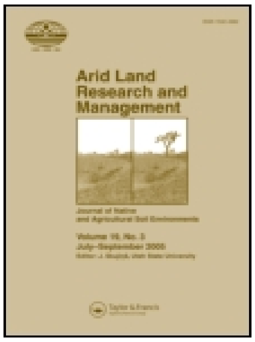

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Partitioning evapotranspiration of desert plants under different water regimes in the inland Heihe River Basin, Northwestern China

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ABSTRACT
Plant transpiration (T), soil evaporation (E), and the proportion of evaporation in evapotranspiration (ET), and their patterns of change were analyzed in a desert habitat along the middle and lower reaches of the Heihe River Basin, Gansu Province, China. Typical desert plants with different life forms were selected and small lysimeter observations were conducted; various species were measured under two soil water regimes using 50% (FC 50%) and 20% (FC 20%) of field capacity in 2 years. Under the FC 50% treatment the observed ratio of T to ET of desert plants was less than one-third, making the ratio of E to ET greater than two-thirds; the proportion of T to ET of desert plants increased to above 40%, and that of E declined to below 60% under the FC 20% treatment. The lowest T of desert plants was 130–140 mm based on the plant crown projection area. The characteristic coefficient of ET of desert plants was twice that of the characteristic coefficient of transpiration. This study found that when ET was measured for the same desert plant species growing in different regions, the ET differed significantly ($P < 0.05$) under the same water regimes; when comparing different plant species in the same region no obvious differences in the transpiration water requirement and ET were observed. The proportion of T in ET increased significantly and E in ET decreased markedly ($P < 0.05$), if the soil moisture content declined to where the plants experienced water stress.

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KEYWORDS
Characteristic coefficient; Heihe River; plant transpiration; soil evaporation; water consumption; water requirement

Water is the most important factor limiting ecosystem diversity and productivity worldwide (Engelbrecht 2012). The water requirements of plants can be expressed in two aspects. First, physiological water requirement of a plant, that is, plants need water to sustain their physiological activities, including plant transpiration, plant surface evaporation, and water consumption needed for plant development mainly in the form of transpiration (T). Second, ecological water consumption refers to soil evaporation (E), which is the water consumption needed to maintain environmental conditions that plants require to sustain growth. The sum of these two is evapotranspiration (ET).

Drought reduces plant productivity, causes plant death and limits plant geographic distribution (Zhao and Running 2010; Blackman, Brodribb, and Jordan 2011). Desert

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ecosystems cover about one-third of the earth's land surface (Newingham et al. 2013). The functions of desert ecosystems are often overlooked because of their sparse vegetation (Newton 2008; Wohlfahrt, Fenstermaker, and Arnone 2008). Desert plants very commonly exhibit self-thinning phenomena; plant density, canopy, and height are all restricted by the water regime (Chang et al. 2012). The need to carry on transpiration creates a physiological water requirement for the plant itself. A plant's transpiration rate can reflect its ability to adapt to both water loss and arid environments; this rate serves as an important physiological index that can be used to measure the plant's water balance, and is also an important basis for plant adaptability and natural selection (Wang et al. 2007).

Desert plants are well-adapted to arid environments and use different mechanisms adapt to water stress (Roy and Mooney 1982; Su et al. 2007). The ability of plants to regulate their demand for water required for transpiration is directly related to their ability to survive and even thrive in arid environments. ET in Mojave Desert plants in the southwestern United States is largely dependent on winter precipitation and the amount of soil water available during the growing season rather than on species composition (Yoder and Nowak 1999). Under natural conditions, many halophytes have low to moderate rates of growth and water consumption, because they generally occur in high-stress environments (Mata-Gonzalez, McClendon, and Martin 2005; Soliz et al. 2011). *Tamarix ramosissima*, an azonal salt-tolerant shrub, does not consume large amounts of water, but does have higher water use efficiency when compared with trees (Glenn and Nagler 2005). ET in this species also varies widely depending on whether the plant grows in a drought or wet year; ET declined dramatically in a drought year to approximately half of that in a wet year (Devitt et al. 1998).

Desert plants grow in harsh environments and experience high temperatures and light stress in summer as well as perennial long-term drought (Su et al. 2007); different species exhibit different water use strategies (Zhou et al. 2014). Accurate ET data are lacking for many desert plants, especially as they relates to the partitioning of ET. How does T and ET of desert plants in an inland river basin change over time? What is the proportion of T in ET? Can the differences in the water requirements and the water consumption patterns of different species in the same habitat be compared? How does a single species adapt its T, E, and ET to different habitat conditions? We hypothesized that desert plants have significantly lower T and no significant difference occurs among different species under drought stress condition. We preliminary believed that E of desert plants forms the major proportion of ET. To test this hypothesis, we used measurements from small lysimeters to distinguish the T and E and to confirm our preliminary expectations about water use in desert plants.

