantations. However, a significant difference was not observed for the SWC in

324   the middle soil layers. In the growing season of 2017, there were significant

325   differences in the shallow ($p < 0.01$), middle ($p < 0.01$) and deep SWC ($p < 0.01$)

326   between 18- and 30-yr *R. pseudoacacia* plantations. In addition, the shallow,

327   middle and deep SWC in the 30-yr *R. pseudoacacia* plantations displayed no

328   significant changes between 2016 and 2017. However, the deep SWC of 18-yr *R.*

329   *pseudoacacia* plantations in 2017 was significant lower ($p < 0.001$) than that in 2016,

330   and this difference was not found in the shallow and middle SWC. Moreover, the

331   shallow and deep SWC of the 30-yr *R. pseudoacacia* plantations did not change

332   significantly among seasons, while the SWC in the middle soil layers exhibited

333   significant differences ($p < 0.05$) among seasons. The shallow and deep SWC of

334   the 18-yr *R. pseudoacacia* plantations changed significantly ($p < 0.05$) among

   seasons, but not for middle SWC.

335
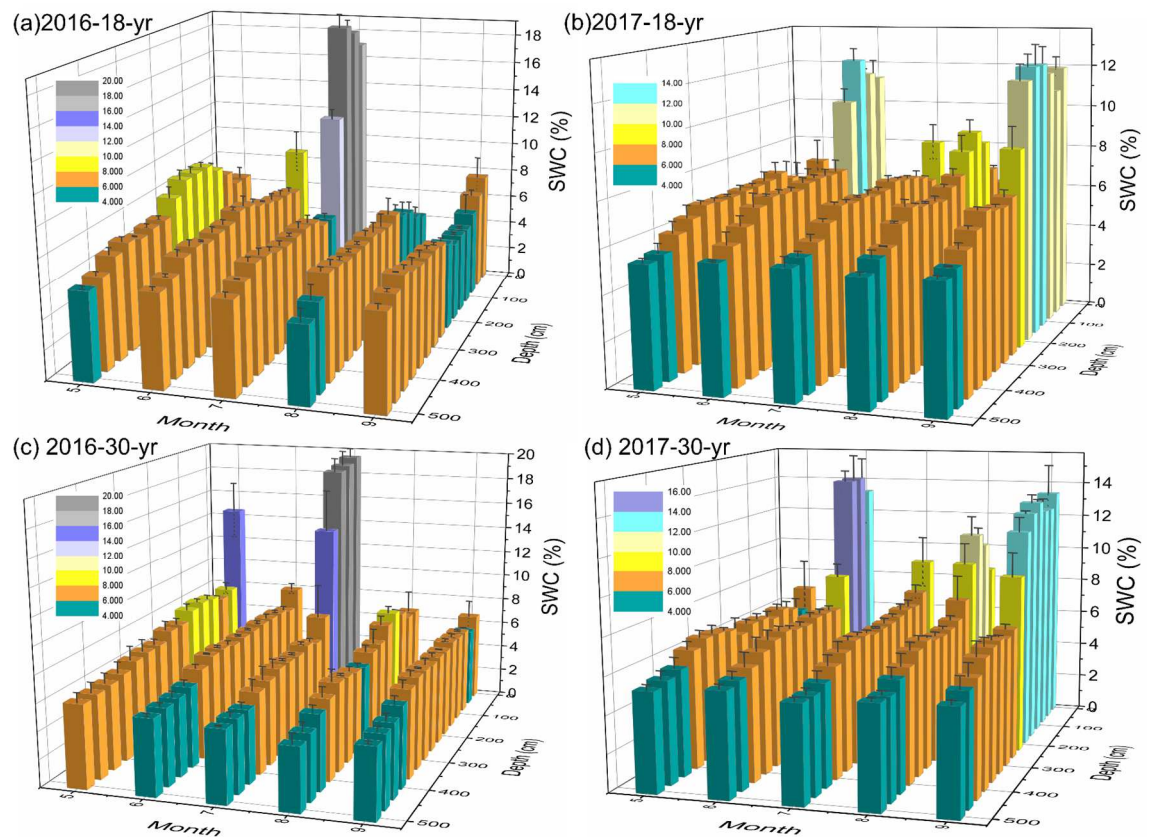
Fig. 4. Seasonal variation in the soil water content (SWC, %) from 18- and 30-yr *R. pseudoacacia* plantations in 2016 and 2017. The error bar represents the standard deviation.

In the growing seasons of 2016, the mean water uptake fractions of 18-yr *R. pseudoacacia* were 35.66% for shallow soil layers, 25.10% for middle soil layers, and 39.24% for deep soil layers. The average proportional contributions of soil water from shallow, middle, and deep layers water to xylem water of 30-yr *R. pseudoacacia* were 40.34%, 21.86%, and 37.80%, respectively. Similar patterns of plant water uptake were observed in 2017 (Fig. 5). The mean fraction of shallow soil water used by 18-yr *R. pseudoacacia* in 2017 was 17.2% higher than that in 2016. However, the water uptake fractions from shallow soil water for 30-yr *R. pseudoacacia* were relatively stable between the growing seasons of 2016 and 2017 (Fig. 5). The water uptake

348 fractions of both 18- and 30-yr *R. pseudoacacia* showed no significant differences

349 among sampling dates in 2016 and 2017. Moreover, for both 18- and 30-yr *R.*

350 *pseudoacacia*, the proportional contributions of soil water from shallow, middle, and

351 deep layers to xylem water exhibited no significant differences during the study

352 period.

