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# The abiotic contribution to total CO<sub>2</sub> flux for soils in arid zone

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## Abstract

As an important component of ecosystem carbon budgets, soil carbon dioxide (CO<sub>2</sub>) flux is determined by a combination of a series of biotic and abiotic processes. Although there is evidence that the abiotic component can be important in total soil CO<sub>2</sub> flux, its relative importance has never been systematically assessed. In this study, the total soil CO<sub>2</sub> flux ( $R_{\text{total}}$ ) was partitioned into biotic ( $R_{\text{biotic}}$ ) and abiotic ( $R_{\text{abiotic}}$ ) components over eight typical landscapes in a desert–oasis ecotone, including cotton field, hops field, halophyte garden, reservoir edge, native saline desert, alkaline soil, dune crest and interdune lowland in the Gurbantunggut Desert, and the relative importance of these two components was analyzed. Results showed that  $R_{\text{abiotic}}$  always contributed to  $R_{\text{total}}$  for the eight landscapes, but the degree of contribution varied greatly. In the cotton and hops fields, the ratio of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$  was extremely low ( $< 10\%$ ); whereas  $R_{\text{abiotic}}$  was dominant in the alkaline soil and dune crest. Statistically,  $R_{\text{abiotic}}/R_{\text{total}}$  decreased logarithmically with rising  $R_{\text{biotic}}$ , suggesting that  $R_{\text{abiotic}}$  strongly affected  $R_{\text{total}}$  when  $R_{\text{biotic}}$  was low. This pattern confirms that soil CO<sub>2</sub> flux is predominantly biological in most ecosystems, but  $R_{\text{abiotic}}$  can dominate when biological processes are weak. On a diurnal basis,  $R_{\text{abiotic}}$  resulted in no net gain or loss of carbon but its effect on instantaneous CO<sub>2</sub> flux was significant. Temperature dependence of  $R_{\text{total}}$  varied among the eight landscapes, determined by the predominant components of CO<sub>2</sub> flux: with  $R_{\text{biotic}}$  driven by soil temperature and  $R_{\text{abiotic}}$  regulated by the rate of change in temperature. Namely, declining temperature resulted in negative  $R_{\text{abiotic}}$  (CO<sub>2</sub> went into soil), while rising temperature resulted in a positive  $R_{\text{abiotic}}$  (CO<sub>2</sub> released from soil). Furthermore, without recognition of  $R_{\text{abiotic}}$ ,  $R_{\text{biotic}}$  would have been either overestimated (for daytime) or underestimated (for nighttime). Thus, recognition that abiotic component in total soil CO<sub>2</sub> flux is ubiquitous in soils has widespread consequences for the understanding of carbon cycling. While the abiotic flux will not change net daily soil CO<sub>2</sub> exchange and not likely directly constitute a carbon sink, it can alter transient soil CO<sub>2</sub> flux significantly, either in magnitude or in its temperature dependency.

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## 1 Introduction

As the primary path to release plant-fixed carbon dioxide (CO<sub>2</sub>) back to the atmosphere (Ryan and Law, 2005), soil CO<sub>2</sub> flux, often referred to as “soil respiration”, releases carbon (C) at a rate that is more than one order of magnitude larger than the anthropogenic emission (Marland et al., 2008). Thus, a small change in soil CO<sub>2</sub> flux can have a strong impact on the balance of atmosphere CO<sub>2</sub> concentration (Raich et al., 2002). Moreover, soil CO<sub>2</sub> flux has been used to characterize certain ecosystem processes and properties, such as soil C turnover time (Barrett et al., 2006; Elberling et al., 2006), the functional role for differing origins of soil organic matter in global C cycling (Crow et al., 2006) and distributions and activities of belowground biotic sources (e.g. microbes; Shamir and Steinberger, 2007). Thus, a mechanistic understanding of soil CO<sub>2</sub> flux is central to understanding the C cycle in terrestrial ecosystems (Ball et al., 2009).

Substantial studies have explored the driving factors of soil CO<sub>2</sub> flux, but large uncertainties remain (Davidson and Janssens, 2006; Carbone et al., 2008; Hardie et al., 2011). At the global scale, soil CO<sub>2</sub> flux is significantly correlated with mean annual temperature and mean annual precipitation (Raich and Schlesinger, 1992; Raich et al., 2002). At the smaller scale, however, no consensus has been reached – dominant factors may vary greatly from region to region (Davidson et al., 1998; Liu et al., 2006) and even differ within the same ecosystem type (Cable et al., 2011; Ma et al., 2013). An important reason for such variations is that soil CO<sub>2</sub> flux is a combination of a series of biotic and abiotic processes, each of which experiences its own flux behavior at a variety of time scales and responds differently to environmental factors (Li et al., 2005; Ryan and Law, 2005). Conventional wisdom is that soil CO<sub>2</sub> flux comprises mainly root (autotrophic) and microbial (heterotrophic) respiration. Heterotrophic respiration is regulated mainly by soil temperature and moisture while autotrophic respiration (e.g. root respiration) may be closely linked to C assimilation and allocation (Li et al., 2005; Tang et al., 2005). Confused by recent observations of the negative flux (i.e. CO<sub>2</sub> goes

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into soil) (Parsons et al., 2004; Stone, 2008; Xie et al., 2009; Shanhun et al., 2012; Ma et al., 2013), uncertainty concerning soil CO<sub>2</sub> fluxes has increased, for there is an unstated hypothesis that biotic sources (including autotrophic and heterotrophic respiration) only release CO<sub>2</sub> out of the soil (Baldocchi, 2003). Abiotic processes, such as carbonate dissolution (Emmerich, 2003; Mielnick et al., 2005; Stevenson and Verburg, 2006), surface adhesion of CO<sub>2</sub> on soil particles (Parsons et al., 2004), ventilation of subterranean cavities (Serrano-Ortiz et al., 2010) and changes in CO<sub>2</sub> solubility in soil water films (Karberg et al., 2005; Ma et al., 2013), were suggested to be related to total CO<sub>2</sub> flux on short time scales. An extreme but powerful example is that in saline desert (Xie et al., 2009) and Antarctic dry valleys (Parsons et al., 2004; Shanhun et al., 2012), where biotic respiration is inherently low due to low biotic activity (Cable et al., 2011), abiotic flux has a pronounced and even dominant contribution to total soil CO<sub>2</sub> flux (Ma et al., 2013). Such an abiotic flux would be combined with biotic flux to determine the magnitude and sign (positive or negative) of the CO<sub>2</sub> flux. Thus, the surface flux can be significantly modified by the “hidden” and neglected abiotic flux, and the extent of this modification varies among different ecosystems and landscapes. To date, however, no experiment has determined the character of the abiotic CO<sub>2</sub> flux, and quantified the magnitude of its impact on the total soil CO<sub>2</sub> flux over a variety of landscapes (Elberling et al., 2014), which represents a significant gap in our knowledge of soil CO<sub>2</sub> fluxes.