Materials and methods

Study area

The study area is located in a typical inland river basin, the Heihe River Basin, in the arid region of northwestern China. The Qilian Mountains in the upper reach of the Heihe River are located on the northeastern margin of the Qinghai-Tibetan Plateau; they serve as the water source for the middle and lower reaches of this river. The middle reach lies in the southern edge of the Badain Jaran Desert and mainly comprises oases and desert; the lower reach, comprising mainly desert and riparian forest, lies in the northern part of the Badain

Jaran Desert and adjoining areas. The middle reach is in an arid desert region in the temperate zone, with an average daily temperature (Ta) of 7.6°C, and annual precipitation (P) of 100–120 mm; however, the potential evaporation (ET_t) is nearly 20 times that of precipitation. The lower reach is in an area of extremely arid desert in the temperate zone, with a Ta of 8.3°C, and P of 30–40 mm; the ET_t is nearly 100 times that of P (Su and Yan 2008). Zonal grey-brown desert soil covers the middle and lower reaches. The groundwater table falls as the vertical distance to the river increases. The depth to the groundwater varies from 2.0 to 5.5 m at a typical oasis in the middle reach and 1.5 to 4.5 m for typical riparian forest in the lower reach. The richness of desert species, which do not rely on groundwater for survival, is significantly higher in the middle reach than that in the lower reach.

Experimental design and plant species

Measurements were conducted in the middle and lower reaches of the Heihe River Basin. Experimental field observations were conducted with small lysimeters that had been designed for this study to observe the water requirements and consumption of desert plants. The small lysimeters were composed of two 40 cm tall galvanized sheet iron cylinders, with the inner and outer cylinder having inside diameters of 30 and 31 cm, respectively. A total of 114 small lysimeters were split into two groups. A total of 54 sets were placed at the Linze Inland River Basin Research Station in the middle reach of the Heihe River (39°20′57″N, 100°07′43″E, 1380 m a.s.l.), and 60 at the Alashan Desert Eco-hydrology Experimental Research Station in the lower reach of the Heihe River (42°02′03″N, 101°03′06″E, 923 m a.s.l.). In each case, the outer cylinders were embedded in an observation field with 1 × 1 m spacing, and were positioned along the same plane as the surrounding field surface. The inner cylinder was inserted into the outer cylinder and could be removed for weighing.

Desert plants produce a very small amount of biomass annually making their actual age difficult to determine, so three plants were selected for analysis with the same growth pattern and vigor, having a 30 cm crown breadth and a height below 50 cm. The selected plants were transplanted into individual lysimeters to represent three repetitions of the experiment. After transplanting, each lysimeter was filled with sandy soil that was typical of soils from the middle and lower reaches of the Heihe River for the respective areas. Three empty lysimeters were placed in an observation field to measure sediment sand during the windy season and precipitation during the observation period. Three lysimeters were supplied with the same amount of water and were filled with sandy soil using the same volume but without any plants to measure soil evaporation as a control experiment.

In a typical agricultural research, the soil moisture content should be maintained at around 70–80% of field capacity to meet needs of crops for normal growth and development (Su et al. 2002; Masinde et al. 2005). Desert plants grow in a harsh droughty environment where they have adapted to low moisture environments (Su et al. 2007). In *Haloxylon ammodendron*, a typical desert plant of the middle reach of the inland Heihe River Basin, the leaf and canopy photosynthetic rates and the photosynthetic capacity will peak when soil moisture content is maintained at (50 ± 10)% of field capacity. If soil moisture increases or decreases, the photosynthetic capacity of *H. ammodendron* declines (Gao et al. 2010). Meanwhile, based on the current field investigation and previous experiments, most desert species suffered severe water stress when soil moisture content was maintained at approximately 20% of field capacity. Based on these data, experiments related to the water requirements and consumption patterns of desert plants were carried out in 2011 with (50 ± 10)% of field capacity (FC 50%), and in 2012 with (20 ± 5)% of field capacity (FC 20%) of soil moisture content maintained, which represented moderate moisture and drought stress, respectively. Measurements of water supply under natural conditions were performed once every 3–5 days during the growing season using TC-60 K large scale electronic balances with 1 g precision (Gandg Measurement Plant Manufacture, Changshu, Jiangsu, China). The amount of supplementary water needed was calculated by monitoring changes in lysimeter weight based on the designed water regimes. Irrigation water was added at a depth of 5 cm under the soil surface.

The sixteen species that were observed in the middle reach of Heihe River Basin were shrubs *Haloxylon ammodendron* (C. A. Mey.) Bge., *Hedysarum scoparium* Fisch. et Mey., *Caragana korshinskii* Kom.; subshrubs *Calligonum mongolicum* Turcz., *Calligonum potanini* A. Los., *Caragana stenophylla* Pojark., *Nitraria sphaerocarpa* Maxim., *Reaumuria soongorica* (Pall.) Maxim., *Ephedra przewalskii* Stapf, *Ephedra intermedia* Schrenk ex Mey.; semishrubs *Salsola passerina* Bunge, *Alhagi sparsifolia* Shap. ex Kell. et Shap., *Asterothamnus alyssoides* (Turcz.) Novopokr., *Artemisia sphaerocephala* Krasch.; and perennial herbs *Limonium aureum* (L.) Hill, *Clinelymus cylindricus* (Franch.) Honda.

