Soil water regulates the control of photosynthesis on diel hysteresis between soil respiration and temperature

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Abstract. Causes for diel hysteresis between soil respiration (R_s) and temperature remain highly controversial. Explanations for the occurrence of hysteresis have involved both biological and physical mechanisms. The specifics of these explanations, however, tend to vary with the particular ecosystem or biome being studied. This study examined the seasonal variation in diel hysteresis and its controlling factors in a desert-shrub ecosystem in northwest (NW) China. The study was based on continuous measurements of R_s, air temperature (T_a), soil temperature at the surface and below (T_{surf} and T_s), volumetric soil water content (SWC), and photosynthesis over a year 2013. Trends in diel R_s were observed to vary with SWC over the growing season. Diel variations in R_s were more closely associated with T_{surf} than with photosynthesis as SWC increased, leading to R_s being in phase with T_{surf}, particularly when $SWC > 0.08$ m^3 m^{-3}. However, as SWC decreased below 0.08 m^3 m^{-3}, diel variations in R_s were more closely related to variations in photosynthesis, leading to a pronounced diel hysteresis and asynchronicity between R_s and T_{surf}. It was indicated that SWC regulates the relative control between photosynthesis and temperature on diel R_s by changing the relative contribution of autotrophic and heterotrophic respiration to total R_s, and thus, causing seasonal variation in diel hysteresis between R_s and temperature. Our findings highlight the importance of biologically-based mechanisms and the role of SWC in regulating diel hysteresis between R_s and temperature.

1 Introduction

Diel hysteresis (asynchronicity) between soil respiration (R_s) and soil temperature (T_s) is widely documented for forests (Tang et al., 2005; Gaumont-Guay et al., 2006; Riveros-Iregui et al., 2007; Vargas and Allen, 2008; Jia et al., 2013), grasslands (Carbone et al., 2008; Barron-Gafford et al., 2011), and desert ecosystems (Wang et al., 2014; Feng et al., 2014). Diel hysteresis, which appears as an elliptical loop in the relationship between R_s and T_s, is difficult to model with theoretical

functions, such as with the Q_{10}, Lloyd-Taylor, Arrhenius, or van't Hoff functions (Lloyd and Taylor, 1994; Winkler et al., 1996; Davidson et al., 2006; Phillips et al., 2011; Oikawa et al., 2014). Diel hysteresis is also not currently addressed in the Q_{10} function for low soil water conditions, leading to a poor understanding of temperature-sensitivity in R_s (Gaumont-Guay et al., 2008; Phillips et al., 2011; Darenova et al., 2014). Therefore, in order to accurately predict soil CO_2 fluxes and their

5   responses to climate change, it is necessary to understand the biophysical mechanisms that control the variation in diel hysteresis.

Over decades of research, two main lines of reasoning have been proposed to explain the causes of diel hysteresis between R_s and T_s. One is based on the physical processes of heat and gas transport in soils (Vargas and Allen, 2008; Phillips et al., 2011; Zhang et al., 2015). Soil CO_2 production is an integrated response to a non-uniform T_s profile (e.g., 0-1 m) at

10 discrete soil depths (e.g., 5 cm, 10 cm), thus T_s used in models is likely different in both magnitude and phase from the average T_s, which is involved in forcing soil CO_2 production (Phillips et al., 2011). However, in recent years, a second line of reasoning has emerged, which puts more importance on the role of biological initiators associated with photosynthate supply (Tang et al., 2005; Kuzyakov and Gavrichkova, 2010; Vargas et al., 2011; Wang et al., 2014). Aboveground photosynthesis, which usually peaks at midday (e.g., 11:00-13:00), provides substrate for belowground roots and rhizosphere-microbe

15 respiration, but oscillates out of phase with T_s, which usually peaks in the afternoon (e.g., 14:00-16:00). These studies point out that it is necessary to take photosynthesis into consideration for a more accurate interpretation of R_s (Tang et al., 2005; Kuzyakov and Gavrichkova, 2010; Vargas et al., 2011). In addition, both physical and biological processes are not mutually exclusive and both likely play important roles in affecting diel variation in R_s (Phillips et al., 2011; Zhang et al., 2015; Song et al., 2015). Currently, the causes of diel hysteresis between R_s and temperature remain largely unexplained.

20 Diel hysteresis between R_s and T_s has been shown to vary seasonally with soil water content (SWC; Tang et al., 2005; Riveros-Iregui et al., 2007; Carbone et al., 2008; Vargas and Allen, 2008; Ruehr et al., 2009; Wang et al., 2014). However, the influences of SWC on diel hysteresis are not consistent, and the mechanisms behind the influence of SWC on diel hysteresis remain also largely unexplained. Some studies have reported that high SWC tends to block CO_2 gas and thermal diffusion, resulting in large hysteresis loops (Riveros-Iregui et al., 2007; Zhang et al., 2015). In contrast, other studies have

25 reported low SWC and high vapour pressure deficits (VPD) promote partial stomata closure, which leads to higher photosynthesis in the morning (e.g., 9:00-10:00) and supressed photosynthesis in mid-afternoon, leading to pronounced diel hysteresis during dry periods (Tang et al., 2005; Vargas and Allen, 2008; Carbone et al., 2008; Wang et al., 2014). To understand the causes of diel hysteresis, it is clear that the role of SWC needs to be considered.

