Heterogeneity of soil surface temperature induced by xerophytic shrub in a revegetated desert ecosystem, northwestern China

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Variation characteristics of the soil surface temperature induced by shrub canopy greatly affects the near-surface biological and biochemical processes in desert ecosystems. However, information regarding the effects of shrub upon the heterogeneity of soil surface temperature is scarce. Here we aimed to characterize the effects of shrub (*Caragana korshinskii*) canopy on the soil surface temperature heterogeneity at areas under shrub canopy and the neighbouring bare ground. Diurnal variations of soil surface temperature were measured at areas adjacent to the shrub base (ASB), beneath the midcanopy (BMC), and in the bare intershrub spaces (BIS) at the eastern, southern, western and northern aspects of shrub, respectively. Results indicated that diurnal mean soil surface temperature under the *C. korshinskii* canopy (ASB and BMC) was significantly lower than in the BIS, with the highest in the BIS, followed by the BMC and ASB. The diurnal maximum and diurnal variations of soil surface temperatures under canopy vary strongly with different aspects of shrub with the diurnal variation in solar altitude, which could be used as cues to detect safe sites for under-canopy biota. A significant empirical linear relationship was found between soil surface temperature and solar altitude, suggesting an empirical predicator that solar altitude can serve for soil surface temperature. Lower soil surface temperatures under the canopy than in the bare intershrub spaces imply that shrubs canopy play a role of 'cool islands' in the daytime in terms of soil surface temperature during hot summer months in the desert ecosystems characterized by a mosaic of sparse vegetation and bare ground.

1. Introduction

Arid and semi-arid ecosystems are often characterized by vegetation patchiness, arranging as a two-phase mosaic of discontinuous vegetated patches surrounded by bare ground patches (Noy-Meir 1973; Rietkerk *et al.* 2004; Kéfi *et al.* 2007). Shrubs, known as 'fertile islands' (Garner and Steinberger 1989) in desert ecosystems, are characterized by higher soil fertility (Schlesinger *et al.* 1996) and less extreme microclimates (Vetaas 1992; Kidron 2010). Shrubs produce ecologically important microclimates (soil and air temperature, humidity, wind speed, solar radiation, soil evaporation, etc.) under their canopies in desert ecosystems (Vetaas 1992; Moro *et al.* 1997; Tracol *et al.* 2011), which greatly affects near-surface biological processes including seed germination (Valientebanuet and Ezcurra 1991; FrancoPizana *et al.* 1996; Mayor *et al.* 2007), soil seed banks (Price and Reichman 1987; Wang

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et al. 2010), seedling establishment, survival and growth (Franco and Nobel 1989; Moro *et al.* 1997; Ludwig *et al.* 2001; Schumacher *et al.* 2008; Griffith 2010), microbial activities (Goberna *et al.* 2007; Jia *et al.* 2010), root growth (Macduff *et al.* 1986), insects population dynamics (Shelef and Groner 2011; Carpintero *et al.* 2011), etc.

Sparse vegetation in desert ecosystems is usually interspersed by large patches of unshaded bare soil, which makes the desert landscape also a patchwork of sharply contrasting thermal environments (Boulet *et al.* 1999; Molles 2008). Desert soil temperatures are very high during the day, which often become lethal for seedlings of many species (Nobel 1984). Shrubs were reported to provide amelioration from high or even extreme surface temperature, characteristic of desert environments and further less soil evaporation at the microscale through a direct shading effect (Lowe and Hinds 1971; Nobel 1984; Hennessy *et al.* 1985; Souch and Souch 1993), by reducing solar radiation reaching the shaded area (Scholes and Archer 1997), which was regarded as the chief factor responsible for the nurse-plant effect in arid and semi-arid regions as suggested by Valientebanuet and Ezcurra (1991) and Kidron (2009). Moreover, sparse shrub vegetation was assumed to create considerable temporal and spatial variation in soil surface temperature regimes (Hinds and Rickard 1968; Pierson and Wight 1991; Humes *et al.* 1994; Castellanos *et al.* 1999). Soil surface temperature under plant canopy was reported to be lower than in the intershrub spaces in the daytime (e.g., Pierson and Wight 1991; Moro *et al.* 1997; El-Bana *et al.* 2002; Kidron 2009, 2010; Tracol *et al.* 2011), and to some extent, it is a supposable fact even to the nonprofessionals in this field. Only meagre information, however, exists regarding the extent to which shrubs alter the soil surface temperature. In particular, lacking are the studies on quantifying the heterogeneity of soil surface temperature at different aspects of shrub.

In this paper, we mainly aimed to characterize the spatial and temporal heterogeneity of soil surface temperature induced by *C. korshinskii* canopy by quantifying the surface temperature variation around it in terms of the distance from and the aspect to the canopy. Also, we discussed how soil surface temperature was influenced by the size and aspect of shrub canopy, as well as the potential maximum influencing values of space around the shrub canopy on the soil surface temperature. Finally, we constructed a linear regression model showing the relationship between soil surface temperature and solar altitude. The current research is expected to be meaningful for a better understanding of soil-vegetation-atmosphere processes at small scale. It also helps us to dig into the amelioration effects of revegetation efforts upon surface microclimate in restored desert ecosystems and its implications to some temperature-dependent near-surface biological and biochemical processes under shrub canopy.

