

1 **A global synthesis of transpiration rate and evapotranspiration**
2 **partitioning in the shrub ecosystems**

3

4 Revised manuscript submitted to *Journal of Hydrology* (HYDROL42164)

5

6 Guangyao Gao ^{a, b}, Di Wang ^{a, c}, Tianshan Zha ^d, Lixin Wang ^e, Bojie Fu ^{a, b, *}

7

8 ^a *State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental*
9 *Sciences, Chinese Academy of Sciences, Beijing 100085, China*

10 ^b *University of Chinese Academy of Sciences, Beijing 100049, China*

11 ^c *College of Water Resources and Civil Engineering, China Agricultural University, Beijing*
12 *100083, China*

13 ^d *Yanchi Research Station, School of Soil and Water Conservation, Beijing Forestry University,*
14 *Beijing 100083, China*

15 ^e *Department of Earth Sciences, Indiana University-Purdue University Indianapolis (IUPUI),*
16 *Indianapolis, IN 46202, United States*

17

18 * Corresponding author.

19 *E-mail address:* bfu@rcees.ac.cn

20 **Abstract**

21 Transpiration (T) is a fundamental process in understanding the ecophysiology of plants,
22 and it is the dominant component of evapotranspiration (ET) in the terrestrial water cycle.
23 Although previous studies have examined T characteristics of shrub ecosystems in some regions,
24 global-scale synthesis that integrates the spatial variations of T, ET and ratio of T to ET (T/ET)
25 and the associated influences of bio-/abiotic factors in the shrub ecosystems is currently lacking.
26 In this study, we synthesized and analyzed T rate, ET rate and T/ET of the shrub ecosystems
27 from the peer-reviewed articles using field observations around the world. These studies were
28 mainly distributed in drylands with aridity index (ratio of precipitation to potential ET) < 0.65,
29 which accounted for 86.4% of the study locations. Globally, the mean daily T and ET rates of
30 shrubs were 1.5 ± 1.0 mm d⁻¹ and 2.4 ± 0.8 mm d⁻¹, with coefficient of variation of 63.2% and 36.2%
31 among the study locations, respectively. Mean T/ET of the shrubs over the growing season was
32 0.54 ± 0.14 , which was generally lower compared with forest, grassland and cropland ecosystems.
33 The T rate of shrubs was positively related to shrub age, shrub height, leaf area index, and
34 vegetation coverage ($p < 0.05$), and the effects of biotic factors on T rate were stronger compared
35 with abiotic factors. The ET rate of shrubs was positively related to aridity index, long-term
36 annual mean precipitation, mean soil water content, as well as shrub height and vegetation
37 coverage ($p < 0.05$). By contrast, the effects of biotic factors on variations of shrub T/ET were
38 weaker than those of abiotic factors, and the T/ET of shrubs was negatively related to aridity
39 index, long-term annual mean precipitation and mean soil water content, but positively related to
40 latitude ($p < 0.05$). This study is an important supplement of our knowledge gap in terrestrial
41 water cycle, and the findings suggest that T accounted for about half of the water into
42 atmosphere from shrub ecosystems, and the variations of T rate of shrubs were mainly controlled

43 by biotic factors, whereas ET rate and T/ET was mainly affected by abiotic factors.

44 *Keywords:* Transpiration, Evapotranspiration partitioning, Shrub, Spatial variations,

45 Biotic/abiotic factors

46

47 **1 Introduction**

48 Evapotranspiration (ET) consists of transpiration (T) through the stomata of plants,
49 evaporation (E) from the soil, and evaporation of water intercepted (I) by the plant canopy and
50 litter layer (Raz-yaseef et al., 2012; Zhang et al., 2021). Evapotranspiration is critical for global
51 water cycle, and it can amount to up to 95% of the annual water budget in drylands with aridity
52 index (ratio of precipitation to potential ET) < 0.65 (Wilcox et al., 2003; Wang et al., 2012; Kool
53 et al., 2014; Zhou et al., 2016). The processes of T and E among ecosystems are distinctly
54 different (Wang et al., 2013). Transpiration is usually coupled with carbon assimilation and
55 associated with plant productivity, whereas E does not directly contribute to production (Kool et
56 al., 2014). Transpiration is strongly influenced by biological factors, while E and I are mostly a
57 result of abiotic processes (Katul et al., 2012). Thus, investigating the variations of T rate and ET
58 partitioning and the associated controlling factors would help to better understand terrestrial
59 hydrological cycles, vegetation productivity and water use efficiency (Wei et al., 2017; Stoy et al.,
60 2019).

61 Climate change appears to increasingly intensify hydrological cycles, and global terrestrial
62 ET showed the declining trend (Jung et al., 2010). In recent years, a number of studies have been
63 conducted to explore global-scale ET and its partitioning in a changing environment. Jasechko et
64 al. (2013) used the distinct isotope effects of T and E to show that T is by far the largest water
65 flux from Earth's continents, representing 80-90% of terrestrial ET. Coenders-Gerrits et al. (2014)

66 revised the input data in the modeling of Jasechko et al. (2013), and proposed a more
67 conservative ratio of T to ET (T/ET), i.e., 35-80%. Schlesinger and Jasechko (2014) focused on
68 81 studies using eddy-covariance and sap flow measurements or isotopic approaches to quantify
69 T/ET and found that T accounts for $61\pm 15\%$ of ET and returns approximately $39\pm 10\%$ of
70 incident precipitation to the atmosphere. Wang et al. (2014) synthesized the published articles
71 that measured at least two of the three components (E, T, and ET) and showed that T/ET ranged
72 from 38-77%. Good et al. (2015) combined two large-scale flux-partitioning approaches to
73 quantify ET components and found that globally, T is $64\pm 13\%$ of ET. Although ranges of global
74 T/ET differed amongst the above studies, ET was dominated by T in the terrestrial hydrological
75 cycles (Zhou et al., 2016).

76 As the main component of ET, T of plants has been measured using multiple methods, for
77 example, by chambers, lysimeter, and sap flow methods (Williams et al., 2004; Stannard and
78 Weltz, 2006; Wang et al., 2010; Rafi et al., 2019). Sap flow is water flux across a given section
79 of trunk diameter at a given period, which is an important indicator of water movement in plants
80 (Liu et al., 2012; Poyatos et al., 2016). Thus, sap flow can be used to indicate the instantaneous T
81 of plants (Granier et al., 1996; Kume et al., 2008; Steppe et al., 2010). A better characterization
82 of sap flow and T dynamics of different ecosystems would improve our understanding of
83 terrestrial hydrological processes, its connection to ecological processes, and its variability under
84 climate change (Poyatos et al., 2016).

85 As an important vegetation type, shrubs are widely distributed throughout the world,
86 especially in drylands (Li et al., 2008; Gwenzu et al., 2014; Dziki et al., 2016), and the area of
87 shrubs is about 2.5×10^7 km², which accounts for 17.6% of global land area (Hansen et al., 2000).
88 Shrubs in drylands have various benefits, such as reducing surface runoff (Farley et al., 2005),

89 altering infiltration spatial pattern (Eldridge et al., 2015), and increasing infiltration rate (Issa et
90 al., 2011) and carbon sequestration (Deng et al., 2014). The sap flow, T and ET characteristics of
91 shrubs and their relationships with affecting factors have been conducted in a number of studies
92 since 1994 (Terwilliger and Zeroni, 1994; Cavanaugh et al., 2011; Ji et al., 2016; Szutu and
93 Papuga, 2019; Wang et al., 2020).

94 Even though the number of studies quantifying shrub T rate, ET rate and T/ET increased
95 over the years, most of these studies focused on one or two shrub species at a specific site.
96 Schlesinger and Jasechko (2014) summarized T dynamics of Mediterranean shrubland, while
97 average T/ET ($47\pm 10\%$, $n=4$) of shrubs in Mediterranean region still needs to be reconsidered
98 due to limited compilation studies. To our best knowledge, there was no report of the dynamics
99 of T rate, ET rate and T/ET in shrubs at global-scale. Understanding the shrubs' spatial
100 characteristics of T rate, ET rate and T/ET at global scale and their influencing factors will be an
101 important supplement of our knowledge gap in hydrological cycle in dryland ecosystems.

102 This study aimed to synthesize the *in situ* measurement-based publications of sap flow and
103 T rate in shrub ecosystems across the world. The objectives of this study were to: (1) examine
104 globally the spatial variations in T rate, ET rate and T/ET for the shrub ecosystems, and (2)
105 understand globally the biotic/abiotic factors controlling the variations in T rate, ET rate and
106 T/ET for the shrub ecosystems.

107 **2 Materials and methods**

108 Using the Web of Science (www.webofknowledge.com) and Google Scholar
109 (www.scholar.google.com), we searched relevant peer-reviewed journal articles that were
110 published in English before December 2020. Literatures that included at least two of the
111 following keywords and phrases were searched: one is shrub or subshrub or shrubland, and the

112 other is sap flow or transpiration or evapotranspiration. To avoid bias in the selection of
113 publications, articles were chosen based on the following criteria: (1) major results, such as sap
114 flow, T rate and T/ET of shrub ecosystems, were exclusively obtained from field measurements
115 (modeled values were not considered), (2) field measurements of sap flow or T rate have to be
116 continuously one month at least.

117 In total, the final dataset comprised data from 43 published articles, and represented 44 sites
118 (Figure 1, Table 1). For each article, the information compiled included location, mean annual
119 precipitation (MAP), mean annual temperature (MAT), soil texture, shrub species, study period,
120 study scale (plant or stand), measurement methods of sap flow and/or T, upscaling methods of T,
121 and ranges of daily sap flow and T rate (Table 1). The data for daily sap flow and daily T rate, as
122 well as mean potential ET and mean soil water content here were collected directly from the text
123 and tables or extracted from figures in each article using GetData Graph Digitizer 2.26 (Sergei
124 Fedorov, Russia). The multiple shrub species in a given article were labeled as separate ones.
125 There were 38 and 6 study locations distributed in drylands with aridity index < 0.65 and
126 non-drylands with aridity index ≥ 0.65 , respectively. The methods for the transpiration
127 measurements in the collected articles included sap flow methods (such as heat balance method,
128 heat pulse method and constant heater method), water balance method, chamber and
129 micro-lysimeter, with sap flow methods in 93.1% of the articles. When upscaling results of sap
130 flow to plant or stand scales, stem cross-sectional area of shrubs was widely used, followed by
131 leaf area and by numbers of branches.

132 Ten of the 43 articles reported ET rate and T/ET of shrub ecosystems (Table 2). All the ten
133 articles were conducted in drylands with aridity index ranging from 0.09 to 0.47. Measurement
134 methods of ET and its components, T range, ET, ratio of ET to precipitation (ET/P) and T/ET

135 were recorded and extracted from each article (Table 2). Among the 10 articles, eddy covariance
136 method, Bowen ratio energy balance method, weighing lysimeter method, combination of sap
137 flow and micro-lysimeter measurements were used to measure ET and its components of shrubs.
138 There were 28 datasets of T/ET during the study period from the 10 articles.

139 The daily mean T and ET rates of shrubs were calculated by averaging the daily T and ET
140 rates for each shrub species over growing season during the study period. The growing season
141 T/ET of shrubs was the ratio of total T to total ET for each shrub species. Summary statistics of T
142 rate, ET rate and T/ET of shrubs, such as means, standard deviation and coefficient of variation,
143 were calculated. The Pearson correlation analysis was used to test the significance of the
144 relationships of daily mean T rate, daily mean ET rate and growing season T/ET with abiotic
145 factors (aridity index, latitude, longitude, long-term annual mean precipitation, long-term annual
146 mean air temperature, long-term annual mean potential ET and mean soil water content) and
147 biotic factors (shrub age, shrub height, stem basal diameter, leaf area index, and vegetation
148 coverage). Some factors, especially the biotic factors, were not available in all the case studies.
149 Thus, the number of sites used in the correlation analysis was different. All statistical analyses
150 were performed with SPSS 16.0 (SPSS Inc., USA).