The eighteen species that were observed in the lower reach were shrub *H. ammodendron*; subshrubs *C. mongolicum, N. sphaerocarpa, Nitraria sibirica* Pall., *R. soongorica, E. przewalskii, Lycium ruthenicum* Murr.; semishrubs *A. sparsifolia, Artemisia arenaria* DC., perennial herbs *Karelinia caspica* (Pall.) Less., *Peganum harmala* L., *Peganum nigellastrum* Bge., *Sophora alopecuroides* L., *Achnatherum splendens* (Trin.) Nevski., *Agropyron desertorum* (Link) Schult. et Schult.; desert riparian trees *Populus euphratica* Oliv., *Elaeagnus angustifolia* L.; and azonal shrub *Tamarix ramosissima* Ledeb. Species that were observed simultaneously in both the middle and lower reaches were *H. ammodendron, C. mongolicum, E. przewalskii*, N. sphaerocarpa, and *R. soongorica*.

Experimental soil properties

The physical properties of typical sandy soils from the middle and lower reaches of the Heihe River Basin were measured. The height of capillary water rise was measured by an experimental setup which refers to Siebold et al. (1997); the sandy soil was manually packed in an organic glass tube (inner diameter, 5 cm; height, 100 cm), closed at its lower end by a pledget. This tube was then dipped in a container of water. Other indices were measured by cutting ring methods in the laboratory (Su et al. 2002). Height of capillary water rise was 65 and 50 cm for soil of the middle and lower reaches, respectively; soil bulk density was 1.58 and 1.67 g cm^{-3}, gravimetric percent in field capacity was 17.6 and 14.8 and saturation water content was 23.7 and 19.9 for soil from the middle and lower reaches, respectively. Sandy soil from the middle reach of the Heihe River had a higher soil capillary water rise, a lower soil bulk density, and a higher field capacity and saturated water content when compared with sandy soil from the lower reach.

An analysis of the distribution of soil particle size showed that, the content of silt and clay (diameter of < 0.05 mm) included 9.3% of total soil particles in soil from the middle reach of the Heihe River. This was 2.4 times higher than that in the lower reach of 3.9%. The content of fine sand (0.05–0.25 mm diameter) in the middle reach was 11.3% higher than that in the lower reach, accounting for 81.7 and 73.4% of all particles, respectively. The water retention capacity of soils in the middle reach was higher than that in the lower reach.

Calculation of transpiration, evapotranspiration, and characteristic coefficient

The water balance method was used to calculate ET [Eq. (1)]:

$$ET = \sum_{i=1}^{n} (LW_i - LW_{i+1} + W_{si} + P_i + S_{si}) \tag{1}$$

where ET is evapotranspiration or soil evaporation, LW_i is the i time weight of the weighing lysimeter, LW_{i+1} is the $(i+1)$ time weight of the weighing lysimeter, W_{si} is the amount of water supply between i and $(i+1)$ time, P_i is the precipitation between i and $(i+1)$ time, and S_{si} is sediment sand and between i and $(i+1)$ time. With kg used as the basic dimension of all weights, three digits were maintained after the decimal point, and ultimately, ET units were converted to mm based on the surface area of the lysimeter.

Soil evaporation was subtracted from ET to calculate transpiration.

Based on the transpiration and ET, the characteristic coefficient was calculated using Eq. (2):

$$K_p = \frac{ET_p}{ET_t} \tag{2}$$

where K_p is the characteristic coefficient of water requirement or water consumption, ET_p is the T or ET, and ET_t is the potential evaporation obtained from the evaporation pan by meteorological observation.

Statistical analysis

The determination of significant differences between T and ET of the same desert species in the middle and lower reaches was performed using a *t*-test. Different species which were in the same area were analyzed by single factor variance analysis, and a multiple comparison of various levels was made using Duncan's new multiple range test.

Results

Potential evaporation and soil evaporation in the middle and lower reaches of the Heihe River Basin

Annual precipitation in the middle reach of the Heihe River Basin was 100.6 mm in 2011 and 110.1 mm in 2012 (mean 105.4 mm), whereas in the lower reach, it was 32.6 and 30.1 mm (mean 31.4 mm), respectively. Precipitation in the middle reach was twice higher than that in the lower reach and this data was consistent with data from normal years.