353
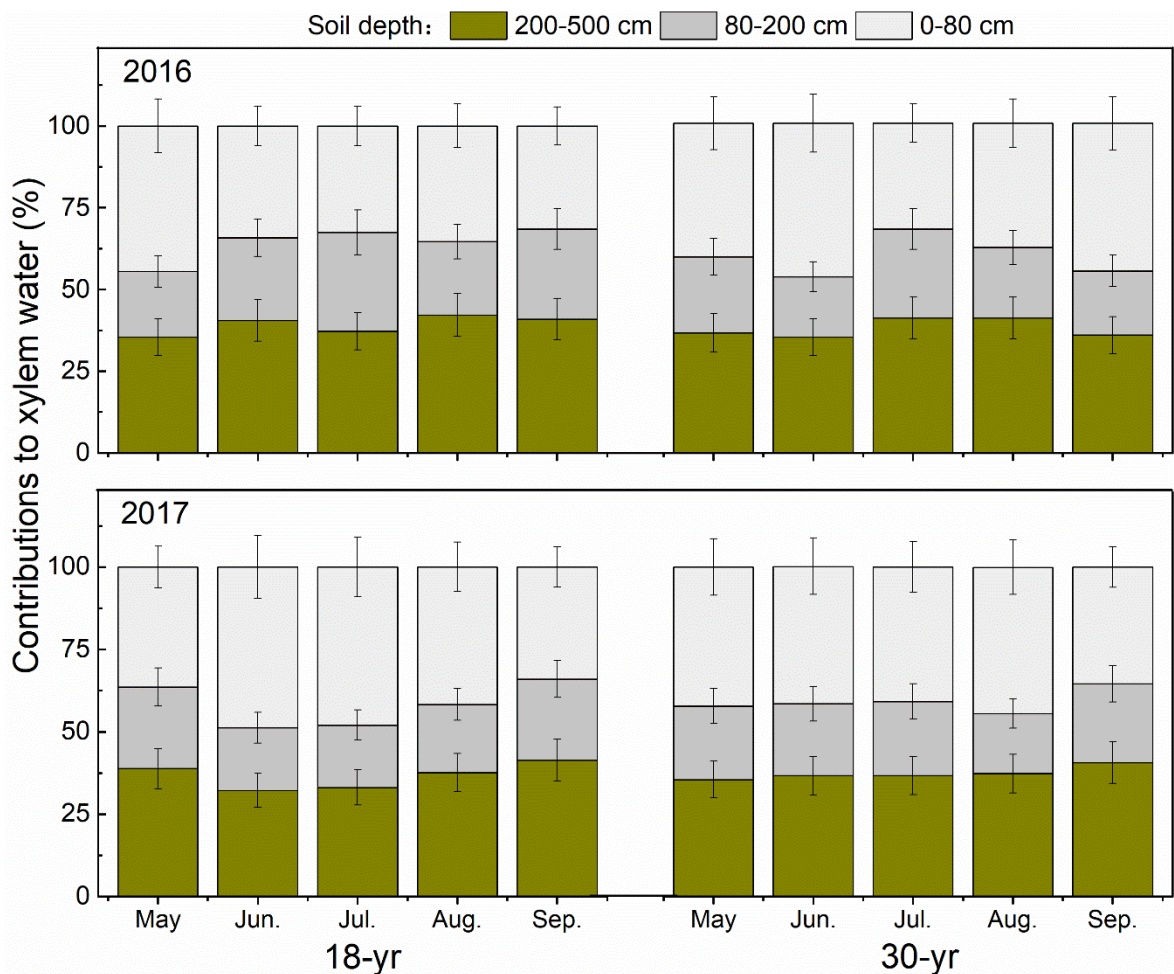
Fig. 5. Seasonal variation in the proportional contributions of soil water from shallow (0–80 cm),

355 middle (80–200 cm) and deep (200–500 cm) layers to xylem water of 18- and 30-yr *R.*

356 *pseudoacacia* during the study period. The error bar represents the standard deviation.

357 ***3.4 Variation in $\delta^{13}C$ values of plant leaves***

358 The leaf $\delta^{13}C$ values of the studied plants varied with sampling time (Fig. 6). In

2016, the mean leaf $\delta^{13}C$ values of 18- and 30-yr *R. pseudoacacia* were −26.25‰ and

−26.66‰, respectively. In 2017, the leaf $\delta^{13}C$ values of 18-yr *R. pseudoacacia* ranged

from −27.14 to −25.31‰, with the average value of −26.36‰, and the mean leaf $\delta^{13}C$

values of 30-yr *R. pseudoacacia* was −25.76‰. The leaf $\delta^{13}C$ values of 30-yr *R.*

pseudoacacia was higher than that of 18-yr *R. pseudoacacia* except for May (Fig. 6).

There were significant differences ($p < 0.05$) in the leaf $\delta^{13}C$ values between 18- and

30-yr *R. pseudoacacia* during the growing season in 2017 but not 2016. In addition,

the leaf $\delta^{13}C$ values of 30-yr *R. pseudoacacia* in 2017 showed significantly ($p < 0.001$)

higher than those in 2016, but this difference was not found in 18-yr *R. pseudoacacia*.

Moreover, the leaf $\delta^{13}C$ values of 30-yr *R. pseudoacacia* changed significantly with

sampling months ($p < 0.001$) in 2016 and 2017. The leaf $\delta^{13}C$ values of 18-yr *R.*

pseudoacacia varied significantly with sampling months ($p < 0.001$) in 2017 but not