151 **3 Results**

152 **3.1 Variations in T rate, ET rate and T/ET of shrubs**

153 Daily mean T rate of shrubs varied with site locations and species, and globally the mean
154 daily T rate of shrubs was $1.5 \pm 1.0 \text{ mm d}^{-1}$ (Figure 2a). Daily mean T rate of shrubs over the
155 growing season ranged from 0.2 to 3.4 mm d^{-1} amongst study locations, with a mean of 1.6 ± 1.0
156 mm d^{-1} and coefficient of variation of 63.2%. The mean value amongst shrub species was about
157 1.9 mm d^{-1} ($0.2\text{-}4.5 \text{ mm d}^{-1}$) with coefficient of variation of 62.2%. Frequency distribution of

158 daily mean T rate of shrubs differed among different classes (Figure 2b). Mean daily T rate of
159 shrubs were mainly distributed in $>2.0 \text{ mm d}^{-1}$ class, followed by $0-0.5 \text{ mm d}^{-1}$, $1.0-2.0 \text{ mm d}^{-1}$,
160 $0.5-1.0 \text{ mm d}^{-1}$ and $1.0-1.5 \text{ mm d}^{-1}$ class, with corresponding percentage of 38.4%, 23.1% 15.4%,
161 15.3% and 7.8%, respectively.

162 Among the 10 articles related to ET partitioning, the total ET of shrubs generally exceeded
163 precipitation during the study period. The mean ET over growing season of shrubs was
164 $330.6 \pm 144.3 \text{ mm year}^{-1}$ ($102.2-523.9 \text{ mm year}^{-1}$) with coefficient of variation of 43.6%. Daily
165 mean ET rate of shrubs ranged from 0.78 to 3.64 mm d^{-1} amongst study locations, with a mean
166 of $2.4 \pm 0.8 \text{ mm d}^{-1}$ and coefficient of variation of 36.2%. The mean ratio of ET to precipitation
167 was 1.48 ± 0.47 , with maximum of 2.39 and minimum of 0.48 (Table 2). The T/ET of shrubs over
168 the growing season also varied amongst different site locations (0.34-0.87) and shrub species
169 (0.34-0.86) with coefficient of variation of 29.3% and 26.5%, respectively. Globally, mean T/ET
170 of shrubs was 0.54 ± 0.14 (Figure 3).

171 **3.2 Relationships between T rate of shrubs and biotic or abiotic factors**

172 Relationships between daily mean T rate and influencing factors in shrubs are shown in
173 Figure 4. Daily mean T rate of shrubs was significantly related to aridity index ($p < 0.01$, $n = 38$),
174 long-term annual mean precipitation ($p = 0.011$, $n = 33$), long-term annual mean potential ET
175 ($p < 0.01$, $n = 26$) and mean soil water content ($p = 0.042$, $n = 19$). As aridity index, long-term annual
176 mean precipitation and mean soil water content increased, daily mean T rate of shrubs showed an
177 increasing trend, whereas daily mean T rate of shrubs decreased as long-term annual mean
178 potential ET increased. There was no significant relationship between daily mean T rate of
179 shrubs and latitude ($p = 0.076$, $n = 38$), longitude ($p = 0.834$, $n = 38$), and long-term annual mean air
180 temperature ($p = 0.219$, $n = 30$).

181 Compared with abiotic factors, the effects of biotic factors on dynamics of daily mean T rate
182 in shrubs were strong (Figure 4). Daily mean T rate of shrubs was positively related to biotic
183 factors, including shrub age ($p<0.01$, $n=22$), shrub height ($p=0.035$, $n=25$), leaf area index
184 ($p<0.01$, $n=21$) and vegetation coverage ($p<0.01$, $n=18$). There was no relationship between daily
185 mean T rate and stem basal diameter ($p=0.602$, $n=22$) in shrubs. As shrub height and leaf area
186 index increased, daily mean T rate of shrubs increased rapidly and reached the maximum values
187 (the threshold of shrub height and leaf area index was about 2.5 m and 3.2 m² m⁻², respectively),
188 and then maintained stable.

189 **3.3 Relationships between ET rate of shrubs and biotic or abiotic factors**

190 Relationships between daily mean ET rate of shrubs and influencing factors are shown in
191 Figure 5. Daily mean ET rate of shrubs was significantly correlated with aridity index ($p=0.008$,
192 $n=27$), long-term annual mean precipitation ($p=0.021$, $n=26$), long-term annual mean air
193 temperature ($p=0.031$, $n=25$) and mean soil water content ($p=0.003$, $n=14$). As aridity index,
194 long-term annual mean precipitation and mean soil water content increased, daily mean ET rate
195 of shrubs showed an increasing trend. No significant relationships could be found between daily
196 mean ET rate of shrubs and latitude, longitude, and long-term annual mean potential ET
197 ($p>0.05$).

198 Biotic factors, such as shrub height ($p=0.04$, $n=13$) and vegetation coverage ($p=0.013$,
199 $n=14$), significantly affected daily mean ET rate of shrubs. Daily mean ET rate of shrubs
200 increased with the increase of shrub height and the increase of vegetation coverage. There was
201 no significant relationship between daily mean ET rate and shrub age ($p=0.270$, $n=14$), stem
202 basal diameter ($p=0.555$, $n=16$), and leaf area index ($p=0.142$, $n=26$).

203 **3.4 Relationships between T/ET of shrubs and biotic or abiotic factors**

204 As shown in Figure 6, the T/ET of shrubs was significantly related to aridity index, latitude,
205 long-term mean annual precipitation, long-term annual mean potential ET and mean soil water
206 content ($p < 0.05$). The T/ET of the shrub ecosystems showed a decreasing trend with the increase
207 of aridity index increased, long-term annual mean precipitation and mean soil water content,
208 whereas T/ET increased with the increase of latitude and long-term annual mean potential ET.
209 There was no significant correlation between T/ET and longitude ($p = 0.573$, $n = 28$) and long-term
210 annual mean air temperature ($p = 0.493$, $n = 26$).

211 Compared to the abiotic factors, the effects of biotic factors on variations in annual shrub
212 T/ET were weak (Figure 6). Among the biotic factors, there were somewhat correlations between
213 T/ET and leaf area index ($p = 0.065$, $n = 26$) and vegetation coverage ($p = 0.099$, $n = 15$) of shrubs.
214 The other biotic factors such as shrub age ($p = 0.982$, $n = 14$), shrub height ($p = 0.698$, $n = 13$) and
215 stem basal diameter ($p = 0.962$, $n = 17$) had little effect on variations of T/ET as indicated in this
216 synthesis.

217 **4 Discussion**

218 **4.1 T and ET rates of shrubs and their influencing factors**

219 Daily mean T rate of shrubs was 1.5 ± 1.0 mm d⁻¹, and it differed with site locations and
220 shrub species, with the coefficient of variation of 63.2% over site locations and 62.3% over shrub
221 species. Daily mean ET rate of shrubs was 2.4 ± 0.8 mm d⁻¹, with the coefficient of variation of
222 36.2%. The T and ET rates of shrubs are usually lower than that of forest and cropland and
223 higher than that of grassland under similar climate and water availability conditions (Schlesinger
224 and Jasechko, 2014; Sun et al., 2019). The dynamics of T rate and ET rate are influenced by
225 multiple factors, including vegetation properties, environmental factors, and anthropogenic
226 management (Nicolás et al., 2005; Scott et al., 2006; Bucci et al., 2008; Liu et al., 2012). It was

227 found that there were significant interspecific differences in T and photosynthesis of *Tamarix*
228 *ramosissima* and *Haloxylon ammodendron* under three precipitation treatments (natural, double
229 and no precipitation) (Xu et al., 2007). Cavanaugh et al. (2011) found that ET and surface soil
230 water content had strong correlation in semiarid shrubland. In this synthesis, differences in shrub
231 age, leaf area index, meteorological factors and soil water content largely existed among site
232 locations and shrub species (Figures 4 and 5), and differences in these variables jointly affected
233 dynamics of sap flow and then lead to differences in T rate and ET rate of shrubs. It should be
234 noted that different measurement and upscaling methods for T rate may also affect the variations
235 of T rates among the study locations. Most of the studies (93.1%) upscaled the results of
236 measured sap flow to estimate T rate. Each SF method has unique sensitivities to error in
237 parameter estimation and their working principle also vary widely (Flo et al., 2019). Furthermore,
238 there were some variations between the estimated T by the two widely upscaling methods on the
239 basis of cross-sectional area and leaf area (Allen and Grime, 1995). It will be considered as our
240 next research plan to investigate the effects of different methods on the variations of T rate.

241 Compared with abiotic factors, effects of biotic factors on daily mean T rate of shrubs were
242 strong as indicated in this study. Plant transpiration is directly connected with vegetation
243 productivity, and T capacity largely depends on hydraulic resistance, root and leaf water potential,
244 and stomatal and leaf conductance (Kool et al., 2014). Hydraulic transport efficiency might also
245 contribute to difference in dynamics of T rate among the shrub species. Many studies have found
246 that plant transpiration is strongly affected by biological factors (Kool et al., 2014;
247 Sanchez-Costa et al., 2015; Wang et al., 2021). The introduced shrub species (*H. rhamnoides*)
248 was found to maintain a relatively high canopy T due to its different physiological characteristics
249 with respect to two native shrub species (*Vitex negundo* and *Spiraea pubescens*) (Fang et al.,

250 2019). Hayat et al. (2020) investigated the biophysical controls on inter-annual variations of sap
251 flow in *S. psammophila* of northwest China, and found that leaf area index was responsible for
252 most of the variations. In this synthesis, we found that daily mean T rate of shrubs was positively
253 and significantly correlated with shrub age, shrub height, leaf area index and vegetation coverage
254 (Figure 4).

255 The daily mean ET rate of shrubs was mainly controlled by abiotic factors, and it was also
256 affected by biotic factors to some degree. In this synthesis, the abiotic factors (aridity index,
257 long-term annual mean precipitation, long-term annual mean air temperature and mean soil water
258 content) and biotic factors (shrub height and vegetation coverage) had strong relationships with
259 variations of daily mean ET rate of shrubs (Figure 5). This mainly due to that the three
260 components of ET depended on different factors. The variations of T rate of shrubs were mainly
261 controlled by biotic factors as indicated in this synthesis, and the variations of soil evaporation
262 and canopy interception are mostly a result of abiotic processes (Katul et al., 2012). Raz-Yaseef
263 et al. (2010) found that the spatial variability of soil evaporation in a semi-arid pine forest was
264 clearly affected by soil water content and solar radiation. Magliano et al. (2019) also highlighted
265 the ecohydrological role of rainfall inputs affecting the generation of rainfall interception and the
266 water spatial distribution in drylands.