In the Gurbantunggut Desert, negative CO<sub>2</sub> flux has been regularly observed in long-term soil monitoring (Xie et al., 2009; Ma et al., 2013). This desert region includes different landscapes, such as saline or sandy desert, farmland, botanical gardens and reservoirs. Correspondingly, soil properties and plant biological and microbial activities vary dramatically among these landscapes, which is likely to have very different effects on biotic or abiotic fluxes. Thus, soil CO<sub>2</sub> flux over these landscapes was predicted to vary greatly due to different compositions of biotic and abiotic components. Addressing this prediction, the total soil CO<sub>2</sub> flux was partitioned into biotic and abiotic parts and the relative importance of these two components was analyzed over eight typical landscapes (cotton field, hops field, halophyte garden, reservoir edge, native saline desert,

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alkaline soil, dune crest and interdune lowland) in this arid region. We hypothesized that biotic flux is largely controlled by soil organic matter content and root biomass due to their inherent association with biotic respiration; whereas, the magnitude of abiotic flux is controlled by inorganic C processes such as dissolution of CO<sub>2</sub> in soil water. 5 Additionally, we predicted that the contribution of abiotic flux to total soil CO<sub>2</sub> flux would be most significant for various desert landscapes.

## 2 Methods

### 2.1 Study areas

This study was conducted on an alluvial plain in the southern Gurbantunggut Desert region, China. With the involvement of human activity, this area has become a typical 10 desert–oasis ecotone. The climate of the region is arid temperate. Soils in this area are poorly weathered, typically with high pH and salt content, low moisture availability and low organic matter content (Table 1); consequently microbial biomass and soil biota abundance are also very low compared to other ecosystems.

15 To determine the potential abiotic contribution to total soil CO<sub>2</sub> flux, eight typical sites were selected based on apparent differences in land use types from oasis to desert: cotton field, hops field, halophyte garden, reservoir edge, native saline desert, alkaline soil, dune crest and interdune lowland in Gurbantunggut Desert. These formed gradients in biological activity, pH and electrical conductivity (EC, a proxy for soil salt content). Soil properties, including soil C content (organic and inorganic C), pH, EC, 20 soil moisture and living root biomass are listed in Table 1.

### 2.2 Control experiment and flux measurement

Based on the above description, a total of eight types of soil samples were selected to represent biological activity, pH and EC gradient in the field. Undisturbed soil was

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obtained by stainless steel tube (height 25 cm, inner diameter 20 cm and outer diameter 21 cm). Specific sampling processes were as follow: first, stainless steel tubes were pounded vertically into the soil by a hammer until the upper edge was about 4 cm from the soil surface, which represented the parameter “offset” in the subsequent CO<sub>2</sub> 5 flux measurements. The soils around the tubes were then dug out, and stainless steel circular plates (3 mm thick), with the diameter slightly greater than the tubes (approximately 20.5 cm), were carefully inserted into the soil along the bottom edge of the tubes. After that, the soil columns were lifted out and the bottom plates were carefully sealed with waterproof fabric to prevent any kind of material exchange (e.g. water or 10 gas). To reduce damage to soil cores in the process of pounding the tubes into the soil, an approximately 15° slope was designed on the outer edge of the bottom end of the stainless steel tube. For each sample site, a total of six undisturbed soil columns were obtained (three for sterilization treatment and another three in natural condition).

A series of sterilization experiments were conducted to partition the potential abiotic 15 contribution to total soil CO<sub>2</sub> flux. The fluxes over sterilized and natural soil were considered abiotic ( $R_{\text{abiotic}}$ ) and total flux ( $R_{\text{total}}$ ), respectively, with the difference between the two representing the biotic flux ( $R_{\text{biotic}}$ ). For sterilized soils, the tops of the stainless steel tubes were sealed by layers of filter and brown paper to minimize water infiltrating into the soil column. Sterilization was achieved in a medical autoclave for 24 h at 20 120 °C. After sterilization treatment, the tubes were placed in an ultraviolet (UV) radiation sterilized room to allow soil cores to equilibrate with surrounding conditions. The non-heated soil remained at ambient field temperature. The tubes were then moved out and reburied in the field with the soil surface inside the tube at an equivalent height to the surrounding soil, so that the tube “wings” were flush with the soil. Doing so allowed the soil temperature to maintain natural fluctuations. It should be noted that all 25 tubes were reburied in the site of native saline desert, which was the nearest site to the laboratory. The aboveground parts of plants, for the heat treatment soils, were removed before the soil column was sealed; for the non-heated soils, to maintain root activity in the flux measurement, the plant aboveground parts were removed immediately before

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measurement started. Furthermore, all measurements were conducted on clear days within 1 month (July) to preserve similar amplitudes and peak times in temperature fluctuation.

CO<sub>2</sub> flux was measured with an Automated Soil CO<sub>2</sub> Flux System (LI-8150, Lincoln, Nebraska, USA), equipped with six long-term monitoring chambers (LI-8100-104, Lincoln, Nebraska, USA). Fluxes were recorded at 30 min intervals for 2 days for each set of soil samples. We denote CO<sub>2</sub> flux from soil to atmosphere with positive values; thus, negative values indicate CO<sub>2</sub> moving from atmosphere into soil.