2016.
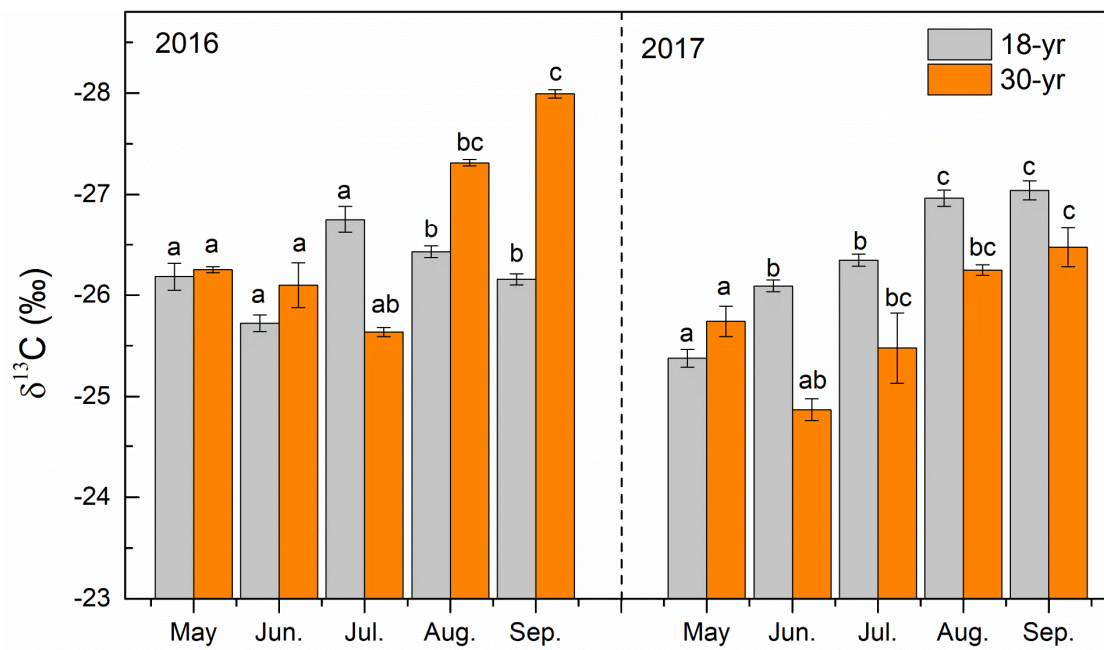
Fig. 6. Seasonal variation in leaf $\delta^{13}C$ values of 18- and 30-yr *R. pseudoacacia* during the study

374 period. Different lowercase letters represent significant differences among sampling times at the p

375 < 0.05 level. The error bar represents the standard deviation.

376

4. Discussion

4.1 Differences in water uptake patterns of R. pseudoacacia at different stand-age

379   The different stand-age *R. pseudoacacia* plantation showed different water use

380 patterns during the study period. The isotopic compositions of xylem water in 30-yr *R.*

381 *pseudoacacia* approached that of shallow soil water (Fig. 2), suggesting that it was

382 mainly derived from shallow soil water during the growing season. The MixSIAR

383 model also predicted that 30-yr *R. pseudoacacia* absorbed 40.34% and 40.88% from

384 shallow soil water in 2016 and 2017, respectively. These values were higher than

385 those for soil water from the middle and deep layers (Fig. 5). Plant water uptake

386 patterns were associated with the vertical distribution of fine roots (Wang et al.,

387 2017b). Previous study showed that the mature tree had a high fine-root area density

388 in the shallow soil layers (Zhang et al., 2018), causing the higher fractions of shallow

389 soil water was absorbed by 30-yr *R. pseudoacacia.* However, 18-yr *R. pseudoacacia*

390 derived the highest proportion (39.24%) of water from deep soil layers in 2016 and

391 41.78% from shallow soil layers in 2017. Our results showed that the proportional

392 contributions of soil water from shallow, middle, and deep layers to xylem water did

393 not display significant differences between the two stand-ages. However, Huo et al.

394 (2018) found that jujube trees of different ages differed significantly with respect to

395 water uptake: older jujube trees were more dependent on deep soil water than young

396   trees in semiarid plantations in China. Previous research reported that the water

397   demand of *R. pseudoacacia* increases with growth and the water uptake depth shifts

398   from shallow to deeper soil layers. Further, when deep soil water consumption

399   reaches a certain level, the water absorption depth returns to the upper layer (Nan et

400   al., 2019).

401   In this study, the 30-yr *R. pseudoacacia* used more water from shallow soil layer

402   than 18-yr *R. pseudoacacia* in 2016, but this capacity may have been offset by

403   increased rainfall. The growing season precipitation in 2017 was 11.14% higher than

404   that in 2016, and 18-yr *R. pseudoacacia* used more shallow soil water than 30-yr *R.*

405   *pseudoacacia*. Moreover, with an increase in rainfall, the utilization fraction of

406   shallow soil water by 18-yr *R. pseudoacacia* in 2017 was 17.2% higher more than that

407   in 2016. However, the proportional contributions of shallow soil water for 30-yr *R.*

408   *pseudoacacia* were relatively stable during the two years (40.34%, 40.88% for 2016

409   and 2017, respectively).

410   These results indicated that water uptake patterns of 18-yr *R. pseudoacacia* were

411   sensitive to the variation of precipitation. This was consistent with our hypothesis (2)

412   that different stand-age *R. pseudoacacia* showed various sensitivity to changes in

413   precipitation in water uptake patterns. Our findings were similar to those of previous

414   studies (Rose et al., 2003; Schwinning et al., 2005). McCole and Stern (2007) found

415   that trees mainly derive water from shallow soil layers when surface soil water is

416   highly available. However, our results disagreed with those of a previous study (Huo

417   et al., 2018) in which the proportional contributions of shallow soil water to jujube

418   trees of different ages did not increase with the rainfall. Goldsmith et al. (2012)

419   reported that different ages of plant species derived water from the same soil layer in a

420   seasonally dry tropical montane cloud forest. There were several possible

421   explanations for this different pattern from the findings reported in previous studies

422   (Goldsmith et al., 2012; Huo et al., 2018; Song et al., 2018). First, the sensitivity to

423   the variation of precipitation in plant water uptake patterns exhibited species-specific.