267 **4.2 T/ET of the shrub ecosystems and its influencing factors**

268 The ratio of T to ET reflects how ecosystem water vapor flux is allocated between physical
269 and biological processes, and the magnitude of T/ET are related to the productive water use in
270 water loss through ET (Hu et al., 2009; Kool et al., 2014). Mean T/ET of shrubs was about
271 0.54 ± 0.14 , which suggested that T account for about half of the water into atmosphere from
272 shrub ecosystems. This result is contrast to the general perception that T is the largest component

273 of ET and dominates terrestrial water fluxes (Jasechko et al., 2013; Wang et al., 2014; Good et al.,
274 2015). In this synthesis, mean T/ET of the shrub ecosystems was lower than that of forest
275 (0.63 ± 0.15), grassland (0.59 ± 0.14) and cropland (0.68 ± 0.13) ecosystems as reported in
276 Schlesinger and Jasechko (2014) and Sun et al. (2019) (Figure 3). Vegetation types clearly affect
277 the magnitude of T/ET, and it was also found that T/ET was highest in tropical rainforest
278 (0.70 ± 0.14), followed by tropical grassland (0.62 ± 0.19), temperate coniferous forest (0.62 ± 0.19),
279 and Mediterranean shrubland (0.47 ± 0.10) (Schlesinger and Jasechko, 2014). Differences in plant
280 morphology and leaf area index lead to the differences in evaporation between different biomes,
281 thus their difference in T/ET (Kato et al., 2004; Hu et al., 2008; Wang et al., 2013). For example,
282 shrubs and forests fundamentally differ in their stature (Götmark et al., 2016). Compared with
283 ecosystems with dense canopies for forests, grassland and cropland, shrubs are characterized
284 with sparse canopies, with bare soil accounting for a larger proportion of the surface area, which
285 exposes greater surface area for soil evaporation to occur, resulting in smaller T/ET values (Gao
286 et al., 2019).

287 In this synthesis, T/ET of the shrub ecosystems significantly decreased with aridity index,
288 i.e., more drought, higher T/ET. There was a weak negative correlation between global T/ET and
289 aridity index across biomes using a mechanistic ecohydrological model by Fatichi and Pappas
290 (2017). This is the results of compensatory effects between a decrease in the proportion of the
291 evaporation from interception and an increase in the proportion of ground evaporation in dry
292 sites (Fatichi and Pappas, 2017). Long-term mean annual precipitation significantly influenced
293 T/ET of the shrub ecosystems in this synthesis. This result is not consistent with the result of
294 Schlesinger and Jasechko (2014) who reported that there was no relationship of global T/ET
295 versus precipitation across all available data ($R^2=0.01$) with a compilation of 81 studies

296 worldwide. This was mainly because T/ET data were collected from various biomes in
297 Schlesinger and Jasechko (2014), and large differences in T/ET existed among different biomes
298 even with similar rainfall regimes and from the same regions.

299 At stand scale, many studies have found that T/ET is influenced by vegetation properties
300 (plant age, stand vegetation cover, leaf area index, etc.) (Jiao et al., 2019). It was found that T/ET
301 of *Nitraria* was lower at senescence stage when comparing with early growth stage, rapid growth
302 stage and peak growth stage (Qiu et al., 2015). Wang et al. (2010) assessed ET partitioning
303 across an experimentally manipulated gradient of woody plant cover and showed that an
304 expected increase in fractional contribution of T/ET as woody cover increased from T/ET=0.61
305 at 25% woody cover to T/ET=0.83 at 100% cover. In this synthesis, biotic factors, such as shrub
306 age, vegetation coverage and leaf area index were not significantly correlated with shrub T/ET
307 ($p>0.05$). The variation of mean annual canopy stomatal conductance governed the inter-annual
308 variation and spatial variation of T/ET (Zhu et al., 2015). Canopy conductance variation was
309 closely related to a range of environmental variables including global radiation, vapor pressure
310 deficit, air temperature and soil water deficit (Granier et al., 2000). The effects of biotic factors
311 on variations of shrub T/ET were weaker than those of abiotic factors in this synthesis. This was
312 mainly due to that fact that these biotic variables were from multiple study locations, and
313 differences in aridity index (range from 0.09-0.47), long-term annual mean precipitation (range
314 from 116.8-530 mm), other environment factors and soil water conditions might also largely
315 affect the dynamics of T/ET of the shrub ecosystems.

316 **5 Conclusions**

317 In this study, we conducted a global synthesis of *in situ* studies that examined T rate, ET
318 rate and T/ET dynamics of the shrub ecosystems, and most of the study sites (86.4%) were

319 distributed in drylands. Mean daily T rate and ET rate of shrubs varied greatly among different
320 locations and shrub species, with the mean value of 1.5 ± 1.0 and 2.4 ± 0.8 mm d⁻¹, respectively,
321 globally. Mean T/ET of shrubs was 0.54 ± 0.14 , which was lower than forest, grassland and
322 cropland ecosystems. Compared with abiotic factors, effects of biotic factors on dynamics of
323 daily mean T rate in shrubs were strong. In contrast, the effects of biotic factors on variations of
324 shrub T rate and T/ET were weaker than those of abiotic factors. This study is the first time to
325 synthesize studies that measured T rate, ET rate and ET partitioning of shrubs throughout the
326 world. The obtained results of T rate, ET rate and ET partitioning of shrubs as well as their
327 relationships with bio-/abiotic factors at a global scale will strengthen our understanding of the
328 characteristics of T rate, ET rate and the contribution of plant water use to ET in shrub
329 ecosystems.

330

331 **Acknowledgements**

332 This research was funded by the National Key Research and Development Program (no.
333 2017YFA0604700), National Natural Science Foundation of China (nos. 41822103 and
334 41991233), and the Youth Innovation Promotion Association CAS (no. Y202013). LW
335 acknowledges partial support from the Division of Earth Sciences of National Science
336 Foundation (EAR-1554894). We thank the two anonymous reviewers for their professional
337 comments which have helped us greatly improve the manuscript.

338

339 **References**

340 Allen, S.J., Grime, V.L., 1995. Measurements of transpiration from savannah shrubs using sap
341 flow gauges. *Agric. For. Meteorol.* 75, 23-41.

342 Bucci, S.J., Scholz, F.G., Goldstein, G., Hoffmann, W.A., Meinzer, F.C., Franco, A.C.,
343 Giambelluca, T., Miralles-Wilhelm, F., 2008. Controls on stand transpiration and soil water
344 utilization along a tree density gradient in a Neotropical savanna. *Agric. For. Meteorol.*
345 148(6), 839-849.

346 Cavanaugh, M.L., Kurc, S.A., Scott, R.L., 2011. Evapotranspiration partitioning in semiarid
347 shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration.
348 *Ecohydrology* 4, 671-681.

349 Coenders-Gerrits, A.M.J., van der Ent, R.J., Bogaard, T.A., Wang-Erlandsson, L., Hrachowitz,
350 M., Savenije, H.H.G., 2014. Uncertainties in transpiration estimates. *Nature* 506, E1-E2.

351 Deng, J., Ding, G., Gao, G., Wu, B., Zhang, Y., Qin, S., Fan, W., 2015. The sap flow dynamics
352 and response of *Hedysarum scoparium* to environmental factors in semiarid northwestern
353 China. *PloS one* 10, e0131683.

354 Deng, L., Liu, G.B., Shangguan, Z.P., 2014. Land-use conversion and changing soil carbon
355 stocks in China's 'Grain-for-Green' Program: a synthesis. *Glob. Change Biol.* 20, 3544-3556.

356 Domingo, F., Villagarcía, L., Brenner, A.J., Puigdefábregas, J., 1999. Evapotranspiration model
357 for semi-arid shrub-lands tested against data from SE Spain. *Agric. For. Meteorol.* 95, 67-84.

358 Dudley, B.D., Marttila, H., Graham, S.L., Evison, R., Srinivasan, M.S., 2018. Water sources for
359 woody shrubs on hillslopes: An investigation using isotopic and sap flow methods.
360 *Ecohydrology* 11, e1926.

361 Dzikiti, S., Gush, M.B., Maitre, D.C.L., Maherry, A., Jovanovic, N.Z., Ramoelo, A., Cho, M.A.,
362 2016. Quantifying potential water savings from clearing invasive alien *Eucalyptus*
363 *camaldulensis* using in situ and high resolution remote sensing data in the Berg River
364 Catchment, Western Cape, South Africa. *For. Ecol. Manage.* 361, 69-80.

365 Flo, V., Martinez-Vilalta, J., Steppe, K., Schuldt, B., Poyatos, R., 2019. A synthesis of bias and
366 uncertainty in sap flow methods. *Agric. For. Meteorol.* 271, 362-374.

367 Eldridge, D.J., Wang, L., Ruiz-Colmenero, M., 2015. Shrub encroachment alters the spatial
368 patterns of infiltration. *Ecohydrology* 8(1), 83-93.

369 Fang, W., Lu N., Zhang Y., Jiao L., Fu, B., 2017. Responses of nighttime sap flow to atmospheric
370 and soil dryness and its potential roles for shrubs on the Loess Plateau of China. *J. Plant Ecol.*
371 11, 717-729.

372 Fang, W., Lu, N., Liu, J., Jiao, L., Zhang, Y., Wang, M., Fu, B., 2019. Canopy transpiration and
373 stand water balance between two contrasting hydrological years in three typical shrub
374 communities on the semiarid Loess Plateau of China. *Ecohydrology*, 12: e2064.

375 Fatichi, S., Pappas, C., 2017. Constrained variability of modeled T:ET ratio across biomes.
376 *Geophys. Res. Lett.* 44, 6798-9803.

377 Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global
378 synthesis with implications for policy. *Glob. Change Biol.* 11, 1565-1576.

379 Fisher, J.B., Baldocchi, D.D., Misson, L., Dawson, T.E., Goldstein, A.H., 2007. What the towers
380 don't see at night: Nocturnal sap flow in trees and shrubs at two AmeriFlux sites in California.
381 *Tree Physiol.* 27, 597-610.

382 Flumignan, D.L., Faria, R.T., 2011. Evapotranspiration components and dual crop coefficients of
383 coffee trees during crop production. *Agric. Water Manage.* 98, 791-800.

384 Gao, L., Zhao, P., Kang, S., Li, S., Tong, L., Ding, R., Lu, H., 2019. Surface soil water content
385 dominates the difference between ecosystem and canopy water use efficiency in a sparse
386 vineyard. *Agric. Water Manage.* 226, 105817.

387 Götmark, F., Götmark, E., Jensen, A.M., 2016. Why be a shrub? A basic model and hypotheses

388 for the adaptive values of a common growth form. *Front. Plant Sci.* 7, 1095.

389 González-Rodríguez, Á.M., Brito, P., Lorenzo, J.R., Gruber, A., Oberhuber, W., Wieser, G., 2017.

390 Seasonal cycles of sap flow and stem radius variation of *Spartocytisus supranubius* in the

391 alpine zone of Tenerife, Canary Islands. *Alpine Bot.* 127, 97-108.

392 Good, S., Noone, D., Bowen, G., 2015. Hydrologic connectivity constrains partitioning of global

393 terrestrial water fluxes. *Science* 349, 175-177.

394 Granier, A., Biron, P., Lemoine, D., 2000. Water balance, transpiration and canopy conductance

395 in two beech stands. *Agric. For. Meteorol.* 100, 291-308.

396 Granier, A., Huc, R., Barigah, S.T., 1996. Transpiration of natural rainforest and its dependence

397 on climatic factors. *Agric. For. Meteorol.* 78, 19-29.

398 Guérin, V., Huché-Théliet, L., Charpentier, S., 2007. Mobilisation of nutrients and transport via

399 the xylem sap in a shrub (*Ligustrum ovalifolium*) during spring growth: N and C compounds

400 and interactions. *J. Plant Physiol.* 164, 562-573.

401 Gwenz, W., Hinz, C., Bleby, T.M., Veneklaas, E.J., 2014. Transpiration and water relations of

402 evergreen shrub species on an artificial landform for mine waste storage versus an adjacent

403 natural site in semi-arid Western Australia. *Ecohydrology* 7, 965-981.