The annual potential evaporation in the middle and lower reaches is showed in Figure 1A. Using the mean of both years, the average annual evaporation in the middle reach was 2141.7 mm. This could be divided into 1417.5 mm in the growing season from May to September and 724.2 mm in non-growing season (the remainder of the year). In the lower reach, the average annual evaporation was 2393.9 mm, with 1590.2 and 803.7 mm in the growing and non-growing seasons, respectively. Potential evaporation in the lower reach was calculated separately for annual, growing season and non-growing season measurement; it was found to be 11.8, 12.2, and 11.0% higher than that in the middle reach in the three time periods, respectively.

Soil evaporation and soil moisture content were closely related to the growing season as defined above. When soil moisture content increased, soil evaporation was intensified (Figure 1B). In the middle reach, when soil moisture content was FC 50% or FC 20% during the growing season, soil evaporation was 462.2 and 177.7 mm, respectively. The soil moisture content of the middle reach of the Heihe River decreased from 8.8 to 3.5% when FC 50% decreased to FC 20%, a decrease of 60%, and soil evaporation declined by 62%.

The soil evaporation in the lower reach was 547.9 mm in the growing season and decreased to 201.5 mm when the soil moisture content fell from FC 50% to FC 20% (Figure 1B). The soil moisture content of the lower reach of the Heihe River decreased from 7.4 to 3.0% when the soil moisture content fell from FC 50% to FC 20%, a decrease of 60%, and soil evaporation declined by 63%.

Under the same water regimes, soil evaporation in the lower reach was 18.5 and 13.4% higher than that in the middle reach under the FC 50% and FC 20% treatment, respectively. The increase in the rate of soil evaporation was higher than the increase in the soil moisture content, and this difference would be likely to increase markedly in more arid regions.

Transpiration and evapotranspiration of the same species in the middle and lower reaches of the Heihe River Basin

Several desert shrubs, *H. ammodendron, C. mongolicum, E. przewalskii, N. sphaerocarpa*, and *R. soongorica*, are widely distributed in the middle and lower reaches of the Heihe River Basin. Synchronous measurement showed that transpiration water requirements of these five species of shrubs in the middle reach under the FC 50% treatment were

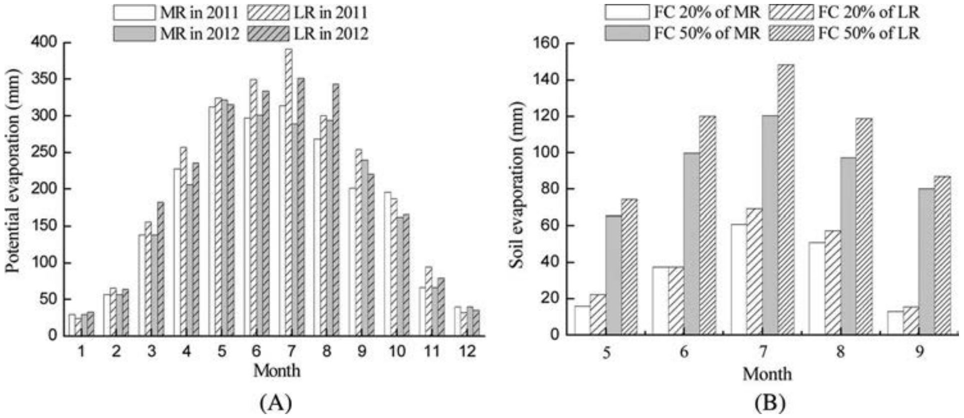

Figure 1. Potential evaporation (A) and soil evaporation under different soil water regimes (B) in the middle (MR) and lower reaches (LR) of the Heihe River Basin. FC 20% and FC 50% indicate soil moisture content was at (20 ± 5) and (50 ± 10)% of field capacity, respectively.

significantly greater than that in the lower reach under FC 50% and in the same region under FC 20%. The ET of these shrubs always increased significantly when soil moisture content was high, so it would decline with decreasing soil moisture content (Figure 2).

The T of *H. ammodendron* in the growing season in the middle reach was 223.0 and 131.9 mm under FC 50% and FC 20%, respectively; in the lower reach, T was 154.0 and 146.6 mm, respectively. These differences were significant under the same water regimes in different areas ($P < 0.05$) (Figure 2A). The same situation was documented for *C. mongolicum, E. przewalskii*, and *N. sphaerocarpa* under two different water regimes in the middle and lower reaches, while the T of *R. soongorica* had no obvious differences under the FC 20% treatment in the middle and lower reaches (Figure 2A).

In the middle reach, the ET of *H. ammodendron* under the FC 50% and FC 20% treatments in the growing season was 685.2 and 309.6 mm, respectively (Figure 2B), a decrease of 55%. In the lower reach, it was 701.9 and 348.1 mm under FC 50% and FC 20%, respectively (Figure 2B); the latter was less than 50% of the former. The ET was significantly different when comparing the same water regimes in different areas ($P < 0.05$) (Figure 2B). *C. mongolicum, E. przewalskii, N. sphaerocarpa*, and *R. soongorica* followed the same pattern of ET as *H. ammodendron* under the two different water regimes in the middle and lower reaches (Figure 2B).