Drylands cover a quarter of the earths's land surface and play an important role in the global carbon (C) cycle (Safriel

30 and Adeel, 2005; Austin, 2011; Poulter et al., 2014). However, compared to forest ecosystems, few previous studies address soil respiration dynamics in drylands. Many studies in forest ecosystems are based on the application of physical soil CO_2 and heat transport models and evaluate the influences of SWC on CO_2 gas and thermal diffusion (Riveros-Iregui et al., 2007; Phillips et al., 2011; Zhang et al., 2015) and, in general, conclude that diel hysteresis can result from physical processes

alone. In comparison, few previous studies have evaluated the causes of diel hysteresis in drylands. Currently, it is not clear whether physical or biological processes (or their combination) dominate the control of diel hysteresis in drylands.

Drylands are characterized with low productivity and as weak organic C storage pools (West et al., 1994; Lange, 2003), which may result in large contributions of autotrophic production of CO_2 (increasing R_s) in drylands. Autotrophic components to R_s occurs as a direct consequence of root respiration, which has been shown to be firmly coupled (within several hours) to recent photosynthesis (Liu et al., 2006; Baldocchi et al., 2006; Högberg and Read, 2006; Bahn et al., 2009; Kuzyakov and Gavrichkova, 2010). Therefore, biologically photosynthesis-related processes may dominate the control of the asynchronicity between R_s and T_s in drylands. In drylands, especially in desert ecosystems characterized by sandy soils, high soil porosity, likely minimizes the influence of SWC on gas diffusion. In addition, water is the primary driver of biological activity in drylands (Noy-Meir, 1973). Under drought conditions, stomata closure in plants at midday reduces water losses, resulting in a suppression of photosynthesis (Jia et al, 2014). Such changes in diel patterns of photosynthesis likely result in modification of diel patterns in R_s, leading to hysteresis between R_s and T_s. Soil water content likely regulates photosynthesis-related processes and, in doing so, causes hysteresis between R_s and T_s to vary over the growing season.

In this study, we hypothesize that: (1) photosynthesis-related processes have a role in controlling hysteresis between R_s and T_s; and (2) SWC regulates the control of photosynthesis-related processes on hysteresis and its variation over the growing season. The main objectives of this research were to: (1) investigate seasonal variation in diel hysteresis between R_s and T_s; (2) explore the causes that lead to variation in diel hysteresis; and (3) understand how SWC influences diel hysteresis. To undertake this work, we measured R_s, SWC, T_s, and photosynthesis continuously in a desert-shrub ecosystem over a year 2013.

2 Materials and Methods

2.1 Site description

The study was conducted at Yanchi Research Station of Beijing Forestry University, Ningxia, northwest China (37°42'31" N, 107°13'37" E, 1550 m a.s.l). The station is located at the southern edge of the Mu Us desert in the transition between the arid and semi-arid climatic zones. Based on 51 years of data (1954-2004) from the Meteorological Station at Yanchi, the mean annual air temperature at the station was 8.1°C and the mean annual total precipitation was 292 mm (ranging between 250 to 350 mm), 63% of which fell in late summer (i.e., July-September; Wang et al., 2014; Jia et al., 2014). Radiation and evaporative demand were high at the station, i.e., annual incoming shortwave radiation was 1.4×10^{-5} MJ m^{-2} and annual potential evaporation was on average 5.5×10^{-3} kg m^{-2} d^{-1}. The soil at the research station was of a sandy type, with a bulk density of 1.6 g cm^{-3}. Soil organic matter, soil nitrogen, and pH were 0.21-2.14 g kg^{-1}, 0.08-2.10 g kg^{-1}, and 7.76-9.08, respectively (Wang et al., 2014; Jia et al, 2014). The vegetation was regenerated from aerial seeding that took place in 1998

and is currently dominated by a semi-shrub species, *Artemisia ordosica*, averaging about 50 cm tall with a canopy size of about 80 cm $\times$ 60 cm (for additional details, see Jia et al. 2014 and Wang et al. 2014 and 2015).