404 Hansen, M.C., Defries, R.S., Townshend, J.R., Sohlberg, R., 2000. Global land cover

405 classification at 1 km spatial resolution using a classification tree approach. *Int. J. Remote*

406 *Sens.* 21 (6-7), 1331-1364.

407 Hayat, M., Zha, T., Jia, X., Iqbal, S., Qian, D., Bourque, C.P.A., Khan, A., Tian, Y., Bai, Y., Liu,

408 P., Yang, R., 2020. A multiple-temporal scale analysis of biophysical control of sap flow in

409 *Salix psammophila* growing in a semiarid shrubland ecosystem of northwest China. *Agric.*

410 *For. Meteorol.* 288-289, 107985.

411 Hu, Z., Yu, G., Fu, Y., Sun, X., Li, Y., Shi, P., Wang, Y., Zheng, Z., 2008. Effects of vegetation
412 control on ecosystem water use efficiency within and among four grassland ecosystems in
413 China. *Glob. Change Biol.* 14(7), 1609-1619.

414 Hu, Z., Yu, G., Zhou, Y., Sun, X., Li, Y., Shi, P., Wang, Y., Song, X., Zheng, Z., Zhang, L., Li, S.,
415 2009. Partitioning of evapotranspiration and its controls in four grassland ecosystems:
416 Application of a two-source model. *Agric. For. Meteorol.* 149, 1410-1420.

417 Huang, J., Zhou, Y., Yin, L., Wenninger, J., Zhang, J., Hou, G., Zhang, E., Uhlenbrook, S., 2015.
418 Climatic controls on sap flow dynamics and used water sources of *Salix psammophila* in a
419 semi-arid environment in northwest China. *Environ. Earth Sci.* 73, 289-301.

420 Huang, L., Zhang, Z.-S., Li, X., 2010. Sap flow of *Artemisia ordosica* and the influence of
421 environmental factors in a revegetated desert area: Tengger Desert, China. *Hydrol. Process.*
422 24, 1248-1253.

423 Huang, L., Zhang, Z., Li, X., 2014. The extrapolation of the leaf area-based transpiration of two
424 xerophytic shrubs in a revegetated desert area in the Tengger Desert, China. *Hydrol. Res.* 46,
425 389-399.

426 Issa, O.M., Valentin, C., Rajot, J.L., Cerdan, O., Desprats, J.-F., Bouchet, T., 2011. Runoff
427 generation fostered by physical and biological crusts in semi-arid sandy soils. *Geoderma*
428 167-168, 22-29.

429 Jasechko, S., Sharp, Z.D., Gibson, J.J., Birks, S.J., Yi, Y., Fawcett, P.J., 2013. Terrestrial water
430 fluxes dominated by transpiration. *Nature* 496, 347-350.

431 Ji, X., Zhao, W., Kang, E., Jin, B., Xu, S., 2016. Transpiration from three dominant shrub species
432 in a desert-oasis ecotone of arid regions of northwestern China: Transpiration from shrubs of
433 oasis-desert ecotone. *Hydrol. Process.* 30, 4841-4854.

434 Jian, S., Wu, Z., Hu, C., Zhang, X., 2016. Sap flow in response to rainfall pulses for two shrub
435 species in the semiarid Chinese Loess Plateau. *J. Hydrol. Hydromech.* 64(2), 121-132.

436 Jian, S., Zhao, C., Fang, S., Yu, K., 2014. Evaluation of water use of *Caragana korshinskii* and
437 *Hippophae rhamnoides* in the Chinese Loess Plateau. *Can. J. Forest Res.* 45, 15-25.

438 Jian, S., Zhao, C., Fang, S., Yu, K., 2015. Effects of different vegetation restoration on soil water
439 storage and water balance in the Chinese Loess Plateau. *Agric. For. Meteorol.* 206, 85-96.

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

443 Jung, M., Reichstein, M., Ciais, P., Seneviratne, S.I., Sheffield, J., Goulden, M.L., Bonan, G.,
444 Cescatti, A., Chen, J., de Jeu, R., Dolman, A.J., Eugster, W., Gerten, D., Gianelle, D., Gobron,
445 N., Heinke, J., Kimball, J., Law, B.E., Montagnani, L., Mu, Q., Mueller, B., Oleson, K.,
446 Papale, D., Richardson, A.D., Rouspard, O., Running, S., Tomelleri, E., Viovy, N., Weber, U.,
447 Williams, C., Wood, E., Zaehle, S., Zhang, K., 2010. Recent decline in the global land
448 evapotranspiration trend due to limited moisture supply. *Nature* 467, 951-954.

449 Katul, G.G., Oren, R., Manzoni, S., Higgins, C., Parlange, M.B., 2012. Evapotranspiration: A
450 process driving mass transport and energy exchange in the soil-plant-atmosphere-climate
451 system. *Rev. Geophys.* 50, RG3002.

452 Kato, T., Kimura, R., Kamichika, M., 2004. Estimation of evapotranspiration, transpiration ratio
453 and water-use efficiency from a sparse canopy using a compartment model. *Agric. Water
454 Manage.* 65(3), 173-191.

455 Kool, D., Agam, N., Lazarovitch, N., Heitman, J.L., Sauer, T.J., Bengal, A., 2014. A review of
456 approaches for evapotranspiration partitioning. *Agric. For. Meteorol.* 184, 56-70.

457 Kume, T., Komatsu, H., Kuraji, K., Suzuki, M., 2008. Less than 20-min time lags between
458 transpiration and stem sap flow in emergent trees in a Bornean tropical rainforest. *Agric. For.*
459 *Meteorol.* 148, 1181-1189.

460 Letts, M.G., Johnson, D.R.E., Coburn, C.A., 2010. Drought stress ecophysiology of shrub and
461 grass functional groups on opposing slope aspects of a temperate grassland valley. *Botany* 88,
462 850-866.

463 Li, X., Liu, L., Gao, S., Ma, Y., Yang, Z., 2008. Stemflow in three shrubs and its effect on soil
464 water enhancement in semiarid loess region of China. *Agric. For. Meteorol.* 148, 1501-1507.

465 Liu, B., Zhao, W., Jin, B., 2011. The response of sap flow in desert shrubs to environmental
466 variables in an arid region of China. *Ecohydrology* 4, 448-457.

467 Liu, C., Du, T., Li, F., Kang, S., Li, S., Tong, L., 2012. Trunk sap flow characteristics during two
468 growth stages of apple tree and its relationships with affecting factors in an arid region of
469 northwest China. *Agric. Water Manage.* 104, 193-202.

470 Magliano, P.N., Whitworth-Hulse, J.I., Baldi, G., 2019. Interception, throughfall and stemflow
471 partition in drylands: Global synthesis and meta-analysis. *J. Hydrol.* 568, 638-645.

472 Mirck, J., Volk, T.A., 2009. Seasonal sap flow of four *Salix* varieties growing on the Solvay
473 wastebeds in Syracuse, NY, USA. *Int. J. Phytoremediat.* 12, 1-23.

474 Naithani, K.J., Ewers, B.E., Pendall, E., 2012. Sap flux-scaled transpiration and stomatal
475 conductance response to soil and atmospheric drought in a semi-arid sagebrush ecosystem. *J.*
476 *Hydrol.* 464-465, 176-185.

477 Nicolás, E., Torrecillas, A., Amico, J.D., Alarcón, J.J., 2005. Sap flow, gas exchange, and
478 hydraulic conductance of young apricot trees growing under a shading net and different water
479 supplies. *Journal of Plant Physiology*, 162, 439-447.

480 Poyatos, R., Granda, V., Molowny-Horas, R., Mencuccini, M., Martínez-Vilalta, J., 2016.
481 SAPFLUXNET: towards a global database of sap flow measurements. *Tree Physiol.* 36,
482 1449-1455.

483 Prieto, I., Kikvidze, Z., Pugnaire, F.I., 2010. Hydraulic lift: soil processes and transpiration in the
484 Mediterranean leguminous shrub *Retama sphaerocarpa* (L.) Boiss. *Plant Soil* 329, 447-456.

485 Qian, D., Zha, T., Jia, X., Wu, B., Zhang, Y., Bourque, C.P.A., Qin, S., Peltola, H., 2015.
486 Adaptive, water-conserving strategies in *Hedysarum mongolicum* endemic to a desert
487 shrubland ecosystem. *Environ. Earth Sci.* 74, 6039-6046.

488 Qiu, G., Li, C., Yan, C., 2015. Characteristics of soil evaporation, plant transpiration and water
489 budget of *Nitraria* dune in the arid Northwest. *Agric. For. Meteorol.* 203, 107-117.

490 Qu, Y., Kang, S., Li, F., Zhang, J., Xia, G., Li, W., 2007. Xylem sap flows of irrigated *Tamarix*
491 *elongata* Ledeb and the influence of environmental factors in the desert region of Northwest
492 China. *Hydrol. Process.* 21, 1363-1369.

493 Rafi, Z., Merlin, O., Le Dantec, V., Khabba, S., Mordelet, P., Er-Raki, S., Amazirh, A.,
494 Olivera-Guerra, L., Ait Hssaine, B., Simonneaux, V., Ezzahar, J., Ferrer, F., 2019.
495 Partitioning evapotranspiration of a drip-irrigated wheat crop: Inter-comparing eddy
496 covariance-, sap flow-, lysimeter- and FAO-based methods. *Agric. For. Meteorol.* 265,
497 310-326.

498 Raz-yaseef, N., Rotenberg, E., Yakir, D., 2010. Effects of spatial variations in soil evaporation
499 caused by tree shading on water flux partitioning in a semi-arid pine forest. *Agric. For.*
500 *Meteorol.* 150, 454-462.

501 Raz-yaseef, N., Yakir, D., Schiller, G., Cohen, S., 2012. Dynamics of evapotranspiration
502 partitioning in a semi-arid forest as affected by temporal rainfall patterns. *Agric. For.*

503 Meteorol. 157, 77-85.

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

507 Schlesinger, W.H., Jasechko, S., 2014. Transpiration in the global water cycle. Agric. For.
508 Meteorol. 189-190, 115-117.

509 Scott, R.L., Huxman, T.E., Cable, W.L., Emmerich, W.E., 2006. Partitioning of
510 evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert
511 shrubland. Hydrol. Process. 20, 3227-3243.

512 She, D., Xia, Y., Shao, M., Peng, S., Yu, S., 2012. Transpiration and canopy conductance of
513 *Caragana korshinskii* trees in response to soil moisture in sand land of China. Agroforest.
514 Syst. 87, 667-678.

515 Stannard, D.I., Weltz, M.A., 2006. Partitioning evapotranspiration in sparsely vegetated
516 rangeland using a portable chamber. Water Resour. Res. 42(2), 1-13.

517 Steinwand, A.L., Harrington, R.F., Groeneveld, D.P., 2001. Transpiration coefficients for three
518 Great Basin shrubs. J. Arid. Environ. 49, 555-567.

519 Steppe, K., Pauw, D.J.W.D., Doody, T.M., Teskey, R.O., 2010. A comparison of sap flux density
520 using thermal dissipation, heat pulse velocity and heat field deformation methods. Agric. For.
521 Meteorol. 150, 1046-1056.

522 Stoy, P., El-Madany, T., Fisher, J., Gentine, P., Gerken, T., Good, S., Klosterhalfen, A., Liu, S.,
523 Miralles, D., Pérez-Priego, O., Rigden, A., Skaggs, T., Wohlfahrt, G., Anderson, R.,
524 Coenders-Gerrits, A., Jung, M., Maes, W., Mammarella, I., Mauder, M., Wolf, S., 2019.
525 Reviews and syntheses: Turning the challenges of partitioning ecosystem evaporation and

526 transpiration into opportunities. *Biogeosciences* 16, 3747-3775.