The T of *H. ammodendron* in the growing season from May, June, July, August, September was 28.8, 44.4, 90.4, 44.8, and 14.6 mm, respectively, under FC 50% in the middle reach. The same regularity was also exhibited in *C. mongolicum, E. przewalskii, N. sphaerocarpa*, and *R. soongorica* under the same water conditions; that is, most of the T occurred in July with the higher temperature and intensive light, compared with other growing months. The T of these shrubs had no significant regularity in different months

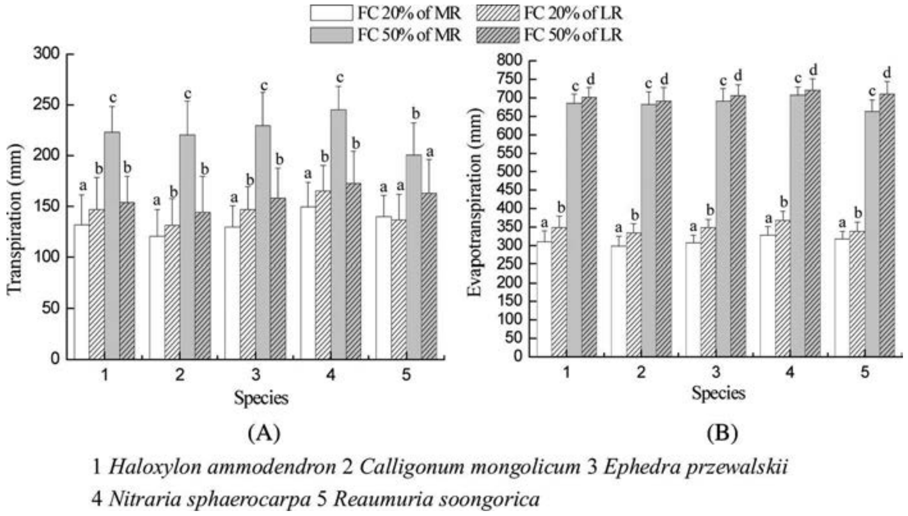

Figure 2. Comparison of transpiration (A) and evapotranspiration (B) of the same species in the middle (MR) and lower reaches (LR) of the Heihe River Basin. FC 20% and FC 50% indicate soil moisture content was at (20 ± 5) and (50 ± 10)% of field capacity, respectively. The transpiration and evapotranspiration rates of the same species under different water regimes in different regions are compared; different lowercase letters indicate significant differences ($P < 0.05$), and the same lowercase letters indicate nonsignificant differences.

under FC 20% in the middle reach, and under FC 50% and FC 20% in the lower reach, but the average value of T was highest in July for the five species in the three conditions.

The ET of *H. ammodendron* in the growing season from May, June, July, August, and September was 94.0, 144.0, 210.8, 141.7, and 94.7 mm, respectively, under FC 50% in the middle reach; it had the same regularity in the lower reach under this water condition. The ET also presented normal distribution characteristics; that is, the ET was highest in July and lower in former and later stage under FC 20% in the middle and lower reaches. The ET of other species also presented normal distribution characteristics under FC 50% and FC 20% in the middle and lower reaches.

Transpiration and evapotranspiration of desert plants in the middle reach of the Heihe River Basin

Experiments during the growing season using desert plants in the middle reach of the Heihe River Basin showed that the T and ET of various desert plant species with the same canopy diameter did not have significant differences under the two treatments (Figure 3). *S. passerina* had the lowest T and ET values of 190.6 and 652.8 mm, respectively, under FC 50%, while *C. korshinskii* had the highest values of 272.4 and 734.6 mm, respectively. The average T and ET of the sixteen species were 231 and 693 mm, respectively, meaning that T made up one-third of the ET and soil evaporation occupied the other two-thirds.

Under the FC 20% treatment, the T and ET were lowest in *C. stenophylla*, with the values of 89.4 and 267.1 mm, and were highest in *A. alyssoides*, with the values of 156.6