To evaluate the contribution of abiotic flux to the total soil CO<sub>2</sub> flux, ratios of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$  were calculated for the eight sites when  $R_{\text{abiotic}}$  was positive:

$$\text{Ratio} = \frac{R_{\text{abiotic}}}{R_{\text{total}}} \bigg|_{R_{\text{abiotic}} > 0}$$

Cumulative CO<sub>2</sub> exchange of  $R_{\text{biotic}}$  and  $R_{\text{abiotic}}$  were calculated by numerical integration of  $R_{\text{biotic}}$  or  $R_{\text{abiotic}}$  during a particular period (e.g. the period of  $R_{\text{abiotic}} > 0$  or  $R_{\text{abiotic}} < 0$ ) as follows:

$$\text{Cumulative CO}_2 \text{ exchange of } R_{\text{abiotic}} = \sum_{R_{\text{abiotic}} > 0 \text{ or } R_{\text{abiotic}} < 0} R_{\text{abiotic}} \times 44 \times 1800/1000$$

Soil temperature ( $T_{\text{soil}}$ ) was measured at 5 cm below the soil surface in a soil profile close to the chambers, using a thermocouple connected to the LI-8150, and recorded when each flux measurement was taken.

### 2.3 Soil properties measurement

At the completion of each group of flux measurements, approximately 200 g of soil was collected from each soil core to a depth of 10 cm. All the samples were divided into two parts: one part was sealed in aluminum specimen boxes to estimate soil moisture content by conventional balance-weighing and oven-drying method; the other part was

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sealed in a hermetic bag, taken to the laboratory and used to determine pH, EC and soil C contents (i.e. organic and inorganic C). All the soil samples used for chemical analyses were air-dried and sieved (< 1 mm) in advance. Soil pH and EC were determined on a 1 : 5 soil : deionized water suspension, using PP-20 Professional Meter (Sartorius, Germany) and a portable conductivity meter (Hach, USA), respectively. Soil total C and inorganic C were measured using a total organic C/total nitrogen analyzer (multi C/N 3100, Analytik Jena, Germany), and the difference between the two values was taken to represent the organic C content.

In addition, for each intact soil core, living roots were sieved out (100-mesh sieve) and weighed to estimate the living root biomass.

### 2.4 Statistical analyses

One way analysis of variance (ANOVA) was used to test for differences in mean soil properties among the eight landscapes. Stepwise multiple regressions were used to identify predominant factors for total soil CO<sub>2</sub> flux and its biotic and abiotic components. All data analysis was performed with SPSS 16.0 and Origin 8.0 software.

## 3 Results

### 3.1 Soil properties

Soil organic C content differed significantly among the eight sites ( $F = 102.5$ ,  $P < 0.001$ ), with a maximum of 15.85 ( $\pm 0.38$ ) g kg soil<sup>-1</sup> in the hops field and a minimum of 0.57 ( $\pm 0.07$ ) g kg soil<sup>-1</sup> in dune crest (Table 1). The average concentration of soil organic C content was 5.98 g kg soil<sup>-1</sup>. The eight sites differed in inorganic C contents ( $F = 92.54$ ,  $P < 0.001$ ), with an average of 5.08 g kg soil<sup>-1</sup>, which is comparable with the average content of organic C. However, there was no significant correlation between organic and inorganic C contents ( $P = 0.83$ ). For example, soil organic C contents were significantly higher than inorganic C in cotton field, halophyte garden, hops

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field and interdune lowland but inorganic C dominated in dune crest, reservoir edge, alkaline soil and native saline desert.

Soil properties varied significantly among the eight sites (Table 1). Gravimetric soil moisture content was highest in the cotton field and lowest in the alkaline soil (5  $F = 79.24$ ,  $P < 0.001$ ), with coefficient of variation of 89.36 %. Soil pH was high for all eight sites, with a minimum of 8.00 ( $\pm 0.10$ ), indicating that the soils were all strongly alkaline. EC, a proxy for soil salt concentration, was in the range of 0.09 ( $\pm 0.01$ ) to 14.23 ( $\pm 0.87$ )  $\text{dS m}^{-1}$ . In addition, the living root biomass, regarded as the most active contributor to  $\text{CO}_2$  flux (Hanson et al., 2000), was low for all eight sites, with average (10  $18.78 \text{ g m}^{-2}$ , but with significant differences among sites. The maximum of living root biomass was  $47.75 (\pm 4.46) \text{ g m}^{-2}$  in the cotton field; whereas there was little root biomass in alkaline soil, with  $0.32 (\pm 0.14) \text{ g m}^{-2}$ . Thus, the eight sites showed significant differences in soil properties and root biomass, along with a wide range of soil organic and inorganic C contents, and provided a natural gradient to differentiate the contributions of  $R_{\text{biotic}}$  and  $R_{\text{abiotic}}$ . (15  $R_{\text{biotic}}$  and  $R_{\text{abiotic}}$ .

### 3.2 Partitioning $R_{\text{total}}$ into $R_{\text{biotic}}$ and $R_{\text{abiotic}}$

$R_{\text{total}}$  exhibited similar diurnal patterns across the eight sites, with positive values in the day and single peaks during 13:00–16:00, but with significant differences in flux rates. For example, the maxima of  $R_{\text{total}}$  were 3.72, 2.03, 2.12, 1.28, 1.13, 0.53, 0.42 (20  $0.45 \mu\text{mol m}^{-2} \text{ s}^{-1}$  in cotton field, hops field, halophyte garden, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, respectively. In particular,  $R_{\text{total}}$  was negative during the night in sites of native saline desert, dune crest and alkaline soil, in which  $R_{\text{biotic}}$  was relatively low in the range of  $0.001\text{--}0.364 \mu\text{mol m}^{-2} \text{ s}^{-1}$  (Fig. 1f–h). By comparing  $\text{CO}_2$  fluxes from soils after sterilization treatment with those in natural condition,  $R_{\text{total}}$  was partitioned into  $R_{\text{biotic}}$  and  $R_{\text{abiotic}}$  (Fig. 1). There were significant differences in  $R_{\text{biotic}}$  among the eight sites, either in flux rate or diurnal pattern. Maximum  $\text{CO}_2$  flux rates decreased following the sequence of hops field, halo-