527 Sun, X., Wilcox, B.P., Zou, C.B., 2019. Evapotranspiration partitioning in dryland ecosystems: A
528 global meta-analysis of in situ studies. *J. Hydrol.* 576, 123-136.

529 Szutu, D.J., Papuga, S.A., 2019. Year-round transpiration dynamics linked with deep soil
530 moisture in a warm desert shrubland. *Water Resour. Res.* 55, 5679-5695.

531 Terwilliger, V.J., Zeroni, M., 1994. Gas exchange of a desert shrub (*Zygophyllum dumosum* Boiss.)
532 under different soil moisture regimes during summer drought. *Plant Ecology.* 115(2),
533 133-144.

534 van den Bergh, T., Körner, C., Hiltbrunner, E., 2018. *Alnus* shrub expansion increases
535 evapotranspiration in the Swiss Alps. *Reg. Environ. Change* 18, 1375-1385.

536 Wang, D., Gao, G., Li, J., Yuan, C., Lü, Y., Fu, B., 2020. Sap flow dynamics of xerophytic shrubs
537 differ significantly among rainfall categories in the Loess Plateau of China. *J. Hydrol.* 585,
538 124815.

539 Wang, L., D'Odorico, P., Evans, J.P., Eldridge, D., McCabe, M., Caylor, K., King, E., 2012.
540 Dryland ecohydrology and climate change: critical issues and technical advances. *Hydrol.*
541 *Earth Syst. Sc.* 16:2585-2603.

542 Wang, L., Niu, S., Good, S.P., Soderberg, K., McCabe, M.F., Sherry, R.A., Luo, Y., Zhou, X., Xia,
543 J., Caylor, K.K., 2013. The effect of warming on grassland evapotranspiration partitioning
544 using laser-based isotope monitoring techniques. *Geochim. Cosmochim. Ac.* 111(15), 28-38.

545 Wang, L., Good, S.P., Caylor, K.K., 2014. Global synthesis of vegetation control on
546 evapotranspiration partitioning. *Geophys. Res. Lett.*, 41, 6753-6757.

547 Wang, L., Caylor, K.K., Villegas, J.C., Barrongafford, G.A., Breshears, D.D., Huxman, T.E.,
548 2010. Partitioning evapotranspiration across gradients of woody plant cover: assessment of a

549 stable isotope technique. *Geophys. Res. Lett.*, 37, 232-256.

550 Wang, H., Li, X., Xiao, J., Ma, M., 2021. Evapotranspiration components and water use
551 efficiency from desert to alpine ecosystems in drylands. *Agric. For. Meteorol.* 298-299,
552 108283.

553 Wei, Z., Yoshimura, K., Wang, L., Miralles, D.G., Jasechko, S., Lee, X., 2017. Revisiting the
554 contribution of transpiration to global terrestrial evapotranspiration. *Geophys. Res. Lett.*, 44,
555 2792-2801.

556 Wilcox, B.P., Breshears, D.D., Seyfried, M.S., 2003. Water balance on rangelands. In: Stewart,
557 B.A., Howell, T.A. (Eds.), *Encyclopedia of Water Science*. Marcel Dekker, Inc., New York,
558 pp. 791-794.

559 Williams, D.G., Cable, W., Hultine, K., Hoedjes, J.C.B., Yezpez, E.A., Simonneaux, V., Er-Raki,
560 S., Boulet, G., Bruin, H.A.R.D., Chehbouni, A., 2004. Evapotranspiration components
561 determined by stable isotope, sap flow and eddy covariance techniques. *Agric. For. Meteorol.*
562 125, 241-258.

563 Wu, X., Tang, Y., Chen, Y., Wen, J., Xie, Y., Lu, S., 2018. Sap flow characteristics and responses
564 to summer rainfall for *Pinus tabulaeformis* and *Hippophae rhamnoides* in the Loess hilly
565 region of China. *Ecol. Evol.* 8, 617-630.

566 Xia, G., Kang, S., Li, F., Zhang, J., Zhou, Q., 2008. Diurnal and seasonal variations of sap flow
567 of *Caragana korshinskii* in the arid desert region of north-west China. *Hydrol. Process.* 22,
568 1197-1205.

569 Xu, H., Li, Y., Xu, G., Zou, T., 2007. Ecophysiological response and morphological adjustment
570 of two Central Asian desert shrubs towards variation in summer precipitation. *Plant. Cell*
571 *Environ.* 30, 399-409.

572 Xu, S., Yu, Z., Ji, X., Sudicky, E.A., 2017. Comparing three models to estimate transpiration of
573 desert shrubs. *J. Hydrol.* 550, 603-615.

574 Yue, G., Zhao, H., Zhang, T., Zhao, X., Niu, L., Drake, S., 2008. Evaluation of water use of
575 *Caragana microphylla* with the stem heat-balance method in Horqin Sandy Land, Inner
576 Mongolia, China. *Agric. For. Meteorol.* 148, 1668-1678.

577 Zha, T., Qian, D., Xin, J., Bai, Y., Yun, T., Bourque, P.A., Ma, J., Wei, F., Wu, B., Peltola, H.,
578 2017. Soil moisture control of sap-flow response to biophysical factors in a desert-shrub
579 species, *Artemisia ordosica*. *Biogeosciences* 14, 4533-4544.

580 Zhang, Y., Wang, X., Pan, Y., Hu, R., Chen, N., 2021. Global quantitative synthesis of effects of
581 biotic and abiotic factors on stemflow production in woody ecosystems. *Global Ecol.*
582 *Biogeogr.* 30, 1713-1723.

583 Zhao, W., Liu, B., 2010. The response of sap flow in shrubs to rainfall pulses in the desert region
584 of China. *Agric. For. Meteorol.* 150, 1297-1306.

585 Zhao, W., Liu, B., Chang, X., Yang, Q., Yang, Y., Liu, Z., Cleverly, J., Eamus, D., 2016.
586 Evapotranspiration partitioning, stomatal conductance, and components of the water balance:
587 A special case of a desert ecosystem in China. *J. Hydrol.* 538, 374-386.

588 Zheng, C., Wang, Q., 2014. Water-use response to climate factors at whole tree and branch scale
589 for a dominant desert species in central Asia: *Haloxylon ammodendron*. *Ecohydrology* 7,
590 56-63.

591 Zhou, S., Yu, B., Zhang, Y., Huang, Y., Wang, G., 2016. Partitioning evapotranspiration based on
592 the concept of underlying water use efficiency. *Water Resour. Res.* 52, 1160-1175.

593 Zhu, X., Yu, G., Hu, Z., Wang, Q., He, H., Yan, J., Wang, H., Zhang, J., 2015. Spatiotemporal
594 variations of T/ET (the ratio of transpiration to evapotranspiration) in three forests of Eastern

595 China. Ecol. Indic. 52, 411-421.

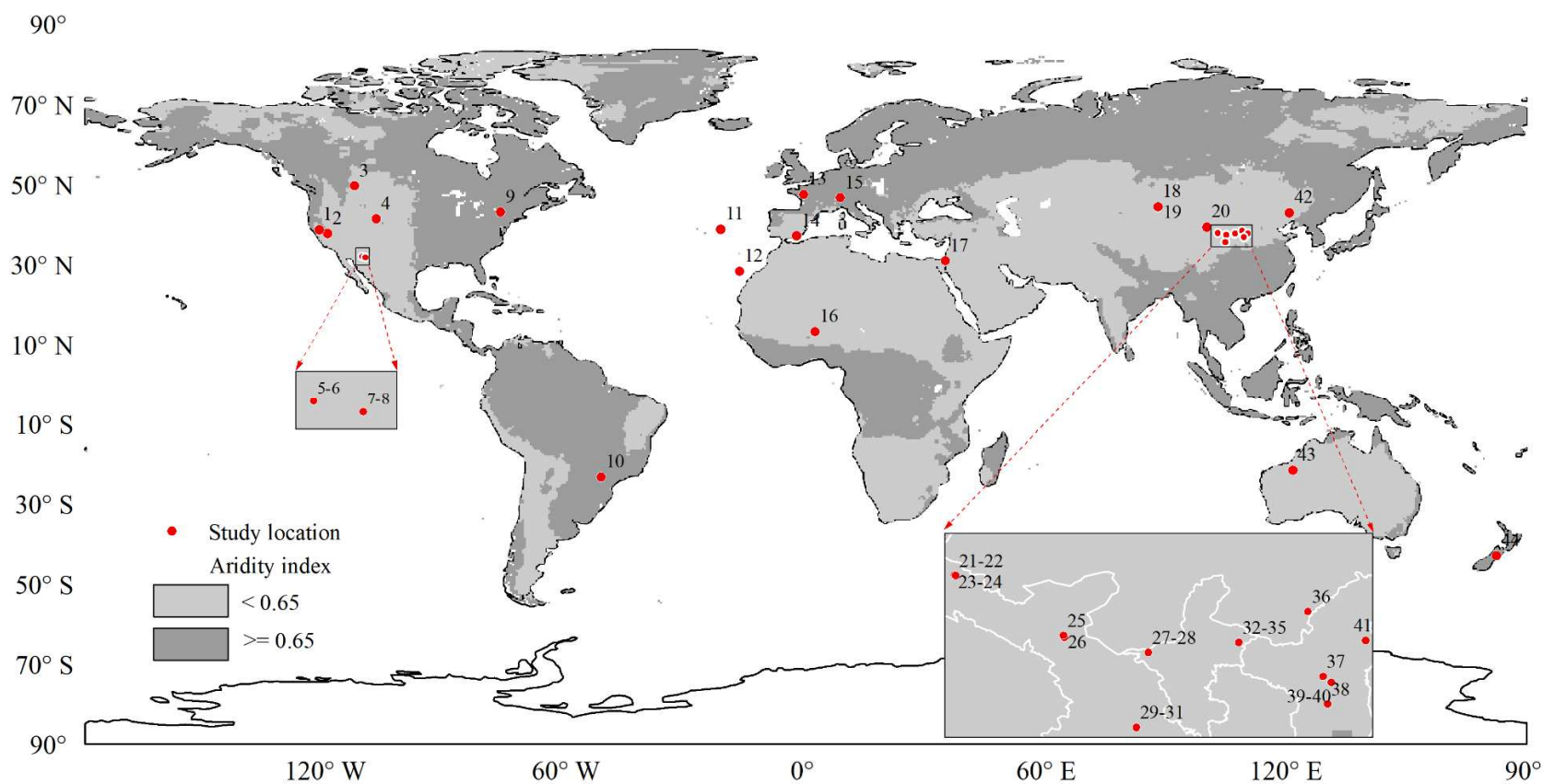


Figure 1. Study locations of 43 published articles related to transpiration of shrub ecosystems across the world. Each location was represented by a red point and by its reference number (see Table 1). Light grey corresponds to drylands with aridity index (ratio between precipitation and potential evapotranspiration) < 0.65 and dark grey corresponds to non-drylands with aridity index ≥ 0.65 .