2.2 Soil respiration and photosynthesis measurement

Two permanent polyvinyl chloride soil collars were initially installed on a small fixed sand dune in March, 2012. The collars were 20.3 cm in diameter and 10 cm in height, with 7 cm inserted into the soil. One collar was set on bare land with an opaque chamber (LI-8100-104, Nebraska, USA) and the other over an *Artemisia ordosica* plant (~10 cm tall) with a transparent chamber (LI-8100-104C). Soil respiration (μmol CO_2 m^{-2} s^{-1}) was directly estimated from CO_2-flux measurements obtained with the opaque-chamber system. Photosynthetic rates (μmol CO_2 m^{-2} s^{-1}) of the selected plants were determined as the difference in CO_2 fluxes between the transparent- and the opaque-chamber.

Continuous measurements of CO_2 fluxes (μmol CO_2 m^{-2} s^{-1}) were made *in situ* over an entire year with a Li-8100 CO_2 gas analyzer and a LI-8150 multiplexer (LI-COR, Nebraska, USA) connected to each chamber. Instrument maintenance was carried out bi-weekly during the growing season, including removing plant-regrowth in the opaque-chamber installation, and cleaning to avoid blackout conditions associated with the transparent-chamber installation. Measurement time for each chamber was 3 minutes and 15 seconds, including a 30-second pre-purge, 45-second post purge, and 2-minute measurement period. The CO_2-flux data collected over 2013 were used in our analysis, after an initial period of site disturbance stabilization from March, 2012 to June, 2012.

2.3 Measurements of temperatures, soil water content and other environmental factors

Hourly soil temperature (T_s, ^{o}C) and volumetric soil water content (SWC, m^3 m^{-3}) at a 10-cm depth were measured simultaneously about 10 cm from the chambers using a LI-8150-203 temperature sensor and EC_{H2O} moisture sensor (LI-COR, Nebraska, USA; see Wang et al., 2014). Other environmental factors were recorded every half hour using sensors mounted on a 6-m-tall flux tower approximately 800 m from our soil CO_2-flux measurement site. Air temperature (T_a, ^{o}C) was measured with a thermohygrometer (HMP155A, Vaisala, Finland). Soil surface temperature (T_{surf}, ^{o}C) was measured with an infrared-emission sensor (Model SI-111, Campbell Scientific Inc., USA). Incident photosynthetically active radiation (PAR) was measured with a light-quantum sensor (PAR-LITE, Kipp and Zonen, the Netherlands) and precipitation (PPT, mm), with three tipping-bucket raingauges (Model TE525MM, Campbell Scientific Inc., USA) placed 50 m from the flux tower (see Jia et al., 2014).

2.4 Data processing and statistical analysis

In this study, the Q_{10} function (e.g., Eq. (1)) is used to describe the response of R_s to temperature. The response of R_s to changes in photosynthesis is characterized by a linear function (Eq. (2)). Correlation coefficient, magnitude of hysteresis, and model performance are used to evaluate whether photosynthesis or temperature dominate diel R_s. Relative importance

(RI) of temperature and photosynthesis in defining R_s over the growing season was calculated with a ratio of $\rho_p : \rho_t$ (Eq. (3)), where ρ_p is the correlation coefficient between photosynthesis and R_s, and ρ_t is the correlation coefficient between temperature and R_s. The greater the RI-value, the more important photosynthesis is to R_s.

$$R_s = R_{10} \times Q_{10}^{(T-10)/10} \tag{1}$$

$$R_s = \text{a} \times P + b \tag{2}$$

$$RI = \frac{\rho_p}{\rho_t} \tag{3}$$

where R_{10} is the respiration at 10°C, Q_{10} is the temperature sensitivity of respiration, T is temperature, and P is photosynthesis (μmol CO_2 m^{-2} s^{-1}), with a and b as regression coefficients.

Measurements of CO_2 fluxes were screened by means of limit checking, i.e., hourly CO_2-flux data < -30 or > 15 μmol CO_2 m^{-2} s^{-1} were considered to be anomalous as a result of, for instance, gas leakage or insect assault and immediately removed from the dataset (Wang et al., 2014, 2015). After limit checking, hourly CO_2 fluxes greater than three times the standard deviation from the calculated mean of 5 days' worth of flux data were also removed. Quality control and instrument failure together resulted in 5% loss of hourly fluxes for all chambers, 4% for temperatures, and 8% for SWC (Fig. 1).

Pearson correlation analysis was used to calculate the correlation coefficient between temperature or photosynthesis and R_s. Cross-correlation analysis was used to estimate hysteresis in temperature-R_s and photosynthesis-R_s relationships. We used root mean squared error ($RMSE$) and the coefficient of determination (R^2) as criteria in evaluating model performance. To evaluate seasonal variation in diel hysteresis, the mean monthly diel cycles of R_s, T_a, T_{surf}, T_s, and photosynthesis were calculated by averaging their hourly means at a given hour over a particular month (Table 1). Exponential and linear regression was used to evaluate influence of SWC on the control of photosynthesis over temperature-R_s hysteresis. Further on, influences of SWC on diel hysteresis was examined in a wet month with highest rainfall and adequate SWC (July, PPT = 117.9 mm) and a dry month with low rainfall and inadequate SWC (August, PPT = 10.9 mm) during the growing season (see Wang et al., 2014). All statistical analyses were performed in MATLAB, with a significance level of 0.05 (R2010b, Mathworks Inc., Natick, MA, USA).