phyte garden, hops field, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, with the average flux rate being  $0.579 \mu\text{mol m}^{-2} \text{ s}^{-1}$ . The diurnal patterns of  $R_{\text{biotic}}$  were all similar to those of  $R_{\text{total}}$  (Pearson's correlation coefficients  $r$  values were in the range of 0.939–0.996,  $P < 0.001$ ). However, for the native saline desert, dune crest and alkaline soil sites,  $R_{\text{total}}$  had a significant relationship (5  $\text{with } R_{\text{abiotic}}$ , with  $r = 0.949, 0.965$  and  $0.993$  ( $P < 0.001$ ), respectively. These variations implied that there were different dominant factors (i.e. abiotic or biotic processes) in  $R_{\text{total}}$ . For  $R_{\text{abiotic}}$ , diel variations were all of alternating positive and negative  $\text{CO}_2$  fluxes over a day, and hourly flux rate fluctuated in the range of  $-0.67$  to  $0.538 \mu\text{mol m}^{-2} \text{ s}^{-1}$  (10 across the eight sites. For each site, the daily sum of hourly flux rate approximated zero (Fig. 1).

### 3.3 Temperature dependence for $R_{\text{total}}$ , $R_{\text{biotic}}$ and $R_{\text{abiotic}}$

Total soil  $\text{CO}_2$  fluxes were all linearly related to temperature (both for  $T_{\text{soil}}$  and  $\Delta T/\Delta t$ ), but with intriguing differences in explanatory degree of the variation in total soil  $\text{CO}_2$  flux among the eight landscapes (Table 2). In the cotton field, halophyte garden and hops field, where biotic flux dominated the total soil  $\text{CO}_2$  flux (Fig. 1),  $T_{\text{soil}}$  accounted for more than 60 % of the total soil  $\text{CO}_2$  flux variance, while  $\Delta T/\Delta t$  alone accounted for < 40 % of this variance. In contrast, for reservoir edge, native saline desert, alkaline soil and dune crest,  $\Delta T/\Delta t$  explained more variance of total soil  $\text{CO}_2$  flux than did  $T_{\text{soil}}$  (20  $\text{Table 2}$ ). Based on the above partitioning results, temperature dependence of biotic and abiotic components of the total soil  $\text{CO}_2$  flux was separately analyzed (Table 2). For  $R_{\text{biotic}}$ , natural variation of  $T_{\text{soil}}$  accounted for most of daily  $R_{\text{biotic}}$  variation for most sites except alkaline soil and dune crest, where  $R_{\text{biotic}}$  was extremely low and with irregular variation (Fig. 1). Thus, the diel temperature cycle was the predominant physical control over  $R_{\text{biotic}}$ . For  $R_{\text{abiotic}}$ , variation in  $T_{\text{soil}}$  was significantly related to diel  $R_{\text{abiotic}}$  variations, but explained far less of the variation in  $R_{\text{abiotic}}$  than did  $\Delta T/\Delta t$  (Table 2). The  $\Delta T/\Delta t$  accounted for an average of approximately 71 % of the  $R_{\text{abiotic}}$  variation across the eight sites. Moreover, the negative values of  $R_{\text{abiotic}}$  coincided with naturally decreasing soil

temperature (when  $\Delta T/\Delta t < 0$ ), and positive values with increasing soil temperature (when  $\Delta T/\Delta t > 0$ ) (Fig. 2).

### 3.4 The relative contribution of $R_{\text{abiotic}}$ to $R_{\text{total}}$

To evaluate the contribution of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$ , ratios of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$  were calculated for the eight sites during the periods of  $R_{\text{abiotic}} > 0$ . The instantaneous ratios were in the range of 0.007–0.995, with an average of 0.33 in all eight sites (Fig. 3). The maximum of  $R_{\text{abiotic}}/R_{\text{total}}$  ratio was in alkaline soil while the minimum was in the cotton field. When the ratios for each site were grouped, the average  $R_{\text{abiotic}}/R_{\text{total}}$  ratio followed a trend of decreasing logarithmically as the cumulative  $\text{CO}_2$  release of  $R_{\text{biotic}}$  rose during the period of  $R_{\text{abiotic}} > 0$  (Fig. 4). Thus, the contribution of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$  was obviously negatively related to increasing  $R_{\text{biotic}}$ . It is noteworthy that the reason that we used cumulative  $\text{CO}_2$  release of  $R_{\text{biotic}}$  as the target variable was that  $R_{\text{abiotic}}$  was balanced in a day –  $\text{CO}_2$  drawn into soil in the night was released during the day (Fig. 1). From this point of view, under the influence of  $R_{\text{abiotic}}$ , apparent  $R_{\text{biotic}}$  was overestimated during the period of  $R_{\text{abiotic}} > 0$  (Fig. 5a). The overestimated ratio for  $R_{\text{biotic}}$  was within the range of 1.07–7.72, with an average of approximately 2. For example, the real value of cumulative  $\text{CO}_2$  release from  $R_{\text{biotic}}$  was  $72.13 \text{ mg m}^{-2} \text{ d}^{-1}$ , which was up to  $340.64 \text{ mg m}^{-2} \text{ d}^{-1}$  lower than the apparent flux in alkaline soil. Conversely, for the period of  $R_{\text{abiotic}} < 0$ , apparent  $R_{\text{biotic}}$  was obviously underestimated due to the abiotic part of the total soil  $\text{CO}_2$  flux, and even to the extent of altering  $\text{CO}_2$  transport direction (Fig. 5b) – despite  $R_{\text{biotic}}$  being always positive according to the conventional wisdom concerning soil respiration. For example, the real cumulative  $\text{CO}_2$  exchange through  $R_{\text{biotic}}$  was 203.17, 287.61, 89.38 and  $63.72 \text{ mg m}^{-2} \text{ d}^{-1}$  in dune crest, native saline desert and interdune lowland, respectively; whereas, corresponding apparent  $R_{\text{biotic}}$ , offset by negative  $R_{\text{abiotic}}$ , all became negative (indicating absorption) with  $-118.00$ ,  $-29.82$ ,  $-445.42$  and  $-329.45 \text{ mg m}^{-2} \text{ d}^{-1}$ .