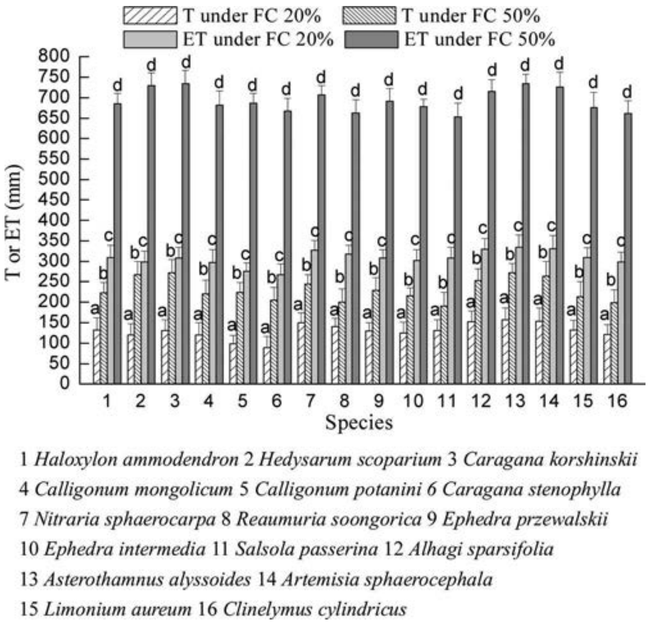

Figure 3. Comparison of transpiration (T) and evapotranspiration (ET) of desert plants in the middle reach of the Heihe River Basin. FC 20% and FC 50% indicate soil moisture content was at (20 ± 5) and (50 ± 10)% of field capacity, respectively. The T and ET of the same species are compared under different water regimes, different lowercase letters indicate significant differences ($P < 0.05$); the same lowercase letters indicate non-significant differences for different species under same water regime.

and 334.3 mm, respectively. The average T and ET of the sixteen species were 130 and 308 mm, respectively, meaning that on average T made up 42% of the ET and soil evaporation made up the other 58%. The T and ET under the FC 20% treatment declined by 44 and 56%, respectively, compared with that under FC 50%.

Obviously, desert plants that had a larger T and ET under normal growth and development may not have a large value under water stress, and vice versa. Water stress can significantly reduce the T and ET and make the proportion of T in ET increase greatly.

Transpiration and evapotranspiration of desert plants in the lower reach of the Heihe River Basin

In the lower reach, various desert plant species with the same canopy diameter had no significant differences in T and ET under the FC 50% and FC 20% treatments in the growing season, which was similar to that in the middle reach. ET of the same species showed significant difference under the two different soil water regimes ($P < 0.05$), and T had no significant difference (Figure 4).

Under FC 50%, T and ET were smallest in *S. alopecuroides*, with the values of 131.9 and 679.8 mm, respectively; and were largest in *N. sphaerocarpa*, with the values of 172.8 and 720.7 mm, respectively. The average T and ET in eighteen species were 151 and 699 mm, respectively, meaning that T occupied 22% of ET; that is 78% of ET evaporated.

Under FC 20%, plants of *P. euphratica, E. angustifolia*, and *T. ramosissima* began to die in the last 10 days of July, so they were not observed again. T and ET were smallest in

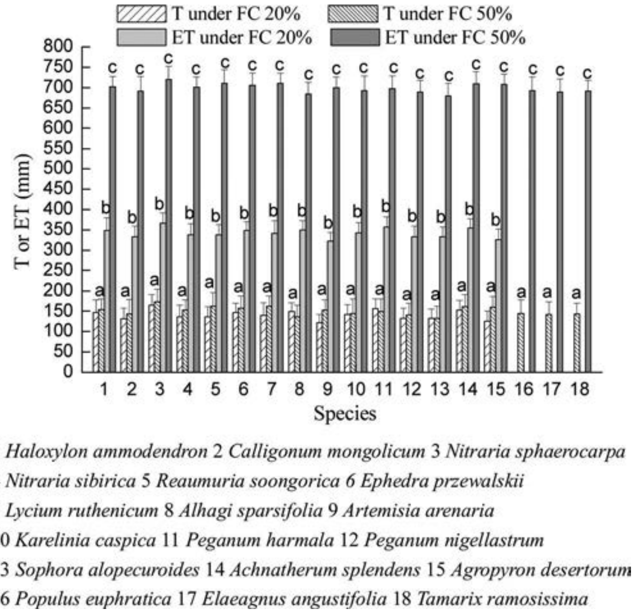

Figure 4. Comparison of transpiration (T) and evapotranspiration (ET) of desert plants in the lower reach of the Heihe River Basin. FC 20% and FC 50% indicate soil moisture content was at (20 ± 5) and (50 ± 10)% of field capacity, respectively. The T and ET of the same species are compared under different water regimes, different lowercase letters indicate significant differences ($P < 0.05$); the same lowercase letters indicate non-significant differences for different species under same water regime.

Table 1. Characteristic coefficients of transpiration (CCT) and evapotranspiration (CCE) of desert plants in the Heihe River Basin. FC 20% and FC 50% indicate soil moisture content was at (20 ± 5) and (50 ± 10)% of field capacity, respectively.

	FC 20%		FC 50%	
Type	CCT	CCE	CCT	CCE
Middle reach	0.09	0.21	0.17	0.50
Lower reach	0.09	0.22	0.09	0.43

A. arenaria, with the values of 121.4 and 322.9 mm, respectively; they were the largest in *N. sphaerocarpa*, with the values of 165.3 and 366.8 mm, respectively. The average T and ET in fifteen species were 141 and 342 mm, respectively, meaning that T occupied 41% of ET on average. No significant difference was observed in T, but the ET declined markedly by 51%, compared with that under FC 50%. The proportion of T in ET largely increased, which was consistent with that in the middle reach.