424   Different plant species had divergent eco-physiological characteristics related to water

425   uptake, such as the distribution and functioning of fine roots (Wang et al., 2017b),

426   recovery ability of photosynthesis after drought stress (Zunzunegui et al., 2018), more

427   rapid leaf turnover, and greater allocation to roots. Moreover, the habitat

428   environments where plants are located may also cause this difference pattern. Habitat

429   environment reflects the differences in water and heat conditions and soil properties,

430   such as sandy land of Inner Mongolia (Song et al., 2018), seasonally dry tropical

431   montane (Goldsmith et al., 2012). In addition, the methods associated with stable

432   isotopes for determining plant water source partitioning also cause this different

433   pattern. For example, SIAR model were used in Huo et al (2018), IsoSource model

434   was applied in Song et al (2018), and MixSIAR model was used in this study. The

435   performances of different isotopic approaches to quantify plant water uptake have

436   been confirmed (Rothfuss and Javaux, 2017; Wang et al., 2019b).

437   The water uptake fractions of 30-yr *R. pseudoacacia* from shallow, middle, and

438   deep soil layers were comparable during the study periods (Fig. 5), indicating

439   the 30-yr *R. pseudoacacia* did not show plasticity in water uptake pattern. There are

       some

440   possible explanations for this interesting phenomenon. Normally, plants' roots obtain

441   resources from shallow soil layers (when available) because the energy costs are

442   lower, and both water and nutrient availability are generally high in the upper layers

443   (Schenk, 2008). Although the growing season precipitation in 2017 was 11.14%

444   higher than that in 2016, the shallow SWC in 30-yr *R. pseudoacacia* plantations

445   hardly changed (*p*>0.05), increasing by only 2% compared to 2016. The most of the

446   precipitation were short-duration heavy rainfall during the growing seasons (Fig. 1).

447   The infiltration excess overland flow was the dominant runoff generation process in

448   this region (Kang et al., 2001). The combined precipitation from three heavy rainfall

449   events accounted for 46.05% of the total rainfall during the growing season of 2017.

450   During these short-duration heavy rainfall events, most of the rainfall was quickly lost

451   in the form of runoff. Thus, despite the increase in rainfall during the growing seasons,

452   there was no significant increase (*p*>0.05) in shallow SWC in 30-yr *R. pseudoacacia*

453   plantations (Fig. 4). Therefore, *R. pseudoacacia* did not absorbed more shallow soil

454   moisture and kept relatively stable in water uptake patterns. In addition, the difference

455   in water uptake patterns of different stand-age of *R. pseudoacacia* may be associated

456   with the distribution and functioning of fine roots which played an essential role in

457   water, nutrient absorption of the plants. Previous study showed that root system of

458   younger trees had higher sensitivity to water (Wang et al., 2020b). The fine roots

459   distribution of different stand-ages trees needs further investigation to provide more

460   insights to the variation of water uptake patterns under different precipitation.

461   Furthermore, a time lag effect may be existed between the variation of plant water

462   sources following precipitation increases and the identification of its consequences.

463   Previous studies detected a time lag between water shortage and plants' responses

464   (Vicente-Serrano et al., 2013; Huo et al., 2018). While it was not possible to collect

465   data with sufficient time resolution to investigate this time lag effect in the current

466   study, future studies are desirable focusing on better spatial and temporal resolutions

467   of stable isotopes in water and plants.

468   *4.2 Differences in plant leaf $\delta^{13}C$ values of different stand-age of R. pseudoacacia*

469   The leaf $\delta^{13}C$ values of 30-yr *R. pseudoacacia* were significant ($p < 0.05$) higher

470   than that of 18-yr *R. pseudoacacia* in 2017. This indicated that there was a higher

471   leaf-level WUE_i in 30-yr *R. pseudoacacia* plantation than the 18-yr *R. pseudoacacia*

472   plantation during the study period of 2017 since the $\delta^{13}C$ value of plant leaves is

473   positively correlated with the leaf-level WUE_i (Farquhar et al., 1989). The leaf $\delta^{13}C$

474   values of 30-yr *R. pseudoacacia* displayed a significant change with the sampling

475   time ($p < 0.01$) (Fig. 6), suggesting that the leaf-level WUE_i varied with the growing

476   season. Some meteorological factors, such as temperature, light, precipitation, and

477   atmospheric CO_2, can influence the leaf $\delta^{13}C$ values of plants by affecting stomatal

478   conductance (g_s) during photosynthesis (Farquhar et al., 1989). In our study, the

479   different stand-age *R. pseudoacacia* plantations were located close to each other, and

480   the variation in atmospheric temperature, precipitation, and light was small in these

481   plantations. In addition, the studied plantations had closed canopies, and the gradient

482   in the atmospheric CO_2 concentrations under the canopy did not vary significantly and

483   could be ignored. Therefore, temperature, light, precipitation, and atmospheric CO_2

484   concentrations had little effect on the difference in carbon isotope compositions

485   between 18- and 30-yr *R. pseudoacacia*. Stand-age was an essential factor which

486   impacts plant photosynthesis. *R. pseudoacacia* plantations reached their mature stage

487   around 30 years (Kou et al., 2016) and 18-year *R. pseudoacacia* plantations was

488   vigorous growth period on the Loess Plateau. Previous studies showed that juvenile *R.*

489   *pseudoacacia* plantations had higher average daily stomatal conductance and ratio of

490   intercellular (C_i) to ambient (C_a) CO_2, carboxylation efficiency compared to mature

491   plantations (Zheng et al., 2011), indicating different stand-age *R. pseudoacacia*

492   plantation had divergent physiological characteristics. Therefore, stand-age

493   plantations may lead to the difference in the leaf-level WUE_i of *R. pseudoacacia.* Our

494   results were consistent with previous studies (Zhang and Jin, 2016; Zheng et al., 2011)

495   which found WUE was higher in the mature forests compared with that in the juvenile

496   plantations in the Loess Plateau. Moreover, the competition for above-ground

497   resources may also cause the difference in leaf-level WUE_i of *R. pseudoacacia.*

498   Nitrogen, phosphorus, and water in soil were essential factor for plant growth and

499   survival. Nitrogen as a belowground resource did not impact on the growth

500   partitioning of *R. pseudoacacia* due to its ability to fix atmospheric nitrogen.