2. Materials and methods

2.1 *Study area*

Measurements were conducted at Shapotou Desert Research and Experiment Station (SDRES) of Chinese Academy of Sciences (37°32′N, 105°02′E, elevation of 1300 m above sea level), located at the southeastern fringe of the Tengger Desert in northwestern China. Mean annual precipitation is only 191 mm (1955–2005, SDRES) with 80% of rain occurring between July and September, and precipitation is the only source of soil water replenishment. Mean maximum air temperature is 24.7°C in July and the mean minimum is −6.1°C in January. Maximum surface temperature can reach to 74°C during summer months. The potential evapotranspiration is as high as 2500 mm during the growing season, resulting in a large annual moisture deficit. The area is surrounded by relatively plain interdunes and free from any disturbances of grazing, fire, and wood chopping. The dune sand mainly consists of fine sand (0.05–0.25 mm), and the clay content is about 0.2%. The sand can thus be classified as *Typic Psammaquents* (Berndtsson *et al.* 1996).

To protect the Baotou-Lanzhou railway against encroaching sand dunes in the Shapotou area, a 16,000 m long (500 m width to the north and 200 m to the south) artificially revegetated protection system was established along the Baotou-Lanzhou railway after the revegetation efforts in the 1950s–1980s, mainly by setting up straw checker boards in the moving sand soil and then planting xerophytic

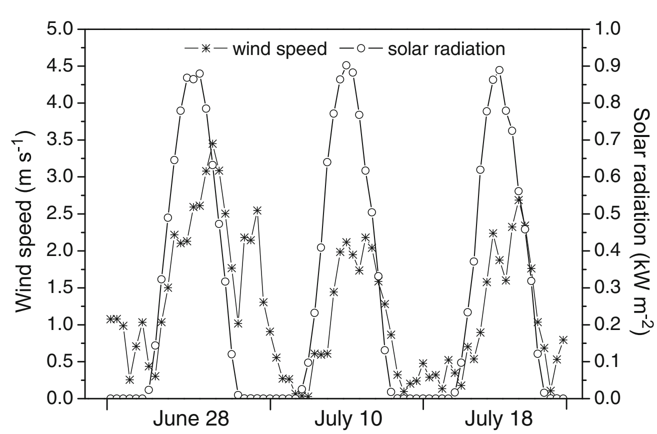

Figure 1. Solar radiation and wind speed at 2 m during the experimental period.

shrub (such as *C. korshinskii*) and dwarf-shrub (such as *Artemisia ordosica*) species within them. The landscape in the revegetation area is characterized by a mosaic of sparse shrubs and herbs and the interspaces covered by biological soil crusts (Li *et al.* 2003; Wang *et al.* 2007). Li *et al.* (2006) had a detailed description about the revegetation procedure.

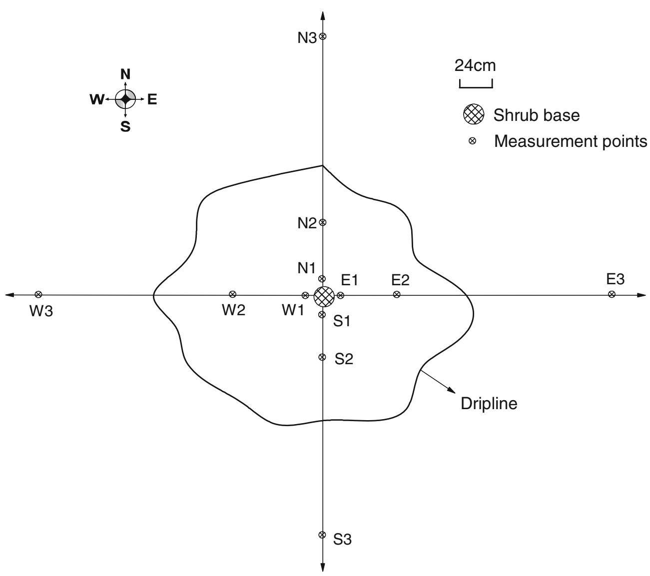

Figure 2. Sketch map of experimental set-up.

2.2 *Shrub description and selection*

C. korshinskii serves as one of the successful xerophytic shrubs in artificial revegetation along the Baotou-Lanzhou railway in the study area. *C. korshinskii* is a multi-stemmed deciduous perennial shrub and looks like an inverted cone. Leaves are pinnately compound and opposite or sub-opposite in arrangement and 6–10 cm long. Each pinna has 6 to 8 pairs of leaflets which are ovate in shape with 7–8 mm length and 2–5 mm width.

A robust and healthy adult shrub of *C. korshinskii* was chosen. The plant is 190 cm in height with a canopy size of 260 (east–west) × 240 cm (north–south) and an LAI (leaf area index) of 0.95. It has 24 stems and the base area can be considered as a circle with a diameter of 15 cm. The crown height is 150 cm.