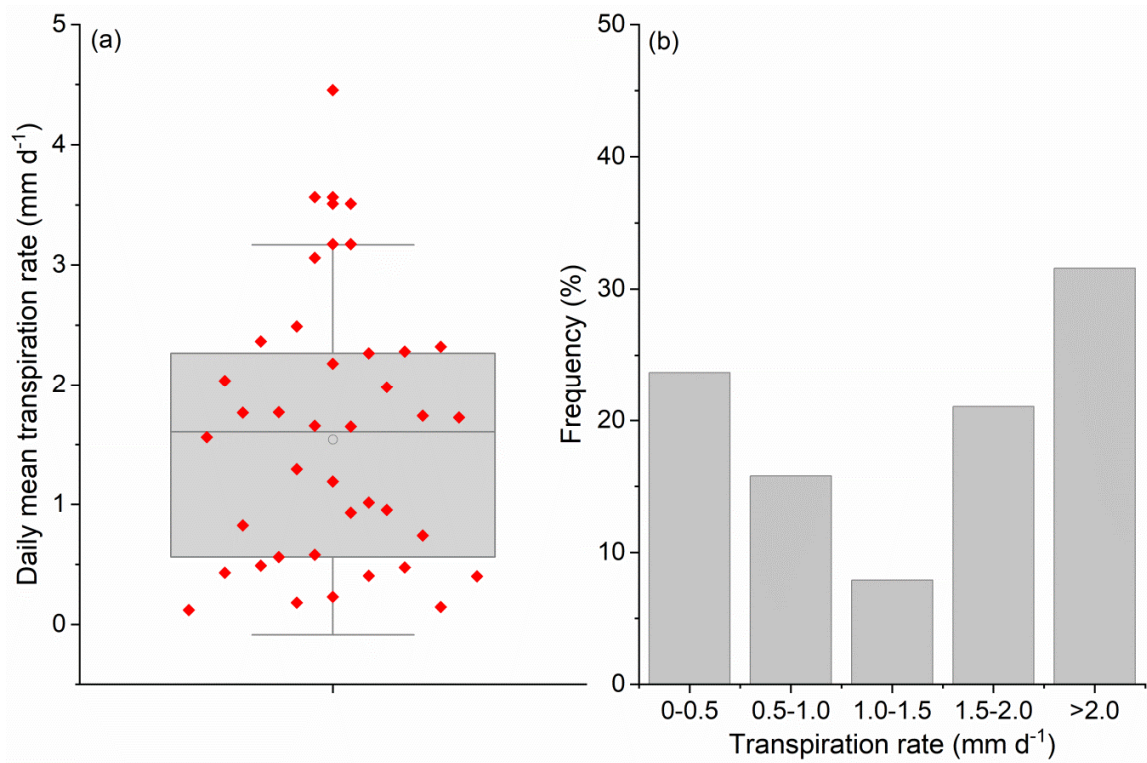


Figure 2. (a) Box-and-whisker diagrams showing mean, standard deviation and the 25, 50 and 75 percentiles for daily mean transpiration rate of shrubs, and (b) frequency distribution of daily mean transpiration rate of shrubs at different classes.

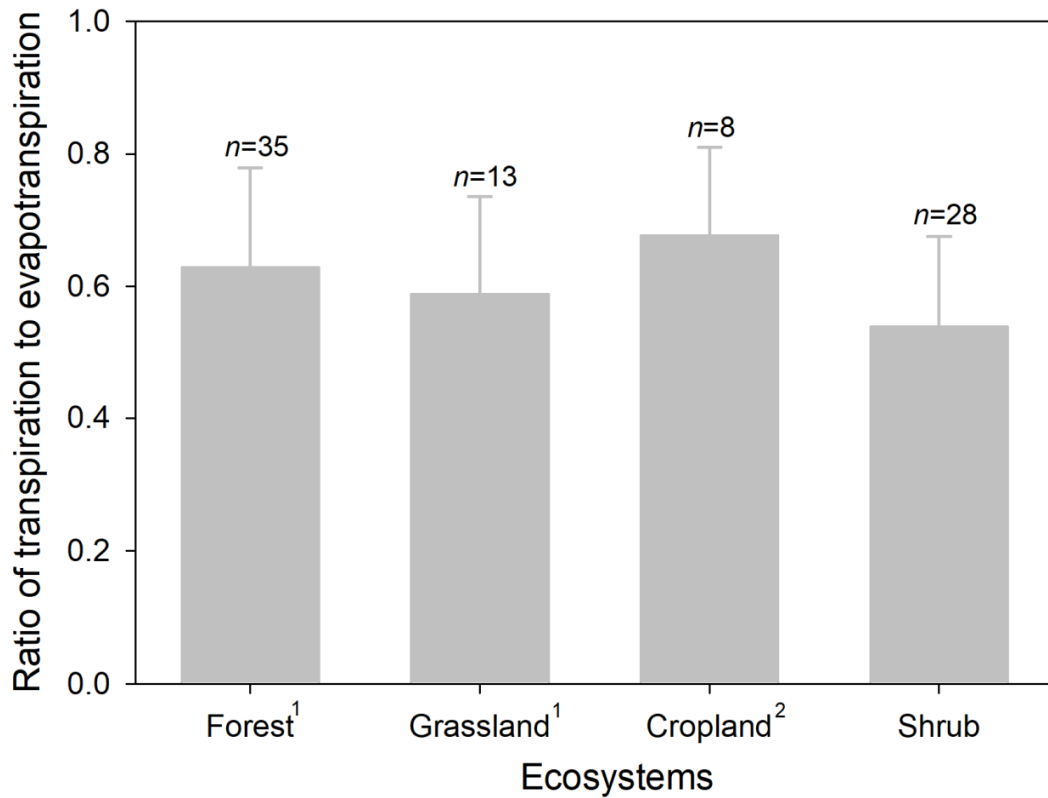


Figure 3. Comparison of the ratio of transpiration to evapotranspiration (T/ET) (mean±standard deviation) over growing season between shrub ecosystem and other ecosystems. Note: 1. T/ET of forest and grassland ecosystems was from Schlesinger and Jasechko (2014); 2. T/ET of cropland ecosystem was from Sun et al. (2019).

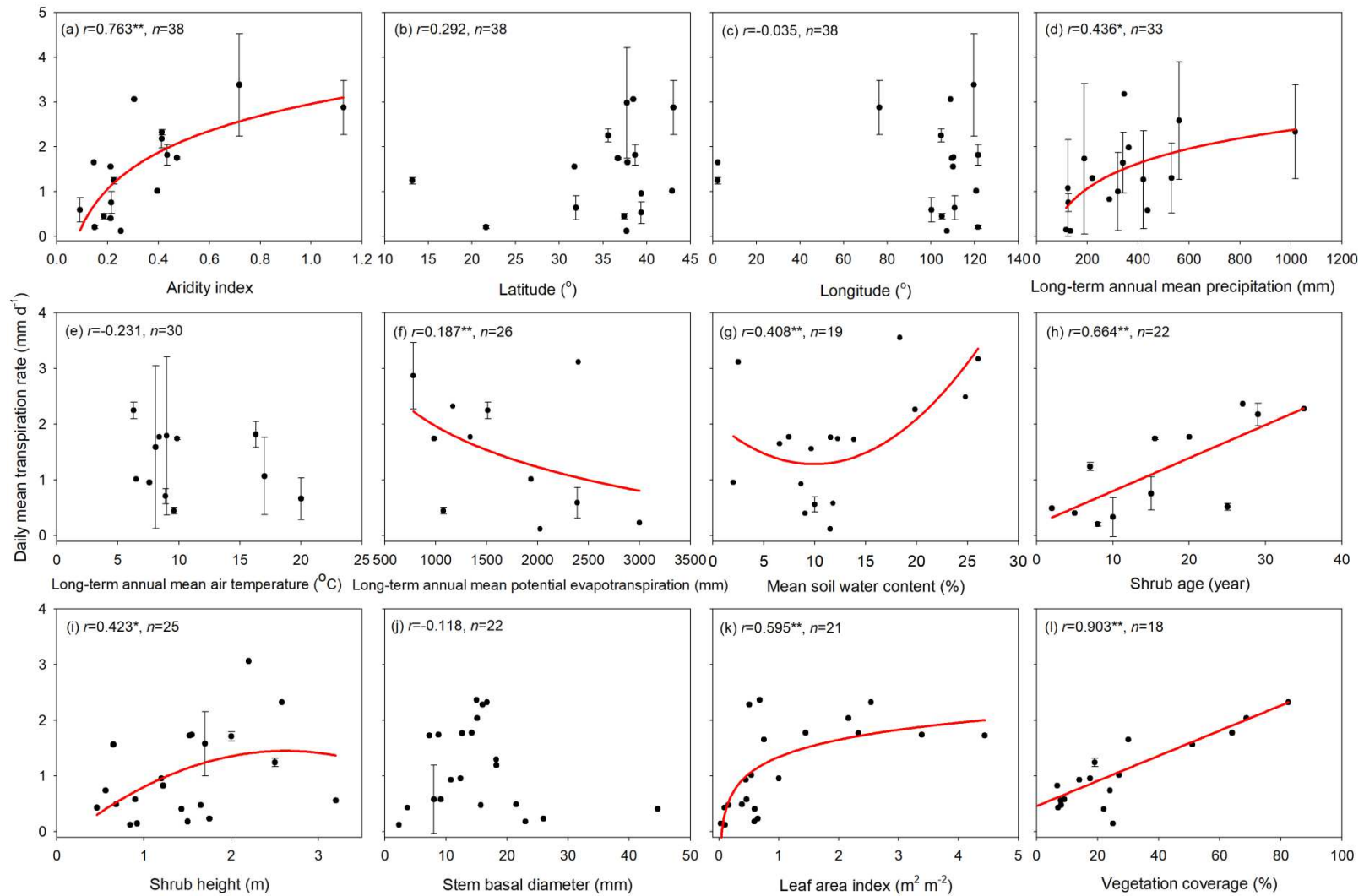


Figure 4. Relationships between daily mean transpiration rate (mean \pm standard deviation) of shrubs and influencing abiotic and biotic factors: (a) aridity index, (b) latitude, (c) longitude, (d) long-term annual mean precipitation, (e) long-term annual mean air temperature, (f) long-term annual mean potential evapotranspiration, (g) mean soil water content, (h) shrub age, (i) shrub height, (j) stem basal diameter, (k) leaf area index, and (l) vegetation coverage.