501   Phosphorus and water as below-ground resources were the key factors affecting

502   growth partitioning and competition of *R. pseudoacacia* (Carl et al., 2018). In our

503   study, the shallow SWC of 30-yr *R. pseudoacacia* plantations was higher significantly

504   ($p < 0.01$) than those in 18-yr *R. pseudoacacia* both in 2016 and 2017. Previous

505   studied showed mature *R. pseudoacacia* plantations had higher phosphorus compared

506 to juvenile plantations (Kou et al., 2016). Higher phosphorus and water led to increase

507 the competition for above-ground resources, mainly sunlight (Carl et al., 2018), which

508 may cause the difference in leaf-level WUE_i of different stand-age *R. pseudoacacia.*

509   The leaf $\delta^{13}C$ values of 18-yr *R. pseudoacacia* showed no significant difference

510 between 2016 and 2017, implying that the leaf-level WUE_i remained relatively stable.

511 However, the leaf $\delta^{13}C$ values of 30-yr *R. pseudoacacia* in 2017 were significantly

512 higher than those in 2016 ($p < 0.001$), indicating that leaf-level WUE_i of 30-yr

513 planation would appear higher in a wet year than in a dry year. This result was

514 consistent with a previous study in the same catchment (Wang et al., 2020a) and

515 indicated that *R. pseudoacacia* displayed opportunistic water uptake strategy.

516 However, some previous studies showed that leaf $\delta^{13}C$ values had a significant

517 negative correlation with precipitation or soil water availability in arid and semi-arid

518 regions (Ale et al., 2018; Zheng et al., 2007). Some reasons may explain this

519 phenomenon that old plantation had higher leaf-level WUE_i in a wetter year. WUE_i is

520 defined as the ratio of photosynthetic rate over g_s, and photosynthetic rate can be

521 expressed as $(g_s / 1.6) * (C_a - C_i)$ (Farquhar et al., 1989). The maximal carboxylation

522 rate (V_{cmax}), a measure of photosynthetic capacity, is usually well correlated with

523 nutrient availability (i.e., nitrogen and phosphorus) (Maroco et al.,2002; Prior et al.,

524 2003). Previous studies reported that a wetter condition can promote phosphorus

525 availability for plants in the semi-arid Loess Plateau (Wu et al., 2019; Xu et al., 2020),

526 thus increasing V_{cmax}. The increase of V_{cmax} would lead to a further drawdown of C_i

527 and result in an increase in $C_a - C_i$. The proportional increase in photosynthetic rate

528   might outweigh that in g_s, therefore ensuring an increase in WUE_i. However, we need

529   to further verify this physiological mechanism in the future research. In addition, the

530   mature tree had a high fine-root area density in the shallow soil layers (Zhang et al.,

531   2018), which accordingly dried more rapidly than the deeper soil, causing the increase

532   of leaf-level WUE_i of mature trees. Furthermore, soil water content significantly

533   affects stomatal conductance during the process of photosynthesis, which

534   subsequently influences the carbon isotope ratios of plants, especially in arid and

535   semiarid regions (Farquhar et al., 1989). Long-term vegetation restoration consumed a

536   large amount of soil water, and when the water was suddenly replenished, this may

537   have had a stimulating effect, leading to an increase in the leaf-level WUE_i of plants.

538   However, the specific mechanism remains to be further explored.

539   *4.3 Implications for afforestation*

540   Water availability is an important factor for successful vegetation restoration in

541   arid and semiarid regions (Wang et al., 2012). Higher precipitation does not

542   necessarily result in larger water availability because runoff drains much of water

543   from the short-duration heavy rainfall due to the low infiltration in semiarid Loess

544   Plateau. Limited precipitation is the only water source for plant growth because the

545   groundwater level is deep (Jia et al., 2017) and most plant roots cannot reach the

546   groundwater of the semiarid Loess Plateau. Artificial forestation has caused excessive

547   consumption of soil water and has resulted in dry soil layers due to inappropriate

548   species use and planting density (Wang et al., 2011). Therefore, the sustainability of

549   revegetation must consider plant water uptake patterns. Our results showed that water

uptake patterns of 18-yr *R. pseudoacacia* were more sensitive to changes in precipitation than those of 30-yr *R. pseudoacacia*, and their leaf-level WUE$_i$ differed significantly during the study period (Fig. 6). The different stand-age plantation trees exhibited the specific effect of water use characteristics response to different precipitation. In the same catchment, Jiao et al. (2016) found stand transpiration of different stand-age black locust trees was significantly different. A previous study also showed that the depths of soil water consumed by *R. pseudoacacia* gradually increased (100–500 cm) with increasing forest stand age (Nan et al., 2019). In our study, the deep SWC of 18- and 30-yr *R. pseudoacacia* plantations showed a significant difference ($p < 0.01$). Therefore, in future afforestation activities, stand-age is an essential factor to be considered to implement the corresponding management measures, which can strengthen the effectiveness of vegetation restoration strategies. In forestland dominated by *R. pseudoacacia*, with the increase in the restoration stage, this species consumed high amounts of deep soil water. Even in the year with high rainfall, the water source used by 30-yr *R. pseudoacacia* did not change significantly (Fig. 4), implying that *R. pseudoacacia* may reach the critical point of growth decline in 30 years. Moreover, the 30-yr *R. pseudoacacia* displayed dieback and some branches had no leaves or withered during the field investigation. In the Fuxian district of the Loess Plateau, Jia et al. (2017) found that the height of *R. pseudoacacia* increased over time before age 20 years, and the rate of plant growth showed a downward trend during the following 20 years, the branches appeared to be increasingly death. Nan et al. (2019) also found that the heights of 20-yr and 40-yr *R.*

pseudoacacia were only 600 cm and 900 cm, respectively and the DBH was

approximately 35 cm and 58 cm, respectively. In our study, the average heights of 18-

and 30-yr *R. pseudoacacia* were 894 cm and 928 cm, respectively, and the

corresponding DBH was 11.34 cm and 12.36 cm. Therefore, it is necessary to carry

out appropriate management measures for forestland after a certain restoration stage.