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### 3.5 Predominant factors for $R_{\text{biotic}}$ and $R_{\text{abiotic}}$

Once  $R_{\text{biotic}}$  and  $R_{\text{abiotic}}$  were partitioned, the predominant factors for  $R_{\text{total}}$  and the corresponding biotic and abiotic components were analyzed (Table 3). Root biomass was significantly correlated with  $R_{\text{biotic}}$ , and explained 91 % of  $R_{\text{biotic}}$  across the eight sites. Soil moisture was significantly correlated with  $R_{\text{abiotic}}$ , but explained less of the variance in abiotic flux than soil pH did. Thus,  $R_{\text{abiotic}}$  was determined by soil pH and soil moisture. While  $R_{\text{abiotic}}$  had an approximately zero sum over a diel cycle, daily cumulative  $\text{CO}_2$  exchange from  $R_{\text{total}}$  equaled that for  $R_{\text{biotic}}$ . As a result, variation in  $R_{\text{total}}$  was also significantly related to living root biomass (model  $R^2 = 0.91$ ,  $P < 0.001$ ).

## 4 Discussion

Based on the variations in  $R_{\text{total}}$  and their biotic and abiotic components across the eight landscapes, we demonstrated that the view that  $R_{\text{total}}$  is predominantly biological (Hanson et al., 2000) is still sound in most ecosystems, but that the abiotic component can dominate when biological processes are weak.

As previously observed (Ball et al., 2009; Ma et al., 2013; Shanahun et al., 2012), temperature was the most important factor influencing the diel cycle of  $R_{\text{total}}$  (Table 2). Natural temperature fluctuation coupled with  $\Delta T/\Delta t$  explained  $> 90\%$  of  $R_{\text{total}}$  variation in all eight landscapes. However, the dominant factor ( $T_{\text{soil}}$  or  $\Delta T/\Delta t$ ) for diel  $R_{\text{total}}$  variation was different, depending on which flux component was dominant (i.e.  $R_{\text{abiotic}}$  or  $R_{\text{biotic}}$ ). When  $R_{\text{total}}$  was not significantly different from  $R_{\text{biotic}}$ , as observed in cotton and hops fields, soil temperature ( $T_{\text{soil}}$ ) accounted for more than 60 % of diel  $R_{\text{total}}$  variation. Whereas, when  $R_{\text{total}}$  was dominated by  $R_{\text{abiotic}}$ , as in alkaline soil and dune crest,  $\Delta T/\Delta t$  dominated diel  $R_{\text{total}}$  variation. Such variations suggested that soil temperature ( $T_{\text{soil}}$ ) mainly controlled  $R_{\text{biotic}}$  while  $\Delta T/\Delta t$  determined  $R_{\text{abiotic}}$  (Table 2). Similar results were reported in Antarctic dry valley soils (Ball et al., 2009). Temperature-dependent diel variation – flux positively correlated with  $\Delta T/\Delta t$  – was general for  $R_{\text{abiotic}}$  in the eight

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landscapes, but  $R_{\text{biotic}}$  showed a completely different diurnal pattern with no response to soil temperature in dune crest and alkaline soil. In general, respiration is insensitive to temperature under very high soil moisture conditions – e.g. saturated (Luo and Zhou, 2006; Cable et al., 2011). In dune crest and alkaline soil, however, soil moisture content was extremely low (Table 1). Drought reduces the thickness of soil water films, correspondingly inhibiting microbial activities and lowering substrate availability (Davidson and Janssens, 2006; Borken and Matzner, 2009) – additionally, soil microbial and soil organic matter were inherently low (soil microbial biomass C < 40 mg kg<sup>-1</sup> in these two soils, unpublished data). In addition, living roots were also scarce or even absent in these two soils (Table 1). Considering the above characteristics of dune crest and alkaline soil, diel variation of  $R_{\text{biotic}}$  at these two sites was low and temperature insensitivity of  $R_{\text{biotic}}$  can be easily understood as a lack of biotic activity (including root respiration and microbial activity) and appropriate substrate. When this was the case, diurnal variation of  $R_{\text{total}}$  was basically the same as variation of  $R_{\text{biotic}}$ ; whereas, temperature dependence of  $R_{\text{total}}$  was a combined effect of both biotic and abiotic components. Although the diurnal variation of  $R_{\text{total}}$  with temperature is not unusual, it is intriguing that there was a change in the determination of temperature response.

$R_{\text{abiotic}}$ , regulated by  $\Delta T/\Delta t$ , was also observed in Antarctic soils (Ball et al., 2009; Parsons et al., 2004; Shanhun et al., 2012), which are also characterized by high soil pH, high soil salt content and low organic C content as also in deserts. Abiotic control over the size of the reservoir of dissolved inorganic C (DIC) in the soil solution, as outlined by Henry's Law, was suggested to be responsible for diel variation of  $R_{\text{abiotic}}$  (Plummer and Busenberg, 1982; Karberg et al., 2005; Ball et al., 2009; Shanhun et al., 2012). Rising temperature allowed CO<sub>2</sub> to be dissolved in soil solution, and decreasing temperature induced CO<sub>2</sub> release on a daily basis (Fig. 2). Thus, there was a diel pattern of alternating positive and negative CO<sub>2</sub> fluxes with a zero sum in abiotic flux (Fig. 1). In a soil, the magnitude of  $R_{\text{abiotic}}$  mainly depended on soil pH and soil moisture (Table 3), when temperature fluctuation was fixed. In the present study, > 60% of variation in abiotic flux over the eight landscapes was explained by variation in soil

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pH. A similar result was found in alkaline desert soils (Xie et al., 2009), where CO<sub>2</sub> uptake was significantly correlated with soil pH. Increasing soil moisture also lead to greater positive and lower negative fluxes (greater variation in abiotic flux magnitude) by providing for a large source or sink of DIC involved in the exchange (Ball et al., 2009; Shanhun et al., 2012).