2.3 *Experimental design and field measurements*

Soil surface temperature was measured by a TC-1100 Digital Thermocouple Thermometer (Line Seiki Co. Ltd., Tokyo, Japan) with a measurement range from 0 to 200°C and an accuracy of ±0.1°C. Thermometer connects Marlox thermocouple (Marlin manufacturing Corporation) to measure temperature. Three calm (mean wind speed less than 2 m s^{-1} during daytime) and cloudless days (June 28, July 10 and July 18, 2011), typical of summer days in study area, were chosen for

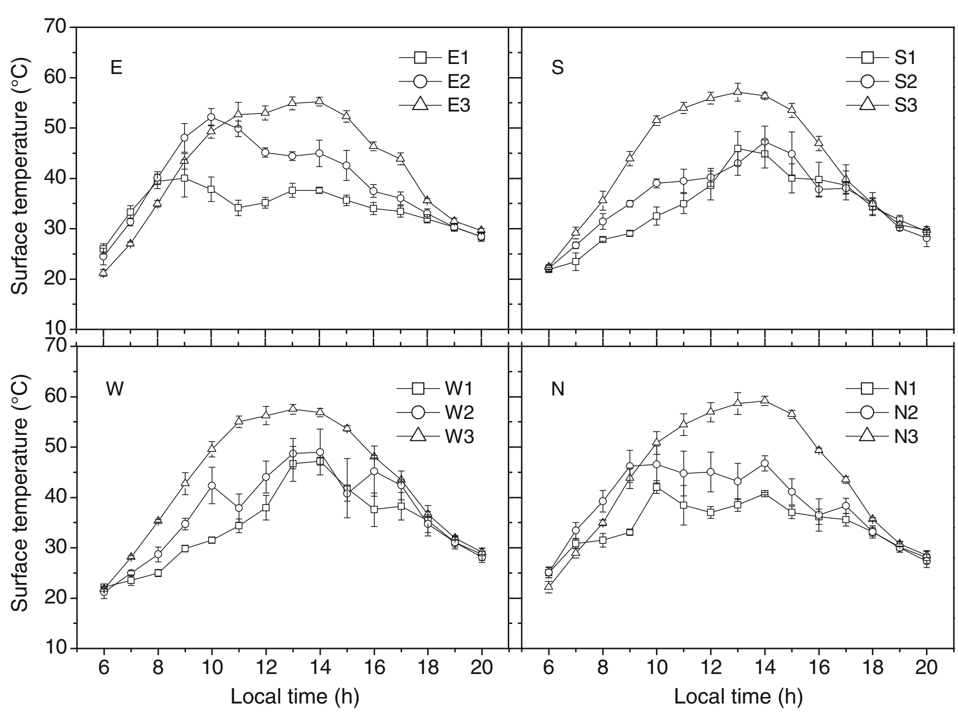

Figure 3. Average diurnal variation of surface temperature at each measurement point (as shown in figure 2) at the four shrub aspects (eastern: E; southern: S; western: W; northern: N), respectively. Bars represent the standard error.

measurements to reduce the effects of clouds and wind on surface temperature (figure 1). Soil surface temperature measurements were taken in 1 hour interval from 06:00 to 20:00 local time (roughly from sunrise to sunset). All measurements can be done within 5 minutes each time.

Figure 2 displays the sketch top view of shrub and the measurement location distribution. Transects were placed radiating out in the four cardinal aspects (eastern: E; southern: S; western: W; and northern: N) from the shrub base to intershrub spaces for surface temperature measuring. In each aspect, three thermocouple probes were fixed at the soil surface with one adjacent to shrub base (ASB), one beneath the midcanopy (BMC), i.e., half the distance between shrub base and dripline, and one in the bare intershrub space (BIS). Measurement points include (1) E1, S1, W1 and N1 at the ASB; (2) E2, S2, W2 and N2 at the BMC; (3) E3, S3, W3 and N3 at the BIS. Among them, points in the BIS were completely free of shade. We took three readings at each point for each measurement and these readings were averaged for analysis. The perpendicular distances from the shrub base to the dripline were measured using a ruler rotating with an angle of 15° starting from and finally ending to the eastern aspect as the axis of 0°. Through this, we can get 24 scatter dots to outline the shrub dripline and then determine the canopy vertical projection area of the shrub.

The Leaf Area Index (LAI) of the shrub, one-sided leaf area per unit ground area, was estimated using a Li-Cor LAI-2000 Plant Canopy Analyzer (USA).

The soil is sandy soil covered by thin biological soil crusts at the soil surface. Soil moisture (0–6 cm) was measured by an NH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, England) at areas ASB, BMC and in the BIS in a 2-hour interval during experiment period. We found the volumetric soil moisture was less than 0.01 VV^{-1}, and we thus considered the soil as dry and the soil moisture exerted a negligible effect on soil surface temperature.

Solar radiation and wind speed data at 2 m height above soil surface were derived from an automatic weather station (WS-STD1, UK).