Some water retention measures can be implemented, for example water-fertilizer pits

(60 cm $\times$ 60 cm $\times$ 40 cm) were dug along the contour lines, with the direction parallel

to the slope on the steep forestland. Water-fertilizer pits can intercept runoff and

deliver rainwater to deep soil layers. In addition, appropriate logging is required in

high-density areas to maintain the balance of the water source supply and the needs of

plant growth (Jia et al., 2017). Some restoration methods, such as natural grassland

and abandoned farmland, has little effect on soil water regardless of afforestation age

(Zhang et al., 2016). The choice of shallow-rooted herbs and natural restoration may

be the optimal choices for vegetation restoration on the Loess Plateau. Many *R.*

pseudoacacia plantations may exacerbate soil water deficits, which is not conducive

to the sustainability of vegetation restoration. When the mean annual precipitation

was below 520 mm, the soil water in the 100–300 cm layers was equivalent to or

below the permanent wilting point (Wang et al., 2017a), therefore, *R. pseudoacacia*

should be planted where the mean annual precipitation exceeds 520 mm.

5. Conclusions

This study provides insight into seasonal water use characteristics of

594   different-aged *R. pseudoacacia* plantations (18- and 30-yr) on the Loess Plateau using

595   stable isotope techniques (δ^2H, δ^{18}O and δ^{13}C) combined with the MixSIAR model.

596   The results showed that although the growing season precipitation in 2017 increased

597   by 11.14% compared to 2016, the proportional contributions of shallow soil water to

598   xylem water in 30-yr *R. pseudoacacia* were comparable between the two years

599   (40.34%, 40.88% for 2016 and 2017, respectively), but the water uptake fraction of

600   shallow soil water by 18-yr *R. pseudoacacia* in 2017 was 17.2% higher than that in

601   2016, tracking the precipitation increase with the shallow soil moisture increased by

602   7.60%. These results indicated that the water uptake patterns of 18-yr *R.*

603   *pseudoacacia* were sensitive to the variation of precipitation. The leaf δ^{13}C values of

604   18-yr *R. pseudoacacia* showed no significant difference between 2016 and 2017.

605   However, the leaf δ^{13}C values of 30-yr *R. pseudoacacia* in 2017 were significantly

606   higher ($p < 0.001$) than those in 2016, suggesting that increased precipitation could

607   stimulate leaf-level WUE_i, and older plantations respond to increased water

608   availability by increasing WUE_i instead of switching water sources. SWC was the

609   main factor that caused the differences in the δ^{13}C values of plant leaves between

610   different-aged *R. pseudoacacia*. Overall, the plantation trees exhibited distinct age

611   specific water use characteristics in response to differences in precipitation and

612   resulting water content across soil layers. This study provides insight into revegetation

613   dynamics in semiarid ecosystems. The stand age of plant species should be considered

614   to implement the corresponding management measures to strengthen the effectiveness

615   of vegetation restoration strategies in afforestation activities.

References

Ale, R., Zhang, L., Li, X., Raskoti, B. B., Pugnaire, F. I., Luo, T., 2018. Leaf $\delta^{13}C$ as an indicator of water availability along elevation gradients in the dry Himalayas. Ecological Indicators, 94: 266–273.

Atkinson, J., Bonser, S.P., 2020. "Active" and "passive" ecological restoration strategies in meta-analysis. Restoration Ecology, 28(5): 1032–1035.

Austin, A. T., Yahdjian, L., Stark, J. M., Belnap, J., Porporato, A., Norton, U., Ravetta, D. A., Schaeffer, S. M., 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia, 141(2): 221–235.

Blicharska, M., Smithers, R. J., Mikusiński, G., Rönnbäck, P., Harrison, P. A., Nilsson, M., Sutherland, W. J., 2019. Biodiversity's contributions to sustainable development. Nature Sustainability, 2, 1083–1093.

Brunner, I., Herzog, C., Dawes, M. A., Arend, M., Sperisen, C., 2015. How tree roots respond to drought. Frontiers in plant science, 6: 547.

Carl, C., Biber, P., Veste, M., Landgraf, D., Pretzsch, H., 2018. Key drivers of competition and growth partitioning among *Robinia pseudoacacia L.* trees. Forest Ecology and Management, 430: 86–93.

Chen, W., Li, Z., Jiao, L., Wang, C., Gao, G., Fu, B., 2020. Response of soil moisture to rainfall event in black locust plantations at different stages of restoration in hilly-gully area of the Loess Plateau, China. Journal of Geographical Sciences, 30(3): 427–445.

Ding, Y., Nie, Y., Chen, H., Kelin, W., Querejeta, J. I., 2020. Water uptake depth is coordinated with

leaf water potential, water use efficiency and drought vulnerability in karst vegetation. New Phytologist, 229: 1339–1353.

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

Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. Annual review of plant biology, 40(1): 503–537.

Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annual Review of Earth and Planetary Sciences, 45: 223–243.

Gow, L. J., Barrett, D. J., O'grady, A. P., Renzullo, L. J., Phinn, S. R., 2018. Subsurface water-use strategies and physiological responses of subtropical eucalypt woodland vegetation under changing water-availability conditions. Agricultural and Forest Meteorology, 248: 348–360.