While on a diurnal basis,  $R_{\text{abiotic}}$  resulted in no net gain or loss of C, its effect on instantaneous CO<sub>2</sub> flux was significant. When  $R_{\text{abiotic}} > 0$ , apparent  $R_{\text{biotic}}$  was clearly amplified compared to its real level (Fig. 4a); whereas, apparent  $R_{\text{biotic}}$  was significantly weakened when  $R_{\text{abiotic}} < 0$ , even to the extent of altering CO<sub>2</sub> transport direction (Fig. 4b). Without recognition of  $R_{\text{abiotic}}$ ,  $R_{\text{biotic}}$  would have been either overestimated (for daytime) or underestimated (for nighttime). Similar conclusions were reached by noting the variations in apparent respiratory quotient (defined as the ratio between the CO<sub>2</sub> efflux and the oxygen influx) for three calcareous soil sites (Angert et al., 2015).

Such an abiotic effect on CO<sub>2</sub> flux is proposed to be general to soils, providing soils are alkaline, but the degree varied greatly across different landscapes (Figs. 1 and 4). The relative contribution of abiotic flux to the total soil CO<sub>2</sub> flux (i.e.  $R_{\text{abiotic}}/R_{\text{total}}$ ) is the key to discerning whether  $R_{\text{abiotic}}$  is important (Ma et al., 2013). In conditions of soils with preferable substrates and considerable amount of living roots (Table 1), the biotic component produce large fluxes of CO<sub>2</sub>, which are not significantly affected by  $R_{\text{abiotic}}$ , making such correction unnecessary. However, in some extreme conditions, as in alkaline soil and dune crest, the effect of  $R_{\text{abiotic}}$  was strong and should not be overlooked (Figs. 1 and 4). The ratio of  $R_{\text{abiotic}}/R_{\text{total}}$  decreased logarithmically with increasing  $R_{\text{biotic}}$  (Fig. 4), suggesting a strong effect of  $R_{\text{abiotic}}$  (over  $R_{\text{total}}$ ) appeared when  $R_{\text{biotic}}$  was low. Conditions such as high soil pH, high moisture content, low soil organic C content and few living roots favored  $R_{\text{abiotic}}$  more than  $R_{\text{biotic}}$ , resulting in  $R_{\text{abiotic}}$  comparable to and even far exceeding  $R_{\text{biotic}}$ . Similar results were reported in Dry Valley soils (Shanhun et al., 2012) and 14 saline/alkaline air-dried soils (Ma et al., 2013), in which  $R_{\text{abiotic}}$  had no significant difference to the total soil CO<sub>2</sub> flux.

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**Table 1.** Soil properties and living root biomass at the eight sites.

|                      | Soil organic C<br>(g kg <sup>-1</sup> ) | Soil inorganic C<br>(g kg <sup>-1</sup> ) | pH                       | EC<br>(dSm <sup>-1</sup> ) | Root biomass<br>(g m <sup>-2</sup> ) | Moisture<br>(%, g g <sup>-1</sup> ) |
|----------------------|---|---|--------------------------|----------------------------|--------------------------------------|-------------------------------------|
| Cotton field         | 7.20 <sup>b</sup> (0.47)                | 4.41 <sup>e</sup> (0.11)                  | 8.13 <sup>c</sup> (0.09) | 3.83 <sup>b</sup> (0.92)   | 47.75 <sup>a</sup> (4.46)            | 13.02 <sup>a</sup> (0.52)           |
| Halophyte garden     | 8.00 <sup>b</sup> (0.68)                | 5.96 <sup>c</sup> (0.11)                  | 9.20 <sup>a</sup> (0.06) | 14.23 <sup>a</sup> (0.87)  | 24.19 <sup>c</sup> (3.18)            | 7.60 <sup>b</sup> (0.42)            |
| Hops field           | 15.85 <sup>a</sup> (0.38)               | 4.67 <sup>e</sup> (0.23)                  | 8.00 <sup>c</sup> (0.10) | 1.09 <sup>c</sup> (0.21)   | 38.19 <sup>b</sup> (4.77)            | 7.94 <sup>b</sup> (0.39)            |
| Dune crest           | 0.57 <sup>f</sup> (0.07)                | 1.24 <sup>g</sup> (0.05)                  | 8.93 <sup>b</sup> (0.03) | 0.09 <sup>e</sup> (0.01)   | 0.95 <sup>f</sup> (0.24)             | 0.26 <sup>f</sup> (0.04)            |
| Reservoir edge       | 5.38 <sup>c</sup> (0.98)                | 8.24 <sup>b</sup> (0.20)                  | 8.76 <sup>b</sup> (0.15) | 1.23 <sup>c</sup> (0.33)   | 17.51 <sup>cd</sup> (0.64)           | 8.25 <sup>b</sup> (0.42)            |
| Alkaline soil        | 2.96 <sup>e</sup> (0.09)                | 5.38 <sup>d</sup> (0.12)                  | 9.17 <sup>a</sup> (0.17) | 0.23 <sup>d</sup> (0.05)   | 0.32 <sup>g</sup> (0.14)             | 0.40 <sup>e</sup> (0.03)            |
| Native saline desert | 3.25 <sup>e</sup> (0.60)                | 9.25 <sup>a</sup> (0.18)                  | 8.60 <sup>b</sup> (0.09) | 4.76 <sup>b</sup> (0.82)   | 5.09 <sup>e</sup> (0.32)             | 1.63 <sup>d</sup> (0.11)            |
| Interdune lowland    | 4.62 <sup>d</sup> (0.50)                | 1.52 <sup>f</sup> (0.09)                  | 8.90 <sup>b</sup> (0.10) | 0.11 <sup>e</sup> (0.03)   | 16.23 <sup>d</sup> (0.64)            | 2.50 <sup>c</sup> (0.15)            |
| Average              | 5.98                                    | 5.08                                      | 8.71                     | 3.20                       | 18.78                                | 5.20                                |

Notes: data shown are means (standard deviation),  $n = 3$ ; different superscripted letters within each column denote statistical differences between sites (Fisher's PLSD,  $P < 0.05$ ).