2.4 *Statistical analyses*

We used one-way ANOVA to test the difference of diurnal mean soil surface temperature between the ASB, BMC and BIS and the difference of soil surface temperature at four aspects (eastern,

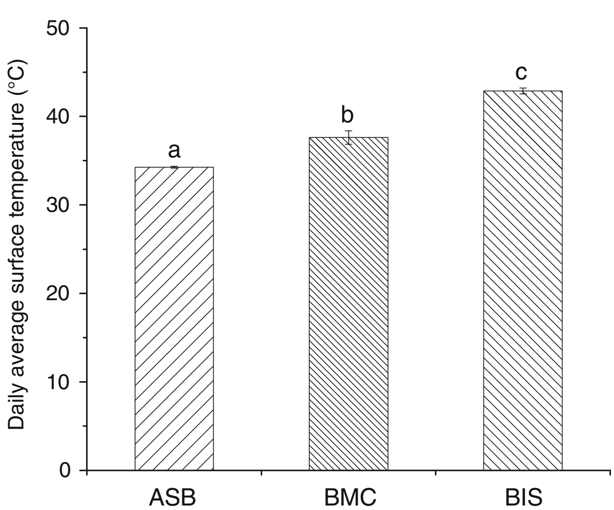

Figure 4. Comparison of the diurnal average surface temperatures (means ± SE at four shrub aspects) that are adjacent to shrub base (ASB), beneath the mid-canopy (BMC) and in the bare intershrub spaces (BIS), respectively. Values with different letters (a, b and c) are significant at P < 0.01.

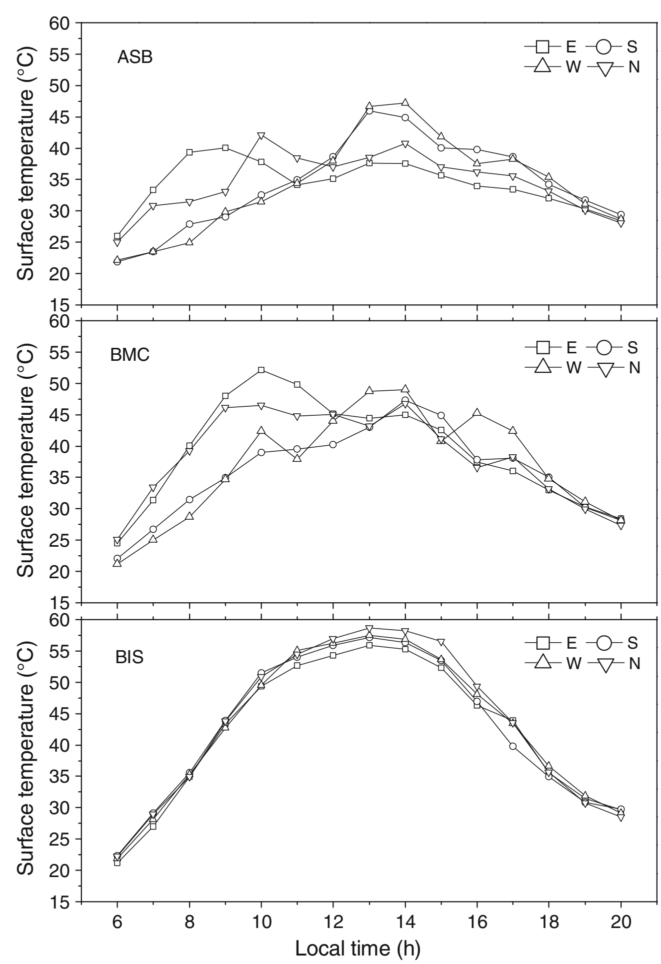

Figure 5. Diurnal variations of surface temperature adjacent to shrub base (ASB), beneath the mid-canopy (BMC) and in the bare intershrub space (BIS) in the eastern (E), southern (S), western (W) and northern (N) aspects of shrub, respectively. Data are measurements of three days averages.

southern, western and northern) of shrub. Correlation analysis was employed to examine the relationship between soil surface temperature and solar altitude. All the ANOVA and correlation analyses were performed using the SPSS 16.0 statistical software (SPSS Inc., Chicago, USA).

3. Results

3.1 *Diurnal variations of soil surface temperature*

Figure 3 illustrates the average diurnal variations of soil surface temperature at each measurement point, respectively. Graphically, the diurnal mean variations of surface temperature in the BIS in the four aspects of shrub (E3, S3, W3 and N3) exclusively exhibited similar parabolic curves, with the diurnal maximum soil surface temperatures occurring around 13:00 (local time), and the lowest values around the sunrise and sunset. However, the diurnal curves of soil surface temperature at the ASB (E1, S1, W1 and N1) and BMC (E2, S2, W2 and N2) were generally lower and asymmetrically distributed comparing with that of BIS. Soil surface temperature started to differ among ASB, BMC and BIS since sunrise and returned to convergence around sunset. Maximum soil surface temperatures occurred around 13:00 at the BIS, followed by the BMC and ASB but not always coincident at 13:00.