3 Results

3.1 Diel patterns of soil respiration, photosynthesis, and environmental factors

Incident photosynthetically active radiation, T_a, T_{surf}, and T_s showed clear and stable diel patterns over the year (Fig. 1a-d), peaking at ~12:00 PM (Local Time, LT), ~16:00 PM, ~14:00 PM, and ~17:00 PM, respectively (Fig. 1a-d). Unlike environmental factors, diel patterns in R_s remained stable over the non-growing season, peaking at 11:00 AM-13:00 PM, and being highly variable during the growing season, peaking between 10:00 AM-16:00 PM (Fig. 1f). Similar to R_s during the

growing season, diel patterns of photosynthesis were also highly variable, peaking between 10:00 AM-16:00 PM (Fig. 1e). Diel patterns of monthly mean R_s were similar to T_{surf} during the wet month and similar to photosynthesis during the dry month (Fig. 2g, h).

3.2 Relative control of photosynthesis and temperature on diel soil respiration

5   Among temperatures at the three soil depths, T_{surf} correlated best with diel R_s, due to the high R^2's with monthly mean diel R_s throughout the year (Table 1). Over the growing season, monthly mean diel R_s was also significantly correlated with photosynthesis (Table 1). The response of R_s to temperature and photosynthesis was affected by SWC during the growing season (Table 2; Fig. 3). During the wet month (July) with precipitation of 117.9 mm, T_{surf} alone explained 97% of the variation in diel R_s (Q_{10} function), whereas photosynthesis explained 67% of it (Fig. 3a, Table 2). However, during the dry

10   season with precipitation of 10.9 mm, photosynthesis explained 88% of the variation in diel R_s, (by way of Eq. (2), whereras T_{surf} explained 76% of it (Fig. 3b, Table 2). Over the growing season, RI of photosynthesis and temperature on R_s was significantly affected by SWC (Fig. 4), and decreased with increasing SWC.

3.3 Effects of soil water content on diel hysteresis in temperature-R_s relationship

Diel hysteresis in both T_{surf}-R_s and photosynthesis-R_s relationships were affected by SWC (Fig. 5). In the wet month (July),

15   monthly mean diel R_s was out of phase with photosynthesis, but in phase with T_{surf} (Fig. 2g). Soil respiration peaked at 16:00 PM, being very similar timing to that of T_{surf} (i.e., 15:00 PM), but four hours later than photosynthesis (peaking at 12:00 PM; Fig. 2g). In the dry month (August), however, diel R_s was in phase with photosynthesis, but out of phase with T_{surf} (Fig. 2h). Both photosynthesis and R_s plateaued between 10:00 AM-16:00 PM, whereas T_{surf} peaked at 15:00 PM (Fig. 2h). Over the growing season, the diel hysteresis between R_s and T_{surf} was linearly related to SWC when $SWC < 0.08$ m^3 m^{-3} (Fig. 5a). No

20   hysteresis was observed when $SWC > 0.08$ m^3 m^{-3} (Fig. 5a). In contrast, diel hysteresis between R_s and photosynthesis was linearly related to SWC, when $SWC < 0.08$ m^3 m^{-3} (Fig. 5b), but ceased to be related, when $SWC > 0.08$ m^3 m^{-3} ($p = 0.439$; Fig. 5b).

4 Discussion

4.1 Physical- vs. biological-processes in the control of diel hysteresis

25   In our study, we found that the diurnal pattern in temperature (T_a, T_{surf}, and T_s) lagged behind that in R_s by several hours, which resulted in a counter-clockwise loop in the relationship between R_s and temperature. Although the magnitude of diel hysteresis between R_s and temperature differed among the three soil depths, their seasonal variation was generally consistent. Among the temperatures measured at the three depths, T_{surf} was more closely related to diel R_s, resulting in weaker hysteresis.

The magnitude of hysteresis between R_s and T_{surf} was in our study comparable to those in other plant systems, e.g., 3.5-5 h in a boreal aspen stand (Gaumont-Guay et al., 2006) and 0-5 h in a Chinese pine plantation (Jia et al., 2013).