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**Table 2.** Parameter estimates and ANOVA values for stepwise regression models of total soil CO<sub>2</sub> flux and the corresponding biotic and abiotic components at different landscapes.

| Landscape            | Model <i>R</i> <sup>2</sup> | Variable                 | Total soil CO <sub>2</sub> flux |          |                               | Model <i>R</i> <sup>2</sup> | Variable                 | Biotic flux        |          |                               |
|----------------------|-----------------------------|--------------------------|---------------------------------|----------|-------------------------------|-----------------------------|--------------------------|--------------------|----------|-------------------------------|
|                      |                             |                          | Parameter estimate              | <i>F</i> | Partial <i>R</i> <sup>2</sup> |                             |                          | Parameter estimate | <i>F</i> | Partial <i>R</i> <sup>2</sup> |
| Cotton field         | 0.938                       | Intercept                | -3.411 ± 0.213                  | -        | -                             | 0.914                       | Intercept                | -2.985 ± 0.225     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.211 ± 0.008                   | 464.435  | 0.912                         |                             | <i>T</i> <sub>soil</sub> | 0.195 ± 0.009      | 478.837  | 0.914                         |
|                      |                             | $\Delta T/\Delta t$      | 0.143 ± 0.034                   | 18.322   | 0.026                         |                             | $\Delta T/\Delta t$      | -                  | -        | -                             |
| Halophyte garden     | 0.966                       | Intercept                | -1.969 ± 0.11                   | -        | -                             | 0.870                       | Intercept                | -0.478 ± 0.09      | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.118 ± 0.004                   | 67.617   | 0.600                         |                             | <i>T</i> <sub>soil</sub> | 0.051 ± 0.004      | 86.495   | 0.658                         |
|                      |                             | $\Delta T/\Delta t$      | 0.388 ± 0.018                   | 476.053  | 0.366                         |                             | $\Delta T/\Delta t$      | 0.120 ± 0.014      | 72.062   | 0.212                         |
| Hops field           | 0.946                       | Intercept                | -1.234 ± 0.12                   | -        | -                             | 0.928                       | Intercept                | -0.908 ± 0.11      | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.09 ± 0.005                    | 53.077   | 0.541                         |                             | <i>T</i> <sub>soil</sub> | 0.077 ± 0.004      | 60.566   | 0.574                         |
|                      |                             | $\Delta T/\Delta t$      | 0.329 ± 0.018                   | 332.293  | 0.405                         |                             | $\Delta T/\Delta t$      | 0.254 ± 0.017      | 217.166  | 0.354                         |
| Dune crest           | 0.890                       | Intercept                | 0.392 ± 0.05                    | -        | -                             | -                           | Intercept                | -                  | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.02 ± 0.002                    | 89.550   | 0.224                         |                             | <i>T</i> <sub>soil</sub> | -                  | -        | -                             |
|                      |                             | $\Delta T/\Delta t$      | 0.131 ± 0.008                   | 89.894   | 0.667                         |                             | $\Delta T/\Delta t$      | -                  | -        | -                             |
| Reservoir edge       | 0.949                       | Intercept                | 0.039 ± 0.067                   | -        | -                             | 0.556                       | Intercept                | -0.202 ± 0.088     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.013 ± 0.003                   | 24.117   | 0.028                         |                             | <i>T</i> <sub>soil</sub> | 0.024 ± 0.003      | 45.433   | 0.502                         |
|                      |                             | $\Delta T/\Delta t$      | 0.296 ± 0.011                   | 530.508  | 0.922                         |                             | $\Delta T/\Delta t$      | 0.032 ± 0.014      | 5.354    | 0.054                         |
| Alkaline soil        | 0.942                       | Intercept                | -0.844 ± 0.05                   | -        | -                             | -                           | Intercept                | -                  | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.033 ± 0.002                   | 289.151  | 0.379                         |                             | <i>T</i> <sub>soil</sub> | -                  | -        | -                             |
|                      |                             | $\Delta T/\Delta t$      | 0.151 ± 0.008                   | 58.024   | 0.563                         |                             | $\Delta T/\Delta t$      | -                  | -        | -                             |
| Native saline desert | 0.860                       | Intercept                | -0.282 ± 0.07                   | -        | -                             | 0.366                       | Intercept                | -0.018 ± 0.053     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.018 ± 0.003                   | 42.804   | 0.136                         |                             | <i>T</i> <sub>soil</sub> | 0.008 ± 0.002      | 13.680   | 0.233                         |
|                      |                             | $\Delta T/\Delta t$      | 0.160 ± 0.011                   | 118.495  | 0.725                         |                             | $\Delta T/\Delta t$      | 0.025 ± 0.008      | 9.188    | 0.132                         |
| Interdune lowland    | 0.950                       | Intercept                | -1.029 ± 0.10                   | -        | -                             | 0.909                       | Intercept                | -0.815 ± 0.076     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.051 ± 0.004                   | 191.614  | 0.218                         |                             | <i>T</i> <sub>soil</sub> | 0.044 ± 0.003      | 74.094   | 0.622                         |
|                      |                             | $\Delta T/\Delta t$      | 0.357 ± 0.015                   | 122.832  | 0.732                         |                             | $\Delta T/\Delta t$      | -0.120 ± 0.012     | 100.428  | 0.263                         |

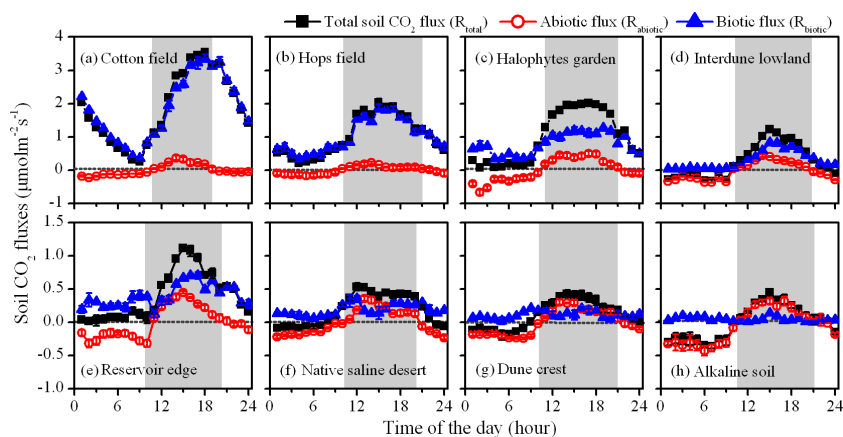
**Table 2.** Continued.