Table 1. *Soil surface temperatures adjacent to shrub base (ASB), beneath the mid-canopy (BMC) and in the bare intershrub space (BIS) at the eastern (E), southern (S), western (W) and northern (N) aspects of shrub, respectively.*

Time	Position											
	ASB				BMC				BIS			
(h)	E	S	W	N	E	S	W	N	E	S	W	N
6	26.0^{a}	21.9^{b}	22.2^{b}	25.0^{a}	24.5^{1}	22.1^{1}	21.2^{1}	25.1^{1}	21.2*	22.4*	21.8*	22.2*
	(1.0)	(0.4)	(0.2)	(1.0)	(1.6)	(0.6)	(1.3)	(1.1)	(0.7)	(0.5)	(0.0)	(1.2)
7	33.3^{a}	23.5^{b}	23.5^{b}	30.9^{a}	31.3^{1}	26.7^{2}	25.0^{2}	33.4^{1}	27.0*	29.1*	28.2*	28.9*
	(1.3)	(1.8)	(1.0)	(0.9)	(0.7)	(0.7)	(0.4)	(1.6)	(0.4)	(1.2)	(0.2)	(0.9)
8	39.4^{a}	27.9^{b}	25.0^{b}	31.5^{c}	40.1^{1}	$31.4^{2,3}$	$28.7^{1,3}$	39.3^{1}	34.9*	35.6*	35.3*	34.9*
	(1.4)	(0.4)	(0.7)	(1.4)	(1.2)	(1.6)	(1.5)	(2.2)	(0.6)	(1.9)	(0.3)	(0.6)
9	40.1^{a}	29.1^{b}	29.8^{b}	33.1^{b}	48.0^{1}	34.9^{2}	34.7^{2}	46.2^{1}	43.4*	43.9*	42.7*	43.8*
	(3.7)	(0.5)	(0.6)	(0.5)	(2.8)	(0.7)	(1.2)	(3.2)	(1.5)	(1.4)	(2.2)	(2.0)
10	37.8^{bc}	32.5^{ab}	31.5^{a}	42.1^{c}	52.1^{1}	39.0^{2}	42.3^{2}	$46.5^{1,2}$	49.3*	51.5*	49.6*	50.8*
	(2.5)	(1.8)	(0.6)	(1.2)	(1.7)	(0.9)	(3.6)	(3.7)	(1.3)	(1.0)	(1.5)	(2.2)
11	34.1^{a}	35.0^{a}	34.4^{a}	38.5^{a}	49.8^{1}	39.5^{2}	37.9^{2}	$44.8^{1,2}$	52.7*	54.0*	55.0*	54.4*
	(1.5)	(2.0)	(1.4)	(3.9)	(1.5)	(2.3)	(2.8)	(4.5)	(2.4)	(1.1)	(1.1)	(2.1)
12	35.2^{a}	38.6^{a}	38.0^{a}	37.0^{a}	45.1^{1}	40.2^{1}	44.0^{1}	45.0^{1}	52.9*	55.9*	56.3*	56.9*
	(1.1)	(2.9)	(2.4)	(1.2)	(0.9)	(1.8)	(3.2)	(3.9)	(1.4)	(1.2)	(1.8)	(1.9)
13	37.6^{a}	45.9^{b}	46.7^{b}	38.5^{a}	44.4^{1}	43.0^{1}	48.7^{1}	43.2^{1}	54.9*	57.1*	57.5*	58.7*
	(1.4)	(3.4)	(3.5)	(1.2)	(0.9)	(2.3)	(3.0)	(3.6)	(1.3)	(1.8)	(1.0)	(2.2)
14	37.6^{a}	44.8^{bc}	47.2^{c}	40.8^{ab}	45.0^{1}	47.3^{1}	49.0^{1}	46.8^{1}	55.2*	56.3*	56.9*	59.2*
	(0.5)	(2.8)	(0.8)	(0.2)	(2.6)	(3.0)	(4.6)	(1.5)	(0.9)	(0.6)	(0.8)	(0.9)
15	35.7^{a}	40.0^{a}	41.8^{a}	37.0^{a}	42.6^{1}	44.9^{1}	40.8^{1}	41.1^{1}	52.3*	53.5*	53.7*	56.5*
	(1.0)	(2.9)	(5.9)	(1.2)	(3.0)	(4.3)	(1.5)	(2.6)	(1.2)	(1.4)	(0.5)	(0.8)
16	34.0^{a}	39.7^{a}	37.6^{a}	36.2^{a}	37.5^{1}	37.8^{1}	45.2^{1}	36.5^{1}	46.3*	46.9*	48.1*	49.4*
	(1.2)	(3.4)	(3.3)	(1.5)	(1.2)	(1.4)	(5.0)	(3.2)	(0.9)	(1.4)	(0.2)	(0.4)
17	33.4^{a}	38.6^{a}	38.3^{a}	35.6^{a}	36.0^{1}	$38.0^{1,2}$	42.4^{1}	$38.3^{1,2}$	43.9*	39.8*	43.5*	43.5*
	(1.1)	(2.9)	(2.7)	(1.3)	(1.3)	(1.0)	(2.9)	(1.5)	(1.2)	(2.9)	(0.2)	(0.7)
18	32.0^{a}	34.3^{a}	35.4^{a}	33.2^{a}	33.0^{1}	35.0^{1}	34.8^{1}	33.2^{1}	35.6*	35.0*	36.7*	35.7*
	(0.8)	(1.7)	(3.0)	(1.2)	(0.9)	(2.2)	(1.7)	(0.9)	(0.4)	(1.2)	(0.5)	(0.2)
19	30.3^{a}	31.7^{a}	31.1^{a}	30.1^{a}	30.3^{1}	30.2^{1}	31.1^{1}	30.0^{1}	31.5*	30.8*	31.9*	30.8*
	(0.8)	(1.0)	(1.3)	(1.0)	(0.6)	(0.5)	(0.9)	(0.8)	(0.6)	(0.6)	(0.3)	(0.5)
20	28.4^{a}	29.4^{a}	28.7^{a}	28.1^{a}	28.4^{1}	28.1^{1}	28.2^{1}	27.4^{1}	29.6*	29.7*	29.2*	28.5*
	(0.9)	(1.0)	(1.2)	(1.2)	(0.8)	(1.8)	(1.1)	(1.3)	(0.4)	(0.1)	(0.7)	(1.0)

Value in parentheses presents standard error. n = 3.
Values with different letters (a, b and c) are significant at the ABS at $P < 0.01$; values with different numbers (1, 2 and 3) are significant at the BMC at $P < 0.01$; values with asterisk (*) are not significant at $P < 0.05$ in the BIS.