Contradictory results exist on the effects of SWC on hysteresis between R_s and temperature. Some studies have reported that the greatest diel hysteresis in temperature and R_s occurs during dry months (Tang et al., 2005; Vargas and Allen, 2008; Carbone et al., 2008; Wang et al., 2014), which is consistent with our finding. Whereas, some studies have reported strong hysteresis-loops under high SWC (Riveros-Iregui et al., 2007; Zhang et al., 2015). These contrasting findings may be a result of differences in soil properties and biophysical processes. In montane-conifer forests (Riveros-Iregui et al., 2007) and pine plantations (Zhang et al., 2015), dense soils have a greater influence on within-soil gas transport, resulting in physical aspects of the soil having a greater control on diel hysteresis. High SWC tends to block gas transport, leading to larger hysteresis than under low SWC. However, sandy soils with high soil porosity, as on our site, have a minor influence on within-soil gas transport processes. As a result of this, biological processes become more important in controlling diel hysteresis. During dry months of the growing season, low SWC causes stomata closure (Tang et al., 2005; Vargas and Allen, 2008; Carbone et al., 2008; Jia et al., 2014; Wang et al., 2014), suppressing photosynthesis (Fig. 2). Diel R_s followed diel photosynthesis under low SWC, resulting in a large hysteresis between R_s and temperature (Fig. 2). Our results confirm the important role of biological processes in regulating diel hysteresis which has been suggested also in many previous studies (Högberg et al., 2001; Tang et al., 2005; Sampson et al., 2007; Kuzyakov and Gavrichkova, 2010; Mencuccini and Hölttä, 2010). It also, thus is consistent with our first hypothesis.

4.2 Causes and the influences of soil water content on seasonal variation in diel hysteresis

In our study, diel R_s varied consistently with T_{surf}, and no observable hysteresis was found when $SWC > 0.08$ m³ m⁻³. However, as SWC decreased from this value, diel R_s varied more closely with photosynthesis, leading to increased diel hysteresis between R_s and T_{surf}. These results suggest that SWC regulated the relative control of photosynthesis and temperature on diel R_s over the growing season, supporting our second hypothesis.

Possible reason for SWC regulation might be associated with changes in the relative contribution of autotrophic and heterotrophic respiration to total R_s in response to rainfall-induced changes in SWC. In our study, the periods with $SWC > 0.08$ m³ m⁻³ only lasted several days (Fig. 1g, h). Resource pool accumulation on the soil surface may have resulted from microbial growth and nutrient mineralization between successive precipitation events (Fisher et al., 1987). Most organic matter and microbes tend to concentrate in the upper part of the soil, whereas plant roots are found much deeper. Consequently, wet periods with $SWC > 0.08$ m³ m⁻³ drive heterotrophic activity, but not enough or long enough to elicit autotrophic activity (Sponseller 2007; Song et al., 2015), leading to a higher relative contribution of heterotrophic respiration to total R_s. Heterotrophic respiration has been reported to respond primarily to soil surface temperature (Lloyd and Taylor, 1994; Winkler et al., 1996). Therefore, diel R_s co-varied much more strongly with T_{surf}, eliminating hysteresis altogether when $SWC > 0.08$ m³ m⁻³. By contrast, dry periods with $SWC < 0.08$ m³ m⁻³ often occurred between successive precipitation

events (Fig. 1g, h). Heterotrophic respiration was observed to be largely suppressed during these periods (Borken et al., 2006), giving opportunity for autotrophic respiration to contribute to total R_s. Since root respiration has been reported to be firmly associated with photosynthesis (Liu et al., 2006; Baldocchi et al., 2006; Högberg and Read, 2006; Kuzyakov and Gavrihkova, 2010), it is not surprising that R_s is seen to co-vary with photosynthesis during dry periods. Although we could

5 not directly show changes in relative contribution between autotrophic and heterotrophic respiration to total R_s, the changes in relative correlation and diel patterns during the dry and wet months could be used to indirectly confirm our inference. Casals et al. (2011) reported that the ratio of autotrophic components increased in response to drought, increasing the influence of recent photosynthate supply to R_s during drought, which is also consistent with our finding.

Our work provides urgently needed new knowledge concerning causes/mechanisms involved in defining variation in
10 diel hysteresis in desert-shrub ecosystems. Based on our work, we suggest that diel photosynthesis should be considered in simulations of diel R_s in drylands, especially when SWC falls below 0.08 m^3 m^{-3}. This information would be particularly useful when processing ecosystem fluxes obtained with eddy covariance measurements, rather than rely on relating daytime simulations of R_s to night-time respiration-temperature relationships. This would involve more complex, iterative methods than are currently used because of the implied feedback.

15 **5 Conclusions**

Soil water content regulated the relative control between photosynthesis and temperature on diel R_s by changing the relative contribution of autotrophic and heterotrophic respiration to total R_s, causing seasonal variation in diel hysteresis between R_s and temperature. Hysteresis was not observed between R_s and T_{surf}, when $SWC > 0.08$ m^3 m^{-3}, but lag-hours increased between the co-variation in the variables as SWC decreased below this threshold. Our findings highlight the importance of
20 biological mechanisms in diel hysteresis between R_s and temperature and the importance of SWC in plant photosynthesis-soil respiration dynamics in dryland ecosystems.