An increase in soil moisture content obviously resulted in significantly accelerated soil evaporation rather than improving plant transpiration in the lower reach of the Heihe River Basin.

Characteristic coefficient of water demand and water consumption of desert plants

According to the definition of an agricultural crop coefficient (Allen et al. 1998), the characteristic coefficient of transpiration (CCT) and the characteristic coefficient of evapotranspiration (CCE) are defined as the ratio of T to local potential evaporation and as the ratio of ET to local potential evaporation, respectively. Based on the experimental results in the study (Figures 3 and 4) and the local potential evaporation (Figure 1A), Table 1 provides the calculated CCT, CCE and their average values in the middle and lower reaches of the Heihe River. The CCT was 0.17 under the FC 50% treatment, and was cut in half under the FC 20% treatment; the CCE was 0.50 under FC 50%, and declined by less than half under FC 20% (Table 1).

For desert plants in the lower reach, the average values of CCT and CCE were 0.09 and 0.43 under FC 50%, respectively. The CCT exhibited no difference between FC 50% and FC 20% in the lower reaches (Table 1), while the CCE of FC 50% was twice that of FC 20%.

Clearly, moisture conditions of FC 50% were suitable for the growth of desert plants in the middle reach of the Heihe River, but plants in the lower reach experienced water stress under those conditions. Desert plants had a coincident CCT to 0.1 under drought stress, and the CCT under moderate water (FC 50%) tended to be close to 0.2. The CCE differed between species under different levels of water stress, but it tended to be the same in all species under severe water stress.

Discussion

The ET conceals a better understanding of the T and E. Under natural conditions, T and E are affected by the combination of meteorological factors, soil water conditions, and plant biological characteristics. Those influences are interrelated and complex, so it is difficult to theoretically and accurately determine the amount of influence various factors had on the water requirements and consumption of plants. Yoder and Nowak (1999) found no significant differences in annual ET between the evergreen shrubs *Larrea* and *Ephedra* relative to two deciduous shrubs *Ambrosia* and *Lycium*, in the Mojave Desert in southern Nevada, USA.

The T and ET of various desert plants with the same canopy diameter in the same region showed no significant differences under the same water regimes; significant differences in ET were observed under different water regimes ($P < 0.05$; Figures 3 and 4). Usually, the transpiration rate does not decrease significantly until the soil moisture falls below 50% of field capacity (Soundar, Vijayalakshmi, and Mariappan 2010). Figure 2 shows that the T under the FC 50% treatment in the middle reach was significantly higher than that under FC 20% in the same region and under these two water regimes in the lower reach; *H. ammodendron* in the middle reach had a strong ability to assimilate carbon (Gao et al. 2010). FC 50% was considered to be a moderate moisture condition for desert plants in the middle reach, because no significant difference was observed in the need for water and water consumption of different plants (Figure 3). Our findings confirmed our hypothesis that desert plants have significantly lower T and no significant difference occurs among different species under drought stress condition.

The results from the middle reach experiment under FC 50% and FC 20% showed that the ET of *C. cylindricus* was 661 and 299 mm in the two experiments, respectively, and T was 199 and 121 mm, respectively (Figure 3). Using the water balance method and the Penman–Montieth formula, Zheng et al. (2010) calculated the ET of congeneric *Clinelymus dahuricus* Turcz ex Griseb. as 425 and 409 mm using those two methods, respectively, in the Xilinguole Grassland of a semiarid region in middle Inner Mongolia, China. Based on the definition of crop water requirement, one can conclude that crops in more arid regions will require more water, while crops in more humid regions require less water (Ma et al. 2006). Annual ET for mesquite (*Prosopis velutina*) along the San Pedro River in Arizona was 400–700 mm (Glenn and Nagler 2005). Averages ET in our measured mesquite (*H. scoparium* and *C. korshinskii*) were 300 and 730 mm, respectively, under FC 20% and FC 50% in the middle reach of the Heihe River Basin (Figure 3). Trees in natural stands require very different amounts of water, and are influenced by their physiological conditions, aquifer depth, soil properties, aquifer salinity, and annual patterns of ground water fluctuation induced by seasonal precipitation and flow patterns (Glenn and Nagler 2005; Hartwell et al. 2010).

Loss of water from the soil surface through evaporation is often a major component of water loss/use in the semi-arid tropics (Jackson and Wallace 1999). Microclimate factors (light, temperature, and air saturation vapor pressure deficit) showed strong correlations to evaporative demand (Jackson and Wallace 1999; Lin 2010). The T of desert plants was mainly regulated by the plant itself, while the ET was mainly affected by the soil moisture. As can be seen from the T and ET of desert plants, most water was consumed by E, so if E decreased, then ET could be greatly reduced as well. We confirmed that E of desert plants forms the major proportion of ET.