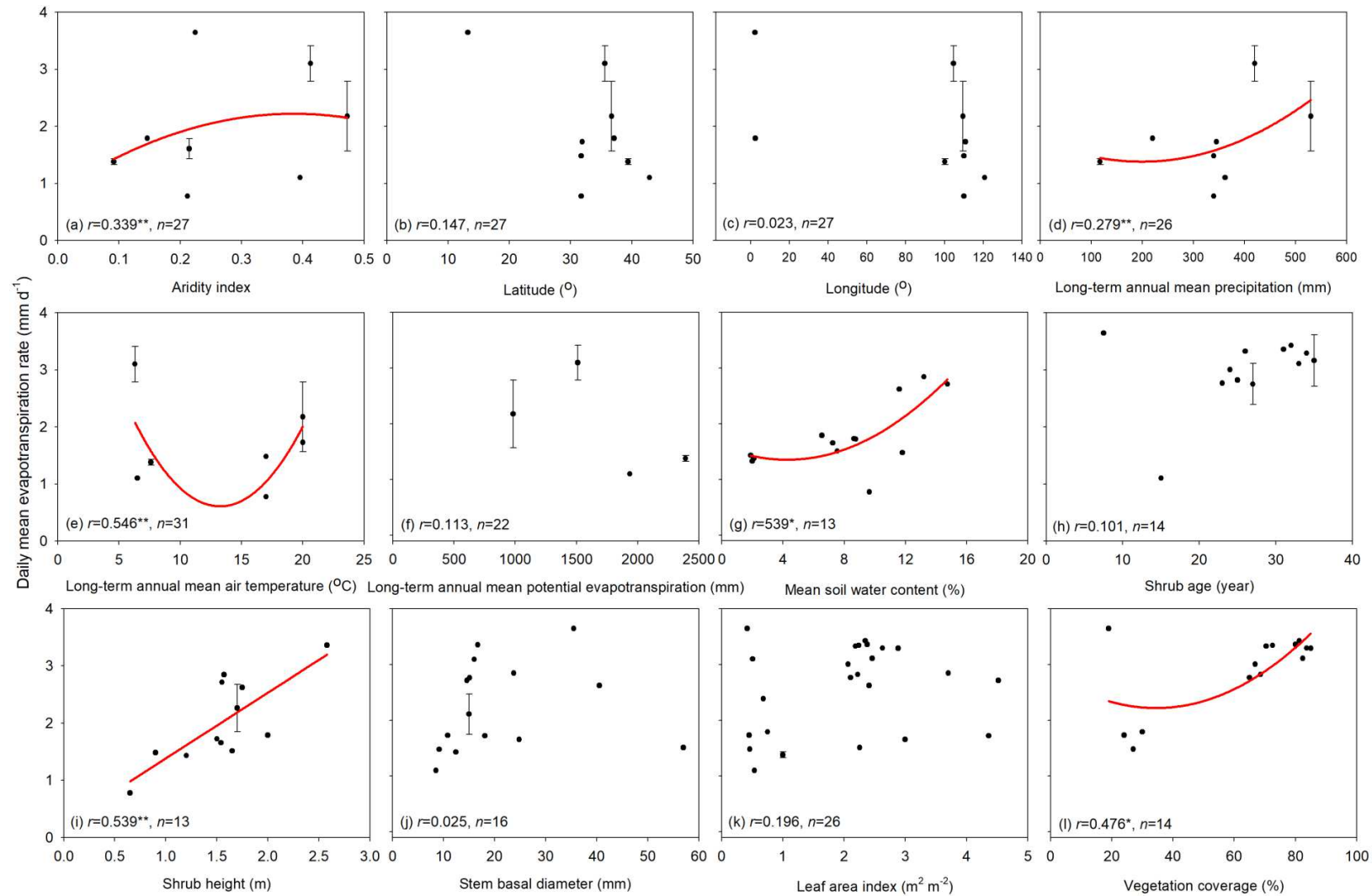


Figure 5. Relationships between daily mean evapotranspiration rate (mean±standard deviation) of shrubs and influencing abiotic and biotic factors: (a) aridity index, (b) latitude, (c) longitude, (d) long-term annual mean precipitation, (e) long-term annual mean air temperature, (f) long-term annual mean potential evapotranspiration, (g) mean soil water content, (h) shrub age, (i) shrub height, (j) stem basal diameter, (k) leaf area index, and (l) vegetation coverage.

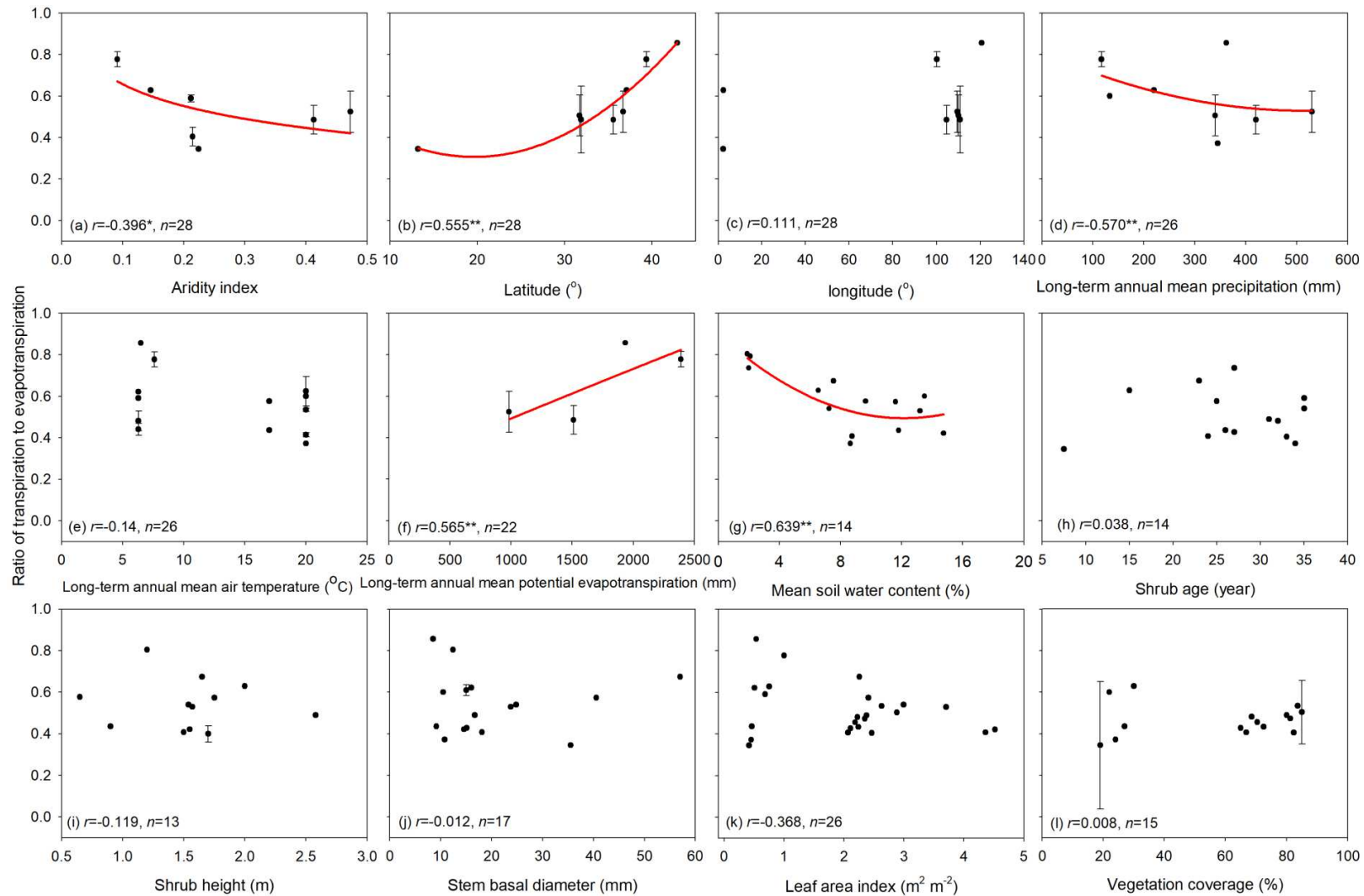


Figure 6. Relationships between ratio of transpiration to evapotranspiration (mean±standard deviation) of shrubs and influencing abiotic and biotic factors: (a) aridity index, (b) latitude, (c) longitude, (d) long-term annual mean precipitation, (e) long-term annual mean air temperature, (f) long-term annual mean potential evapotranspiration, (g) mean soil water content, (h) shrub age, (i) shrub height, (j) stem basal diameter, (k) leaf area index, and (l) vegetation coverage.

Table 1 Detailed information of the 43 published articles related to transpiration of shrubs in this synthesis.

No.	Reference	Location	MAP (mm)	MAT (°C)	Soil texture	Species	Study period	Measurement method	Study scale	Upscale basis	SF density (g cm ⁻² d ⁻¹)	SF volume (ml d ⁻¹)	T rate (mm d ⁻¹)
1	Fisher et al. (2007)	Blodgett Forest, USA (38.68°N, 121.58°W)	560	16.3	Silty loam	<i>Arctostaphylos manzanita</i>	March-December, 2005	HPM	Plant	-	0-94.8	-	-
						<i>Ceanothus cordulatus</i>					0-78.7	-	-
2	Steinwand et al. (2001)	Owens Valley, USA (37.73°N, 119.57°W)	-	-	-	<i>Atriplex lentiformis</i>	March-October	Chamber	Stand	LA	-	-	0-4.36
						<i>Chrysothamnus nauseosus</i>					-	-	0-8.91
						<i>Sarcobatus vermiculatus</i>					-	-	0-7.02
3	Letts et al. (2010)	Oldman River Valley, Canada (49.63°N, 112.83°W)	386	5.7	Chernozems	<i>Artemisia cana pursh</i>	July-September, 2008	HBM	Plant	-	0-587.8	-	-
						<i>Rhus trilobata Nutt</i>					0-664.1	-	-
4	Naithani et al. (2012)	Sierra Madre Mountain, USA (41.38°N, 107.38°W)	341	6.2-7.2	Clay loam	<i>Artemisia tridentata</i>	May-October, 2005	HBM	Plant	LA	723.6-4046.4	-	-
5	Cavanaugh et al. (2011)	Creosote site, USA (31.9°N, 110.83°W)	345	20	Sandy loam	<i>Larrea tridentata</i>	Summer, 2008	HBM	Stand	CSA	-	-	0-1.86
6	Szutu and Papuga (2019)	Creosote site, USA (31.9°N, 110.83°W)	345	20	Sandy loam	<i>Larrea tridentata</i>	July, 2014-March 2015	HBM	Stand	CSA	-	-	0-0.8
7	Cavanaugh et al. (2011)	Lucky Hills site, USA (31.73°N, 110.05°W)	340	17	Coarse loam	<i>Larrea tridentata</i>	Summer, 2008	HBM	Stand	CSA	-	-	0.08-1.08
8	Scott et al. (2006)	Lucky Hills site, USA (31.73°N, 110.05°W)	340	17	Sandy loam	<i>Larrea tridentata</i>	July-October, 2003	HBM	Stand	CSA	-	-	0.01-3.11
9	Mirck and Volk (2009)	Solvay, USA (43.07°N, 76.25°W)	1017	9	-	<i>Salix miyabeana</i>	June-November, 2006 and 2007	HBM	Stand	CSA	-	-	0.07-4.91
						<i>Salix sachalinensis</i>					-	-	0.15-4.38
						<i>Salix sachalinensis</i> and <i>Salix miyabeana</i>					-	-	0.11-7.00
						<i>Salix purpurea</i>					-	-	0.27-6.08
10	Flumignan and Faria (2011)	Londrina, Brazil (23.30°S, 51.15°W)	1400-1600	21.5	Red Latosol	<i>Coffea arabica</i>	September 2004-August 2006	WBM, ML	Stand	-	-	-	0.81-3.84