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Table 1. Analysis of mean monthly diel cycles of soil respiration (R_s), air temperature (T_a), soil surface temperature (T_{surf}), soil temperature at a 10-cm depth (T_s), and photosynthesis (P) in a dominant desert-shrub ecosystem, including correlation coefficients and lag times in R_s *vs.* T_a, T_{surf}, T_s, and P cycles. Pearson's correlation coefficients (r) that are significant (i.e., $p < 0.05$) are denoted in bold.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R_s-T_a	Lag	2	4	3	3	1	1	1	2	1	1	1	1
	r	**0.64**	0.25	**0.49**	**0.46**	**0.85**	**0.85**	**0.93**	**0.76**	**0.94**	**0.89**	**0.78**	**0.77**
R_s-T_{surf}	Lag	1	2	2	2	0	0	0	1	0	0	1	1
	r	**0.82**	**0.57**	**0.75**	**0.72**	**0.96**	**0.96**	**0.98**	**0.87**	**0.98**	**0.97**	**0.89**	**0.87**
R_s-T_s	Lag	4	5	5	5	3	3	2	4	2	2	4	4
	r	-0.06	-0.31	-0.06	-0.07	**0.54**	**0.58**	**0.80**	0.31	**0.77**	**0.65**	0.23	0.12
R_s-P	Lag					-1	-1	-2	0	-1	-1		
	r					**0.84**	**0.83**	**0.82**	**0.94**	**0.86**	**0.88**		

Table 2. Regressions based on the Q_{10} and linear models of soil respiration (R_s) for a wet and a dry month. Variables T_{surf} (°C) refers to the soil surface temperature; P photosynthesis in the dominant shrub layer; R^2 the coefficient of determination; and *RMSE* the root mean squared error.

	Model	Wet month: July	Dry month: August
T_{surf}-R_s	Q_{10}	$R_s = 1.13 \times 1.4^{\frac{T_{surf}-10}{10}}$ $R^2 = 0.97$ $RMSE = 0.0521$	$R_s = 1.12 \times 1.1^{\frac{T_{surf}-10}{10}}$ $R^2 = 0.76$ $RMSE = 0.0796$
P-R_s	Linear	$R_s = 0.03 \times P + 1.61$ $R^2 = 0.67$ $RMSE = 0.1889$	$R_s = 0.04 \times P + 1.29$ $R^2 = 0.88$ $RMSE = 0.05752$
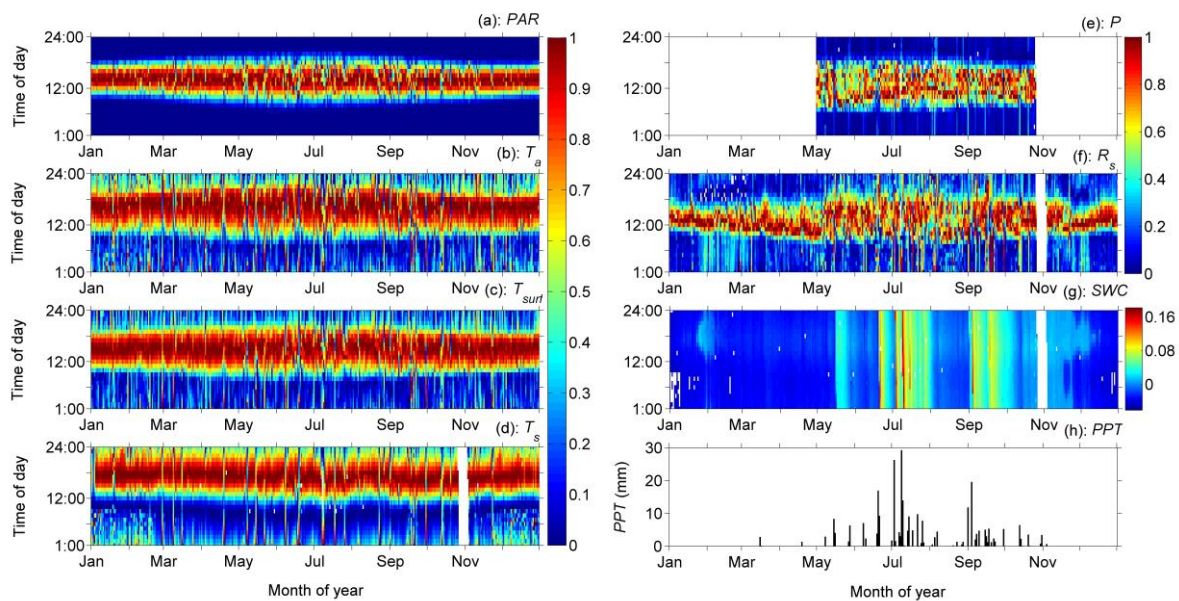
Figure 1. Seasonal variation in incident photosynthetically active radiation (*PAR*), temperature [i.e., air temperature (T_a), soil surface temperature (T_{surf}), soil temperature (T_s)], photosynthesis (*P*), and soil respiration (R_s) in *Artemisia ordosica*, and seasonal variation in soil water content (*SWC*) and precipitation (*PPT*) for 2013. Hourly *PAR*, T_a, T_{surf}, T_s, R_s, and *P* are normalized against all values for each day.