Goldsmith, G.R., Muñoz-Villers L.E., Holwerda, F., McDonnell, J.J., Asbjornsen, H., Dawson, T.E., 2012. Stable isotopes reveal linkages among ecohydrological processes in a seasonally dry tropical montane cloud forest. Ecohydrology, 5(6): 779–790.

Grossiord, C., Sevanto, S., Dawson, T. E., Adams, H. D., Collins, A. D., Dickman, L. T., Newman, B.D., Stockton, E. A., McDowell, N. G., 2017. Warming combined with more extreme precipitation regimes modifies the water sources used by trees. New phytologist, 213(2): 584–596.

Harrison, J. L., Blagden, M., Green, M. B., Salvucci, G. D., Templer, P. H., 2020. Water sources for red maple trees in a northern hardwood forest under a changing climate. Ecohydrology, e2248.

Huo, G., Zhao, X., Gao, X., Wang, S., Pan, Y., 2018. Seasonal water use patterns of rainfed jujube trees in stands of different ages under semiarid Plantations in China. Agriculture, Ecosystems & Environment, 265: 392–401.

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., Wang, G., 2017. Dryland climate change: Recent progress and challenges. Reviews of Geophysics, 55: 719–778.

IPCC, 2019. Summary for policymakers. In: Shukla, P.R., Skea, J., Calvo Buendia, E., MassonDelmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen,R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J.,Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.

Jia, X., Shao, M.a., Zhu, Y., Luo, Y., 2017. Soil moisture decline due to afforestation across the Loess Plateau, China. Journal of Hydrology, 546: 113–122.

Jiao, L., Lu, N., Fu, B., Gao, G., Wang, S., Jin, T., Zhang, L., Liu, J., Zhang, D., 2016. Comparison of transpiration between different aged black locust (*Robinia pseudoacacia*) trees on the semi-arid Loess Plateau, China. Journal of Arid Land, 8(4): 604–617.

Jiao, L., Lu, N., Fang, W., Li, Z., Wang, J., Jin, Z., 2019. Determining the independent impact of soil water on forest transpiration: A case study of a black locust plantation in the Loess Plateau, China. Journal of Hydrology, 572: 671–681.

Kang, S., Zhang, L., Song, X., Zhang, S., Liu, X., Liang, Y., Zheng, S., 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. Hydrological Processes, 15(6): 977–988.

Kerhoulas, L.P., Kolb, T.E., Koch, G.W., 2013. Tree size, stand density, and the source of water used across seasons by ponderosa pine in northern Arizona. Forest Ecology and Management, 289: 425–433.

Kou, M., Garcia-Fayos, P., Hu, S., Jiao, J., 2016. The effect of *Robinia pseudoacacia* afforestation on soil and vegetation properties in the Loess Plateau (China): A chronosequence approach. Forest Ecology and Management, 375: 146–158.

Lanning, M., Wang, L., Benson, M., Zhang, Q., Novick, K.A., 2020. Canopy isotopic investigation reveals different water uptake dynamics of maples and oaks. Phytochemistry, 175: 112389.

Liu, S., Chen, Y., Chen, Y., Friedman, J. M., Hati, J. H. A., Fang, G., 2015. Use of ^{2}H and ^{18}O stable isotopes to investigate water sources for different ages of *Populus euphratica* along the lower Heihe River. Ecological Research, 30(4): 581–587.

Mackay, D. S., Savoy, P. R., Grossiord, C., Tai, X., Pleban, J. R., Wang, D. R., McDowell, N.G., Adams, H., Sperry, J. S. 2020. Conifers depend on established roots during drought: results from a coupled model of carbon allocation and hydraulics. New Phytologist, 225(2): 679–692.

Maroco, J. P., Breia, E., Faria, T., Pereira, J. S., Chaves, M. M., 2002. Effects of long-term exposure to elevated CO_2 and N fertilization on the development of photosynthetic capacity and biomass accumulation in Quercus suber L. Plant, Cell & Environment, 25(1): 105–113.

McCole, A.A., Stern, L.A., 2007. Seasonal water use patterns of *Juniperus ashei* on the Edwards Plateau, Texas, based on stable isotopes in water. Journal of Hydrology, 342(3-4): 238–248.

Nan, G., Wang, N., Jiao, L., Zhu, Y., Sun, H., 2019. A new exploration for accurately quantifying the effect of afforestation on soil moisture: A case study of artificial *Robinia pseudoacacia* in the Loess Plateau (China). Forest Ecology and Management, 433: 459–466.

Prior, L. D., Eamus, D., Bowman, D. M., 2003. Leaf attributes in the seasonally dry tropics: a comparison of four habitats in northern Australia. Functional Ecology, 17(4): 504–515.

Rose, K., Graham, R., Parker, D., 2003. Water source utilization by *Pinus jeffreyi* and *Arctostaphylos patula* on thin soils over bedrock. Oecologia, 134(1): 46–54.

Rothfuss, Y., Javaux, M., 2017. Reviews and syntheses: Isotopic approaches to quantify root water uptake: a review and comparison of methods. Biogeosciences, 14, 2199–2224.

Saugier, B., Ehleringer, J.R., Hall, A.E., Farquhar, G.D., 2012. Stable isotopes and plant carbon-water relations. Elsevier, Amsterdam.

Schwinning, S., Starr, B.I., Ehleringer, J.R., 2005. Summer and winter drought in a cold desert ecosystem (Colorado Plateau) part I: effects on soil water and plant water uptake. Journal of Arid Environments, 60(4): 547–566.

Schenk, H. J., 2008. Soil depth, plant rooting strategies and species' niches. New Phytologist, 178(2): 223–224.

Song, L., Zhu, J., Li, M., Zhang, J., Li, D., 2018. Water use strategies of natural Pinus sylvestris var. Mongolica trees of different ages in Hulunbuir Sandy Land of Inner Mongolia, China, based on stable isotope analysis. Trees, 32(4): 1001–1011.