11	Prieto et al. (2010)	Rambla Honda, Spain (38.8°N, 21.36°W)	250	18.2	Loamy sand	<i>Retama sphaerocarpa</i>	Spring and Autumn, 2006 and 2007	HBM	Plant	-	-	112.1-405.8	-	
12	González-Rodríguez et al. (2017)	Canary Islands, Spain (28.3°N, 16.57°W)	300	10.4	-	<i>Spartocytisus supranubius</i>	April 2013-December 2014	CHM	Plant	-	4.0-100.7	-	-	
13	Guérin et al. (2007)	Angers, France (47.5°N, 0.58°W)	802	-	-	<i>Ligustrum ovalifolium</i>	March-July, 2002	HBM	Plant	-	-	0-866.4	-	
14	Domingo et al. (1999)	Rambla Honda, Spain (37.13°N, 2.37°W)	220	-	Loamy sand	<i>Retama sphaerocarpa</i>	March-May, 1997	HBM	Stand	LA	-	-	1.34-1.96	
15	van den Bergh et al. (2018)	Ursern valley, Swiss (46.6°N, 8.57°E)	1485	-	Loamy sand	<i>Alnus viridis</i>	May-September, 2010 and 2011	HBM	Plant	LA	-	0-3694.6	-	
16	Allen and Grime (1995)	Sadoré, Niger (13.23°N, 2.23°E)	-	-	Coarse sand	<i>Guiera senegalensis</i>	May-October, 1990	HBM	Stand	LA	-	0-16540.8	0.71-1.67	
									Stand	CSA	-	-	0.38-2.21	
17	Terwilliger and Zeroni (1994)	Sede Boker, Israel (30.88°N, 34.77°E)	-	-	-	<i>Zygophyllum dumosum</i>	Summer, 1989	Chamber	Plant	-	0-1.16	-	-	
18	Xu et al. (2007)	Fukang, China (44.28°N, 87.93°E)	161	6.6	Saline-alkali soil	<i>Tamarix ramosissima</i>	April-September, 2005	HPM	Plant	LA	0.32-0.89	-	-	
											0.28-0.32	-	-	
19	Zheng and Wang (2014)	Gurbantünggüt Desert, China (44.42°N, 87.9°E)	200	6.9	Sand	<i>Haloxyylon ammodendron</i>	Growing season, 2009-2011	HBM	Plant	-	-	795.4-8691.8	-	
20	Zhao et al. (2016)	Heihe River, China (39.38°N, 100.13°E)	116.8	7.6	Sand	<i>Calligonum mongolicum</i>	May-October, 2008-2010	HBM	Stand	CSA	-	-	0.38-1.53	
21	Xu et al. (2017)	Linze, China (39.37°N, 100.13°E)	125	8.9	Loamy sand	<i>Haloxyylon ammodendron</i>	May-October, 2014 and 2015	HBM	Stand	CSA	-	-	-	0-1.12
											-	-	-	0.05-1.43
											-	-	-	0-1.65
22	Ji et al. (2016)	Linze, China (39.37°N, 100.13°E)	123.5	9	Loamy sand	<i>Haloxyylon ammodendron</i>	May-October, 2014	HBM	Stand	CSA	0.46-38.5	-	0.01-0.94	
											0.62-80.29	-	0.01-0.85	
											0.8-90.33	-	0.01-0.28	
23	Liu et al. (2011)	Linze, China (39.37°N, 100.11°E)	116.8	7.6	Sand	<i>Nitraria sphaerocarpa</i>	June-October, 2008	HBM	Plant	-	8.61-110.89	-	-	
											14.32-316.73	-	-	

24	Zhao and Liu (2010)	Linze, China (39.37°N, 100.11°E)	116.8	7.6	Sand	<i>Nitraria sphaerocarpa</i> <i>Elaeagnus angustifolia</i>	June-October, 2008	HBM	Plant	-	15.7-110.9 6.7-316.7	-	-
25	Qu et al. (2007)	Wuwei, China (37.87°N, 102.83°E)	164.4	8	-	<i>Tamarix ramosissima</i>	April-October, 2004	HPM	Plant	-	-	2960-5210	-
26	Xia et al. (2008)	Tenger Desert, China (37.83°N, 102.85°E)	160	8	Sand	<i>Caragana korshinskii</i>	April-October, 2004	HBM	Plant	-	-	2800-4200	-
27	Huang et al. (2014)	Shapotou, China (37.45°N, 104.95°E)	188.2	9.6	Sand	<i>Caragana korshinskii</i> <i>Artemisia ordosica</i>	April-October, 2008-2012	HBM	Stand	LA	0.2-1.82 0.58-2.31	-	0.06-0.75 0-0.98
28	Huang et al. (2010)	Shapotou, China (37.45°N, 104.95°E)	187	-	Sand	<i>Artemisia ordosica</i>	May-October, 2004	HBM	Plant	-	-	37.5-350	-
29	Jian et al. (2014)	Dingxi, China (35.58°N, 104.65°E)	420	6.3	Silty loam	<i>Caragana korshinskii</i> <i>Hippophae rhamnoides</i>	June- September, 2013	HBM	Stand	LA	-	-	0.52-4.21 0.57-3.99
30	Jian et al. (2015)	Dingxi, China (35.58°N, 104.65°E)	420	6.3	Silty loam	<i>Caragana korshinskii</i> <i>Hippophae rhamnoides</i>	May-September, 2009-2013	HBM	Stand	LA	-	-	0.12-3.95 0.29-4.35
31	Jian et al. (2016)	Dingxi, China (35.58°N, 104.65°E)	420	6.3	Silty loam	<i>Caragana korshinskii</i> <i>Hippophae rhamnoides</i>	June- September, 2012	HBM	Plant	-	42.3-349.3 45.1-332.4	-	-
32	Zha et al. (2017)	Yanchi, China (37.7°N, 107.22°E)	287	8.1	Sand	<i>Artemisia ordosica</i>	May-September, 2013 and 2014	HBM	Stand	LA	-	-	0-0.24
33	Qian et al. (2015)	Yanchi, China (37.7°N, 107.22°E)	292	8.1	Sand	<i>Hedysarum mongolicum</i>	June-October, 2012	HBM	Plant	-	30-1000	-	-
34	Deng et al. (2015)	Yanchi, China (37.7°N, 107.22°E)	287	8.1	Dark loessial soil	<i>Hedysarum scoparium</i>	May-October, 2011	HBM	Plant	-	-	720-12890	-
35	Hayat et al. (2020)	Yanchi, China (37.7°N, 107.22°E)	287	8.1	Sand	<i>Salix psammophila</i>	May-September, 2012-2017	HBM	Plant	LA	0.01-0.63	-	-
36	Huang et al. (2015)	Haililutu catchment, China (38.47°N, 108.94°E)	340	8.1	Sand	<i>Salix psammophila</i>	May-July, 2011	HBM	Stand	NB	-	-	0-6.24
37	Fang et al. (2017)	Yan'an, China (36.7°N, 109.52°E)	530	10.6	Silty loam	<i>Vitex negundo</i> <i>Hippophae rhamnoides</i> <i>Spiraea pubescens</i>	June-September, 2015	HBM	Plant	-	203.5-905.8 9.2-540.9 54.5-228.7	-	-

38	Fang et al. (2019)	Yan'an, China (36.7°N, 109.52°E)	530	10.6	Silty loam	<i>Vitex negundo</i>	June-September, 2015 and 2016	HBM	Stand	CSA	-	-	0.09-3.39
						<i>Hippophae rhamnoides</i>					-	-	0.05-3.48
						<i>Spiraea pubescens</i>					-	-	0.07-3.38
39	Wang et al. (2020)	Shenmu, China (38.81°N, 110.37°E)	437	8.4	Sand	<i>Caragana korshinskii</i>	June-September, 2015 and 2016	HBM	Plant	-	-	50.8-2756.9	-
						<i>Salix psammophila</i>				-	-	85.1-2753.4	-
40	Wu et al. (2018)	Ansai, China (36.85°N, 109.31°E)	500	8.8	Silty loam	<i>Hippophae rhamnoides</i>	June-August, 2015	CHM	Plant	-	0-8.5	-	-
41	She et al. (2012)	Yulin, China (37.75°N, 110.37°E)	437	8.4	Sandy loam	<i>Caragana korshinskii</i>	May-October, 2006	HBM	Stand	CSA	-	-	0-3.54
42	Yue et al. (2008)	Naiman, China (42.91°N, 120.7°E)	362	6.5	Sand	<i>Caragana microphylla</i>	June- September, 2006	HBM	Stand	LA	-	-	0.04-1.99
43	Gwenzi et al. (2014)	Pilbara region, Australia (21.58°S, 121.52°E)	320	-	-	<i>Acacia bivenosa</i>	October 2008-October 2009	CHM	Stand	CSA	-	-	0.14-0.32
44	Dudley et al. (2018)	Lang's Gully, New Zealand (42.93°S, 172.42°E)	943	9.4	Silty loam	<i>Discaria toumatou</i>	December 2014- May 2016	HPM	Plant	-	-	0-980	-

Note: MAP, long-term mean annual precipitation; MAT, long-term mean annual temperature; HBM, heat balance method; HPM, heat pulse method; CHM, constant heater method; WBM, water balance method; ML, micro-lysimeter; CSA, cross-sectional area; LA, leaf area; NB, number of branches; SF, sap flow; T, transpiration.

Table 2. Detailed information of the ten published articles on evapotranspiration partitioning of shrubs in this synthesis.

No.	Reference	Location	MAP (mm)	MAT (°C)	Soil texture	Species	Study period	Measurement methods			Value during the study period				
								ET	E	T	P (mm)	T (mm)	ET (mm)	ET/P	T/ET
1	Allen and Grime (1995)	Sadorê, Niger (13.23°N, 2.23°E)	-	-	Coarse sand	<i>Guiera senegalensis</i>	May-October, 1995	EC	-	SF	454	158	459	1.01	0.34
2	Domingo et al. (1999)	Rambla Honda, Spain (37.13°N, 2.37°W)	220	-	Loamy sand	<i>Retama sphaerocarpa</i>	March-May, 1997	BREB	ML	SF	83	101.1	161	1.94	0.63
3	Scott et al. (2006)	Lucky Hills site, USA (31.73°N, 110.05°W)	340	17	Sandy loam	<i>Larrea tridentata</i>	June-October, 2003	EC	-	SF	176	121	210	1.19	0.58
4	Yue et al. (2008)	Naiman, China (42.91°N, 120.7°E)	362	6.5	Sand	<i>Caragana microphylla</i>	June, 2006	WL	-	SF	62.4	113	132	2.12	0.86
5	Cavanaugh et al. (2011)	Creosote site, USA (31.9°N, 110.83°W)	345	20	Sandy loam	<i>Larrea tridentata</i>	Summer, 2008	EC	-	SF	259.6	54.7	147.1	0.57	0.37
		Lucky Hills site, USA (31.73°N, 110.05°W)	340	17	Coarse loam			EC	-	SF	211.8	44.5	102.2	0.48	0.44
6	Zhao et al. (2016)	Heihe River, China (39.38°N, 100.13°E)	116.8	7.6	Sand	<i>Calligonum mongolicum</i>	May-October, 2008-2010	-	ML	SF	104.9-113.8	146.8-172.7	199.4-214.8	1.75-2.06	0.73-0.80
7	Jian et al. (2015)	Dingxi, China (35.58°N, 104.65°E)	420	6.3	Silty loam	<i>Caragana korshinskii</i>	May-September, 2009-2013	-	ML	SF	215.1-458.8	180.7-231.7	422.9-510.7	1.11-1.97	0.41-0.48
						<i>Hippophae rhamnoides</i>		-	ML	SF	215.1-458.8	192.5-268.8	475.5-523.9	1.09-2.39	0.41-0.53
8	Jian et al. (2014)	Dingxi, China (35.58°N, 104.65°E)	420	6.3	Silty loam	<i>Caragana korshinskii</i>	June-September, 2013	-	ML	SF	268	173.4	293.4	1.09	0.59
						<i>Hippophae rhamnoides</i>			ML	SF	268	236.6	380.7	1.42	0.62
9	Szutu and Papuga (2019)	Creosote site, USA (31.9°N, 110.83°W)	133	20	Sandy loam	<i>Larrea tridentata</i>	July 2014-March 2015	EC	-	SF					0.6
10	Fang et al. (2019)	Yan'an, China (36.7°N, 109.52°E)	530	10.6	Silty loam	<i>Vitex negundo</i>	June-September, 2015 and 2016	-	ML	SF	123-302.6	107.2-180.6	198.5-341.1	1.13-1.61	0.52-0.54
						<i>Hippophae rhamnoides</i>			ML	SF		122.3-180.3	181.4-314.4	1.04-1.47	0.57-0.67
						<i>Spiraea pubescens</i>			ML	SF		84.1-137.02	206.7-325.3	1.07-1.68	0.41-0.42

Note: MAP, long-term mean annual precipitation; MAT, long-term mean annual temperature; ET, evapotranspiration; E, soil evaporation; T, transpiration; P, precipitation; EC, eddy covariance method; BREB, Bowen ratio energy balance; WL, weighing lysimeter method; ML, micro-lysimeter.