5 Each hourly value (*y*-axis) for each day (*x*-axis) is shown as a value of 1 through 0; 1 denotes the peak value for the day and 0, the daily minimum.
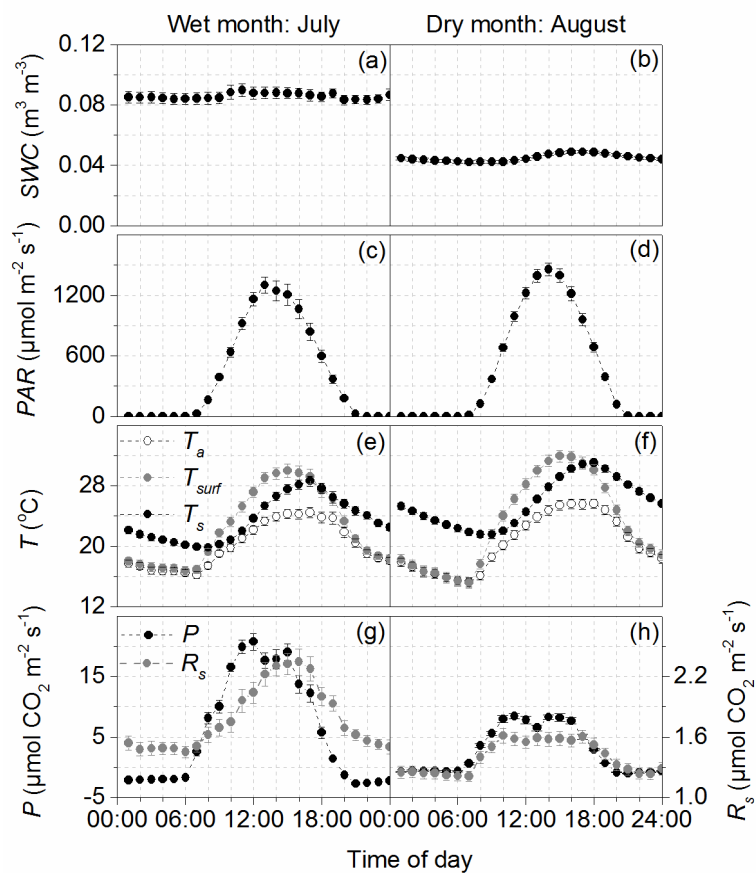
Figure 2. Mean monthly diel cycle of soil water content (*SWC*), incident photosynthetically active radiation (*PAR*), temperature [air temperature (T_a), soil surface temperature (T_{surf}), soil temperature (T_s)], soil respiration (R_s), and photosynthesis (*P*) in *Artemisia ordosica* during a wet (July) and dry (August) month. Each point is the monthly mean for a particular time of day. Bars represent standard errors.
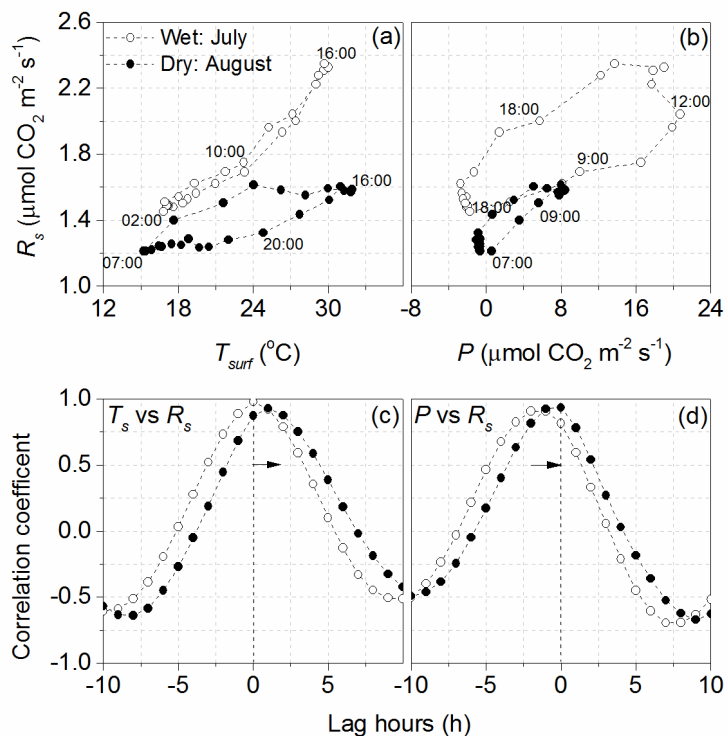