Stock, B.C., Semmens, B.X., 2013. MixSIAR GUI UserManual, version 3.1., http://conserver.iugocafe.org/user/brice.semmens/MixSIAR.

Volkmann, T.H., Haberer, K., Gessler, A., Weiler, M., 2016. High-resolution isotope measurements

resolve rapid ecohydrological dynamics at the soil-plant interface. New phytologist, 210(3): 839–849.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Begueria, S., Trigo, R., LopezMoreno, J.I., Azorin-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Moran-Tejeda, E., Sanchez-Lorenzo, A., 2013. Response of vegetation to drought time-scales across global land biomes. PNAS, 110 (1): 52–57.

Wang, C., Wang, S., Fu, B., Yang, L., Li, Z., 2017a. Soil Moisture Variations with Land Use along the Precipitation Gradient in the North–South Transect of the Loess Plateau. Land Degradation & Development, 28(3): 926–935.

Wang, J., Fu, B., Lu, N., Wang, S., Zhang, L., 2019a. Water use characteristics of native and exotic shrub species in the semi-arid Loess Plateau using an isotope technique. Agriculture, Ecosystems & Environment, 276: 55–63.

Wang, J., Lu, N., Fu, B., 2019b. Inter-comparison of stable isotope mixing models for determining plant water source partitioning. Science of the Total Environment, 666, 685–693.

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

Wang, J., Fu, B., Wang, L., Lu, N., Li, J., 2020a. Water use characteristics of the common tree species in different plantation types in the Loess Plateau of China. Agricultural and Forest Meteorology, 288-289: 108020.

Wang, L., d'Odorico, P., Evans, J. P., Eldridge, D. J., McCabe, M. F., Caylor, K. K., King, E. G., 2012. Dryland ecohydrology and climate change: critical issues and technical advances. Hydrology and Earth System Sciences, 16(8): 2585–2603.

Wang, S., An, J., Zhao, X., Gao, X., Wu, P., Huo, G., Robinson, B.H., 2020b. Age-and climate-related water use patterns of apple trees on China's Loess Plateau. Journal of Hydrology, 582: 124462.

Wang, Y., Shao, M.A., Zhu, Y., Liu, Z., 2011. Impacts of land use and plant characteristics on dried soil layers in different climatic regions on the Loess Plateau of China. Agricultural and Forest Meteorology, 151(4): 437–448.

Wu, X., Tang, Y. K., Chen, C., Jia, C., Chen, Y. M., 2019. Photosynthesis light response characteristics and environmental adaptability of *Hippophae rhamnoides*, *Pinus tabuliformis*, and *Robinia pseudoacacia* in the Loess hilly region of China. Acta Ecologica Sinica, 39(21): 8111–8125.

Xu, M., Zhong, Z., Sun, Z., Han, X., Ren, C., Yang, G., 2020. Soil available phosphorus and moisture drive nutrient resorption patterns in plantations on the Loess Plateau. Forest Ecology and Management, 461: 117910.

Yu, Y., Zhao, W., Martinez-Murillo, J. F., Pereira, P., 2020. Loess Plateau, from degradation to restoration.Science of the Total Environment, 738: 140206.

Zhao, Y., Wang, Y., He, M., Tong, Y., Zhou, J., Guo, X., Liu, J., Zhang, X., 2020. Transference of *Robinia pseudoacacia* water-use patterns from deep to shallow soil layers during the transition period between the dry and rainy seasons in a water-limited region. Forest Ecology and Management, 457: 117727.

Zhang, D., Jin T.T., 2016.Variations of water-carbon exchange at leaf scale and leaf nutrient content of *Robinia pseudoacacia* with slope aspect and stand age in a small catchment of the Loess Plateau. Chinese Journal of Ecology, 35(2): 354–362.

780   Zhang, Y., Deng, L., Yan, W., Shangguan, Z., 2016. Interaction of soil water storage dynamics and
781   long-term natural vegetation succession on the Loess Plateau, China. Catena, 137: 52‒60.

782   Zhang, Y., Huang, M., Lian, J., 2015. Spatial distributions of optimal plant coverage for the dominant
783   tree and shrub species along a precipitation gradient on the central Loess Plateau. Agricultural
784   and Forest Meteorology, 206: 69‒84.

785   Zhang, Z., Huang, M., Zhang, Y., 2018. Vertical distribution of fine-root area in relation to stand age
786   and environmental factors in black locust (*Robinia pseudoacacia*) forests of the Chinese Loess
787   Plateau. Canadian Journal of Forest Research, 48(10): 1148‒1158.

788   Zheng, Y., Zhao, Z., Zhou, J.J., Zhou, H., Liang, Z.S., Luo, Z.B., 2011. The importance of slope aspect
789   and stand age on the photosynthetic carbon fixation capacity of forest: a case study with black
790   locust (*Robinia pseudoacacia*) plantations on the Loess Plateau. Acta Physiologiae Plantarum,
791   33(2): 419‒429.

792   Zhou, H., Zhao, W., Zhang, G., 2017. Varying water utilization of *Haloxylon ammodendron* plantations
793   in a desert-oasis ecotone. Hydrological Processes, 31(4): 825‒835.

794   Zunzunegui, M., Boutaleb, S., Díaz Barradas, M. C., Esquivias, M. P., Valera, J., Jáuregui, J., Tagma, T.,
795   Ain-Lhout, F., 2018. Reliance on deep soil water in the tree species *Argania spinosa*. Tree
796   Physiology, 38(5): 678‒689.

797   Zheng, S., Shangguan, Z., 2007. Spatial patterns of foliar stable carbon isotope compositions of C_3
798   plant species in the Loess Plateau of China. Ecological Research, 22(2): 342‒353.

799