Differences in means of diurnal soil surface temperature were highly significant ($P < 0.01$) among ASB, BMC and BIS, as shown in figure 4. Mean soil surface temperature was 42.9°C at the BIS and decreased by 5.3°C towards BMC (37.6°C), and by 8.6°C towards ASB (34.3°C). In particular, the differences of surface temperature between ASB, BMC and BIS were the most pronounced around local noon time. For example, the mean soil surface temperature at the ASB, BMC and BIS approached 37.2, 43.6 and 55.5°C at 13:00, i.e., there was a difference of 18.3°C between BIS and ASB, and an 11.9°C difference between BIS and BMC.

3.2 *Effects of shrub aspects on soil surface temperature*

Generally, as shown in figure 5 and table 1, the soil surface temperatures under shrub canopy (ASB and BMC) were larger in the eastern and northern aspects than in the southern and western aspects before 12:00, but the tendency was opposite after 12:00. Occasionally, significant differences of soil surface temperature were found among different shrub aspects at the ASB and BMC (table 1). For example, at 09:00 at the ASB, soil surface temperature at the eastern aspect was 11.0, 10.3 and 8.0°C higher ($P < 0.01$) than at the southern, western and northern aspects, respectively, while at 14:00, soil surface temperature at the eastern aspect was 7.2, 9.6 and 3.2°C lower than at the southern, western and northern aspects, respectively. However, in the BIS, no significant difference of soil surface temperature was found at the four aspects around shrub during the observation periods. Although, the differences in soil surface temperature existed between the four aspects at a specific time of the day, no significant differences between the mean of the diurnal surface temperatures were found between the four aspects of shrub. The shading effect of canopy was observed more pronounced at the ASB and BMC at the western aspect of the shrub in the morning and that was the case for the eastern aspect of shrub in the afternoon, because area under canopy in the eastern aspect of shrub received more solar radiation than in the western aspect in the morning but less in the afternoon, it varied with the diurnal variation of solar altitude. Moreover, time difference of the diurnal maximum soil surface temperature existed under canopy at different aspects. For example, at the ASB, soil surface temperature at the eastern aspect reached its peak around 09:00 and then decreased, while it happened around 14:00 at the western aspect, i.e., there was a 5 hours delay of the diurnal maximum soil surface temperature occurring at western aspect of shrub comparing with that at eastern aspect. Similar phenomenon was also evidenced at the BMC.

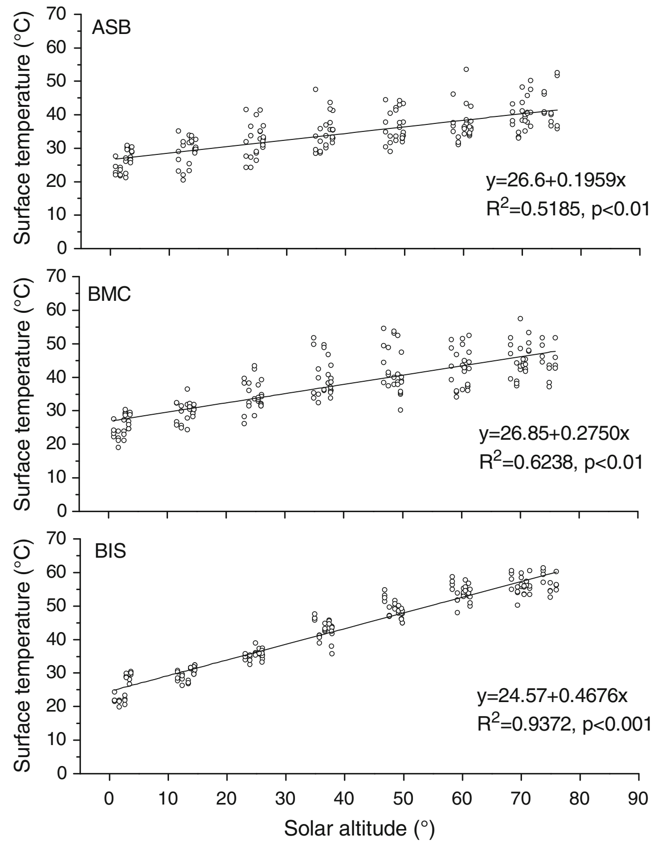

Figure 6. Relationships between surface temperature and solar altitude adjacent to shrub base (ASB), beneath the mid-canopy (BMC) and in the bare intershrub spaces (BIS), respectively.