In this study involving data collected from experiments conducted in the lower reach of the Heihe River, the ET and T of *T. ramosissima* were 692 and 144 mm in the growing season, respectively, in the FC 50% treatment (Figure 4). Van Hylckama (1974) reported an annual ET of 700–800 mm for *T. ramosissima*. Sala, Smith, and Devitt (1996) reported the measured T at the leaf level tended to be similar across riparian species. Figure 4 revealed no significant difference between T and ET of several desert riparian species, such as trees of *P. euphratica, E. angustifolia* and the shrub, *T. ramosissima*. Although desert riparian species and desert species can resist atmospheric drought, the requirement for soil water in desert riparian species was higher than that in desert species. The desert species could survive under a FC 20%, but riparian species could not tolerate it and begin to die.

The crop coefficient is commonly used to calculate the water requirements of crops, and various crops require widely different amounts of water; therefore, the concept of a reference crop has been introduced. The United Nations Food and Agriculture Organization defined ET of the reference crop as the ET observed for extensive grassland, which was completely covered by a normal growth of grass with an average height of 12 cm and experiencing no water shortage; this was also called the potential ET (ET_0) (Allen et al. 1998). The ET_0 was calculated by the modified Penman–Monteith formula (FAO56-PM) and using local meteorological data (Allen et al. 1998); then, the crop water requirement was obtained using the crop coefficient (Saylan and Bernhofer 1993; Allen et al. 1994). FAO56-PM is a combination model that is based on the energy balance and mass transfer principles. Valipour (2015) compared the calculated ET_0 from twenty-two radiation-based models with the results from FAO56-PM in Iran, and found the best weather conditions in which to use radiation-based equations. The temperature-based models were also selected and adopted to calculate ET_0 under different weather conditions (Valipour 2014a); ET_0 was then computed by the new mass transfer-based models for suitable and specific weather conditions, allowing the most precise estimation to be obtained (Valipour 2014b). Desert plants are different from crops and they did not conform to the assumed conditions of FAO56-PM, so the method used to estimate potential evapotranspiration needs further investigation.

Arid regions have very sparse vegetation density and cover. Experimental results showed that there were no significant interspecific differences in T and ET of desert plants with the same canopy diameter within the same reach of the river in this study. Therefore, the ET in this region cannot be calculated using the Penman–Montieth formula. So the characteristic coefficient of transpiration (CCT) and characteristic coefficient of evapotranspiration (CCE) were introduced to estimate the T and ET of desert plants based on the potential evaporation of this specific region.

The difference between T and ET of various desert species in the same reach was rather small and had a convergent adaptation; that is, high soil evaporation and low plant transpiration were its distinguishing characteristics. Generally, the T of crop leaves accounts for 60–80% of the ET and the E of plant interstitial evaporation occupies only 20–40%. As the crop canopy covers a greater and greater portion of the ground, the E becomes less and less (Hsiao and Xu 2005). From desert plants in the middle reach of the Heihe River Basin, one can see that the T accounted for one third of the ET and the E occupied two thirds under FC 50%, which was contrary to the typical ratios found in farmland. During the growing season, the proportion of E in ET was approximately one third and varied mainly with crop leaf area (Béziat et al. 2013). The E decreased by more than 60% in the middle and lower reaches of the Heihe River in this study when comparing the FC 20% and FC 50% treatments (Figure 1B); therefore, reducing soil moisture content could significantly reduce soil evaporation. The ET of desert plants would be reduced significantly if E is reduced. The study of self-thinning density and moisture nutrition area based on the lowest value of the T and ET of desert plants, can help researchers better understand the distribution patterns of arid land plants and their coverage under natural conditions, and this can help them to promote the stability of desert vegetation.

Conclusions

The proportion of average transpiration (T) and soil evaporation in evapotranspiration (ET) of desert plants in the middle and lower reaches of the Heihe River was 22–33% and 67–78% under the FC 50% treatment, and more than 41% and below 59% under the FC 20% treatment, respectively.

Desert plants under drought stress have a characteristic coefficient of transpiration that was consistently close to 0.1 and 0.2 under moderate moisture conditions. The characteristic coefficient of water consumption was different under different degrees of water stress, and the characteristic coefficient of evapotranspiration tends to be more consistent when water stress is more severe.

The T of desert plants in the Heihe River Basin was 230 mm under moderate soil water conditions, and T was one third of ET; the lowest value of T was 130–140 mm, and of ET was 310–340 mm. The ET of the same desert species in different regions was significantly different under the same water conditions. No significant difference was observed in the T and ET of different desert species with the same canopy diameter in the same regions. Under drought stress, soil water content of plants decreased, the E and ET were also reduced significantly; however, the T changed little and the proportion of T in ET increased obviously. Additional investigation is needed related to how moderate soil water conditions can be maintained for desert plants, so that the decrease in E that resulted in an increased proportion of T in ET can be better documented.

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