Figure 3. Diel soil respiration (R_s) *vs.* soil surface temperature (T_{surf}), diel R_s *vs.* photosynthesis in *Artemisia ordosica* (*P*), and their lag correlations during a wet (July) and dry (August) month.
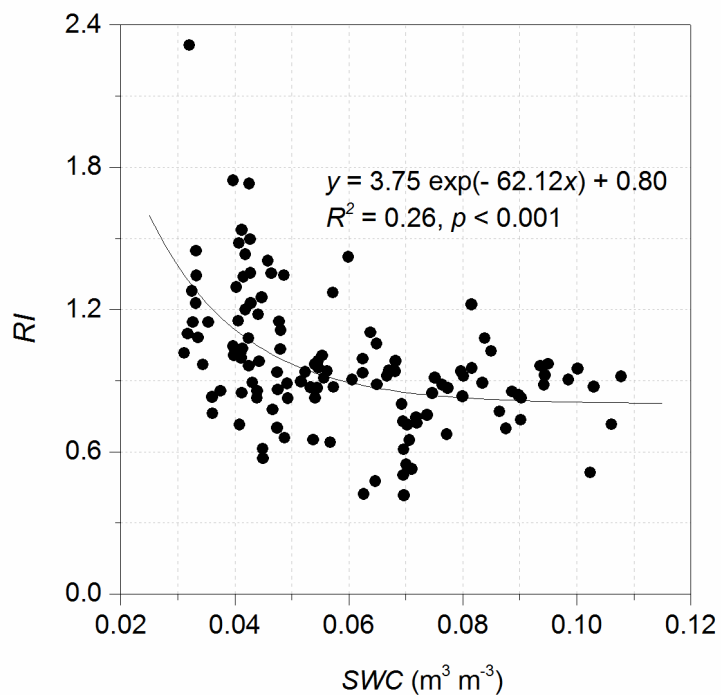
Figure 4. Relationship between soil water content (*SWC*) and the relative importance (*RI*) of soil surface temperature and photosynthesis in *Artemisia ordosica* with respect to diel soil respiration.
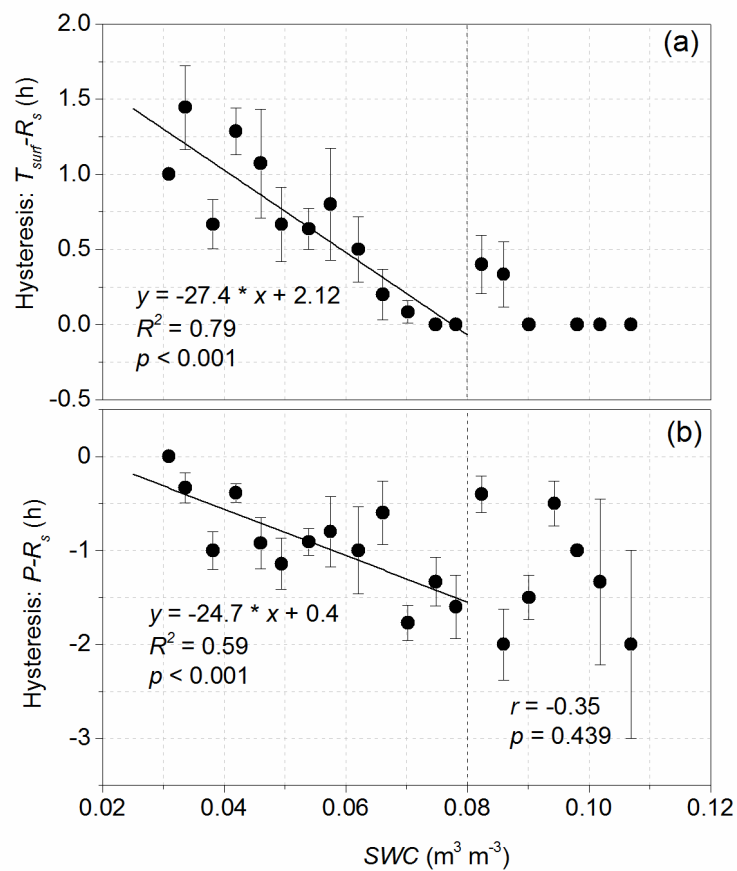
Figure 5. Lag time between soil respiration (R_s) and soil surface temperature (T_{surf}), R_s, and photosynthesis in *Artemisia ordosica*, and in relation to soil water content (*SWC*). Lag time were bin-averaged using *SWC*-intervals of 0.004 m^3 m^{-3}.