3.3 *Statistical relationship between surface temperature and solar altitude*

Figure 6 illustrates the statistical relationship between soil surface temperature and solar altitude. Soil surface temperature increased with the increasing of solar altitude and a well correlated linear relationship was found between them with a coefficient of determination of 0.9372, 0.6238 and 0.5185 for BIS, BMC and ABS, respectively. Soil surface temperature under canopy (ABS and BMC) had a slower increase as solar altitude increased than in the BIS.

4. Discussion and conclusions

In this study, a notable shrub effect on soil surface temperature variations was identified. Soil surface temperatures under the canopy (ASB and BMC) of *C. korshinskii* were significantly ($P < 0.01$) lower than in the BIS. The difference of diurnal mean surface temperature between BIS and ASB was 8.6°C and it can be as high as 18.3°C at 13:00, and the counterparts between BIS and BMC were 5.3°C and 11.9°C at 13:00, respectively. In addition, diurnally, soil surface temperature under shrub canopy showed less variability as compared to the BIS, i.e., shrub canopy buffers the diurnal variability of soil surface temperature. We thus concluded that in addition to the well known role of 'fertile islands' (Garner and Steinberger 1989), shrubs also play a notable role of 'cool islands' in the daytime in a narrow sense. In terms of soil surface temperature, desert landscape can also be described as a mosaic of cool islands under shrub canopies and the warmer islands in the bare intershrub spaces. Note that the 'cool islands' effect under shrub canopies works only in the daytime, nighttime temperatures under the canopies may be a little higher than in the intershrub spaces (Kidron 2010; D'Odorico *et al.* 2010). Our study area experienced a long term artificial revegetation, which transformed the former landscape with bare and homogeneous moving sand dunes into the landscape characterized by a mosaic of the sparse shrubs and herbs and the interspaces covered by biological soil crusts (e.g., Li *et al.* 2006). There is a substantial increase in biodiversity and a great improvement of soil fertility after long term revegetation (Li *et al.* 2004). *C. korshinskii*, a nitrogen-fixing legume, showed good performance in the revegetation and is regarded as one of the chief sand-fixing shrubs in desert areas. Our results showed that the shrub *C. korshinskii*, serving as a natural barrier against the external harsh thermal conditions, provided amelioration from high soil surface temperature especially at midday and may further greatly modify the microhabitat under the canopies. Thus, this also suggests an amelioration effect of revegetation efforts upon surface microclimate in terms of soil temperature around plants mainly by planting xerophytic shrubs into the straw checker boards in Shapotou area where the maximum surface temperature of bare sandy soil can be as high as 74°C in summer months (Wang *et al.* 2002). 'Cool islands' effect induced by shrubs may have been playing and are expected to play a positive role in the succession of the revegetated ecosystem of study area.

Our experimental results, combined with previous studies (e.g., Pierson and Wight 1991; Tielbörger and Kadmon 1995; Retana and Cerda 2000; Hastwell and Facelli 2003; Armas and Pugnaire 2005; Kidron 2009, 2010; Celaya-Michel and Castellanos-Villegas 2011; Zhou *et al.* 2011; Kidron and Vonshak 2012), imply that the differential degrees of soil temperature induced by shrub canopy may strongly affect some of the temperature-dependent near-surface biochemical and biological processes, including in differential soil moisture regime and soil evaporation, different rates of soil nitrogen mineralization, seed germination and annuals establishment, microbial activities and insect dynamics, with important implications for the formation and expansion of fertile islands in arid landscapes. Kidron (2009, 2010) indicated that, concerning the fertile islands in arid and semi-arid zones, the primary and principal role of shrubs was in altering the microclimate rather than in improving the nutrient status of the soil. Protected from direct sun and wind, shrubs are responsible for lower soil temperature, which is likely to be highly correlated with conditions such as reduced solar radiation and soil evaporation and the longer wetness duration following rain and higher relative humidity under shrubs (Kidron 2010; Kidron and Vonshak 2012). Therein, as was found in the Negev Desert, the daylight wetness duration of habitats covered with microbiotic crusts both under and adjacent to shrub, varying with aspects of shrub, further affected the photosynthetic activity and hence biomass of microbiotic crusts and a good positive linear relation was found between them (Kidron and Vonshak 2012). In the desert, soil temperature and soil water are the two most crucial factors governing seed germination (Forcella *et al.* 2000). In fact, the wetter and mild surface soils existing under the shrub canopy may facilitate seed germination and vegetation establishment and growth, while the drier and parched soil in the severe areas of interspaces may prevent these processes (Hastwell and Facelli 2003; Armas and Pugnaire 2005). Wang *et al.* (2010) found that forb seeds were more abundant under *C. korshinskii* than in the interspaces in the study area, which, according to our results, may suggest a higher seed germination rate and further more surviving plants beneath shrubs than in the intershrub spaces. In fact, higher density of annuals is always found under shrub canopy, as reported by Tielbörger and Kadmon (1995) in the Negev Desert. Moreover, 'cool islands' in deserts are often favourable for higher microbial activities under shrub canopy and would further enhance microbially driven ecosystem processes (Goberna *et al.* 2007), which is associated with higher rates of soil carbon and nitrogen mineralization and organic matter decomposition, etc. For example, Jia *et al.* (2010) noticed that *C. korshinskii* promotes the soil microbial biomass and activity. Zhou *et al.* (2011) found a significantly higher soil carbon mineralization potential beneath *C. korshinskii* in the study area. Celaya-Michel and Castellanos-Villegas (2011) reported a higher rate of nitrogen mineralization under the canopy of shrubs, particularly under nitrogen-fixing legumes, compared to open interspaces in arid and semi-arid ecosystems. Additionally, shading by shrubs provides shelter for insects, reptiles and other organisms in hot summer months. For instance, by studying ants as bioindicators in the Tabernas Desert, Carpintero *et al.* (2011) reported higher densities of individuals and species richness under shrub canopy than in the interspaces, and pointed out that lower soil temperature beneath canopy may be the main factor. The soil surface temperature measurements made in the present study also showed that aspect of shrub strongly affected soil surface temperature heterogeneity around the shrub. The diurnal maximum temperatures and the diurnal variations of surface temperature at the ASB and BMC varied strongly with different aspects of shrub (figure 5). Diurnal variation of soil surface temperature are often more important to plants and animals than the average temperature (Joyce 2009). These results suggest that maximum temperatures or diurnal temperature variations can be used as cues to detect safe sites for the biota under the canopy. For example, Retana and Cerda (2000) noticed that ant communities track spatial and temporal variability in the thermal environment and reached the similar conclusions as above Carpintero *et al.* (2011). Accordingly, the amelioration of the thermal environment produced by the patchy shrubs plays an important role in the under-canopy biota in desert ecosystems.

The lower under-canopy soil temperatures could mainly be explained by shading of shrub canopy which attenuates the solar radiation reaching the shaded soil surface, as suggested by e.g., Kidron (2010). Shading by shrub canopies might be especially important in deserts where the solar radiation is strong and the canopy cover is often low (Zou *et al.* 2010). Soil moisture (<0.01 VV^{-1}) was assumed to exert a negligible effect on the heterogeneity of soil surface temperature in the present study, because the measurements of surface temperature were taken when the soil surface was dry, which removed the influences of soil moisture. The diurnal behaviour of soil surface temperature would be rather complex when the surface is in wet conditions, since more of the solar radiation reaching the soil would be applied to evaporate soil water but not mostly to heat the soil resulting in less sensible heat and a smaller temperature increase than in dry conditions (Minnis *et al.* 1997). In the study area, the annual mean precipitation is only 191 mm and in the most time of the year the soil surface is in dry conditions, and the three days we chose for measurements are of typical in the hot summer months. Thus, our results are of representative and meaningful.

The surface temperature heterogeneity beneath shrub canopy was attributed to the uneven shading of shrub canopy over time in the daytime, depending on the canopy architecture and the diurnal variations in solar altitude. Solar radiation was greatly attenuated through shrub canopy (Thomas and Kliebenstein 2000; Forseth *et al.* 2001), and the size and shape of shade is determined both by canopy architecture and the diurnal variation of solar altitude (Kuuluvainen and Pukkala 1989; Zou *et al.* 2010; Raz-Yaseef *et al.* 2010). Thus, shading by shrub is dynamic over time, which also would generate a rather complex variability of soil surface temperature around shrub. In the present study, for example, partial shading was experienced by the habitats at the western aspect during early morning and eastern aspect during the late afternoon, which caused higher soil surface temperatures at the eastern aspect in the morning and lower values in the afternoon compared with that at the western aspect. At 08:00 and 18:00, a warming can be seen on sunward side of the shrub, and a long light shadow is obvious on the lee side. At 14:00, shadow is much smaller, but the shading is intense. Time difference of the diurnal maximum soil surface temperature at different aspects beneath the shrub canopy (figure 5) is also attributable to the dynamic shading. We thus assume that there exists a dynamic shading area around shrub varying with the variation of solar altitude that influences soil surface temperature. Even though, theoretically, we can predict the shading area of canopy according to the solar altitude and precisely measured shrub canopy geometry, it is, however, hard to precisely predict soil surface temperature around shrubs, because surface temperature reveals the dynamic equilibrium between incoming and outgoing energy flux (Garratt 1992), it is a function of soil, vegetation and atmospheric variables which vary in space, plus the shading of canopy is dynamic and uneven due to complex canopy architecture.

Moreover, our results indicated that the diurnal variations of solar altitude correlated well with soil surface temperature, and empirically, soil surface temperature linearly increased as solar altitude increased (figure 6). The correlation of soil surface temperature and solar altitude was not so strong for ABS and BMC as for BIS due to the variations of soil surface temperature owing to varying canopy shading in the ABS and BMC but not in the BIS at different aspects of shrub. Although there is no direct causation between solar altitude and soil surface temperature, a functional relationship between them can be proposed. It should be noted that solar altitude influence soil surface temperature in an indirect way through altering the intensity of solar radiation striking soil surfaces over time. In addition, empirical formulas in figure 6 showed that soil surface temperature beneath the shrub canopy (ABS and BMC) had a slower increase as solar altitude increased than in the BIS. The statistical relationship between solar altitude and soil surface temperature implies that solar altitude could be used as a predicator of soil surface temperature, especially for that of bare soil.

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