| Landscape            | Model <i>R</i> <sup>2</sup> | Variable                 | Abiotic flux       |          |                               |
|----------------------|-----------------------------|--------------------------|--------------------|----------|-------------------------------|
|                      |                             |                          | Parameter estimate | <i>F</i> | Partial <i>R</i> <sup>2</sup> |
| Cotton field         | 0.898                       | Intercept                | -0.338 ± 0.042     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.113 ± 0.002      | 62.335   | 0.145                         |
|                      |                             | $\Delta T/\Delta t$      | 0.116 ± 0.007      | 137.474  | 0.753                         |
| Halophyte garden     | 0.883                       | Intercept                | -0.913 ± 0.091     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.036 ± 0.004      | 100.792  | 0.268                         |
|                      |                             | $\Delta T/\Delta t$      | 0.207 ± 0.014      | 71.942   | 0.615                         |
| Hops field           | 0.860                       | Intercept                | -0.257 ± 0.036     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.010 ± 0.001      | 51.363   | 0.164                         |
|                      |                             | $\Delta T/\Delta t$      | 0.080 ± 0.006      | 102.916  | 0.696                         |
| Dune crest           | 0.947                       | Intercept                | -0.527 ± 0.034     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.021 ± 0.001      | 234.69   | 0.280                         |
|                      |                             | $\Delta T/\Delta t$      | 0.122 ± 0.005      | 90.306   | 0.667                         |
| Reservoir edge       | 0.897                       | Intercept                | -0.431 ± 0.061     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.017 ± 0.002      | 48.811   | 0.110                         |
|                      |                             | $\Delta T/\Delta t$      | 0.175 ± 0.010      | 170.899  | 0.792                         |
| Alkaline soil        | 0.934                       | Intercept                | -0.886 ± 0.053     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.033 ± 0.002      | 252.507  | 0.379                         |
|                      |                             | $\Delta T/\Delta t$      | 0.150 ± 0.008      | 56.058   | 0.555                         |
| Native saline desert | 0.891                       | Intercept                | -0.289 ± 0.049     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.011 ± 0.002      | 33.215   | 0.083                         |
|                      |                             | $\Delta T/\Delta t$      | 0.134 ± 0.008      | 189.246  | 0.808                         |
| Interdune lowland    | 0.924                       | Intercept                | -0.489 ± 0.051     | -        | -                             |
|                      |                             | <i>T</i> <sub>soil</sub> | 0.019 ± 0.002      | 91.102   | 0.157                         |
|                      |                             | $\Delta T/\Delta t$      | 0.163 ± 0.008      | 147.964  | 0.767                         |

**Table 3.** Parameter estimates and ANOVA values for stepwise multiple regression models of total soil CO<sub>2</sub> flux and the corresponding biotic and abiotic components across the eight landscapes. The model  $R^2$  for total soil CO<sub>2</sub> flux, biotic flux and abiotic flux were 0.91, 0.91 and 0.89, respectively, and all  $P < 0.005$ .

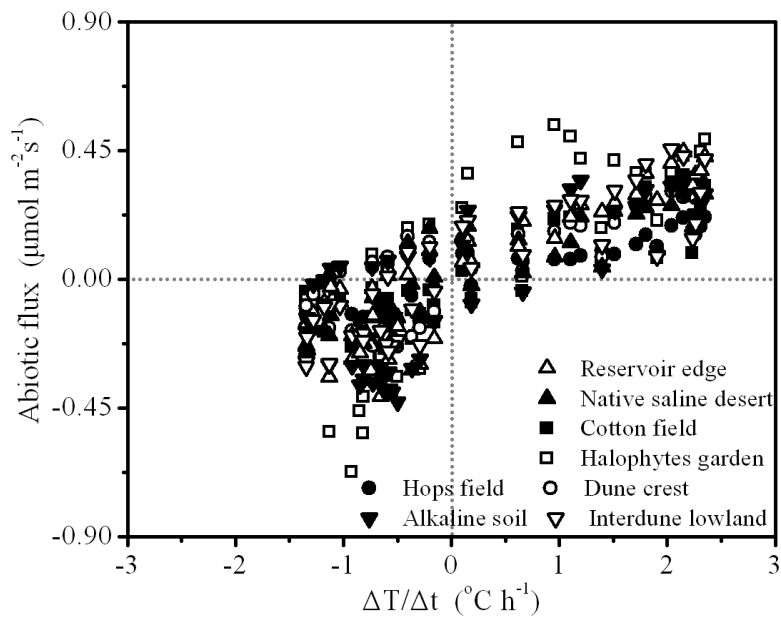
| Total soil CO <sub>2</sub> flux |                       |        |           |               |
|---------------------------------|-----------------------|--------|-----------|---------------|
| Variable                        | Parameter estimate    | $F$    | $P$       | Partial $R^2$ |
| Intercept                       | $-203.43 \pm 433.44$  |        | 0.65      | N.A.          |
| Root biomass                    | $131.78 \pm 17.47$    | 56.86  | $< 0.001$ | 0.91          |
| Biotic flux                     |                       |        |           |               |
| Variable                        | Parameter estimate    | $F$    | $P$       | Partial $R^2$ |
| Intercept                       | $-202.31 \pm 400.10$  |        | 0.63      | N.A.          |
| Root biomass                    | $128.10 \pm 16.13$    | 63.05  | $< 0.001$ | 0.91          |
| Abiotic flux                    |                       |        |           |               |
| Variable                        | Parameter estimate    | $F$    | $P$       | Partial $R^2$ |
| Intercept                       | $-2157.71 \pm 396.65$ |        | 0.003     | N.A.          |
| pH                              | $278.58 \pm 43.97$    | 9.324  | 0.001     | 0.61          |
| Soil moisture                   | $15.03 \pm 4.22$      | 12.691 | 0.016     | 0.28          |

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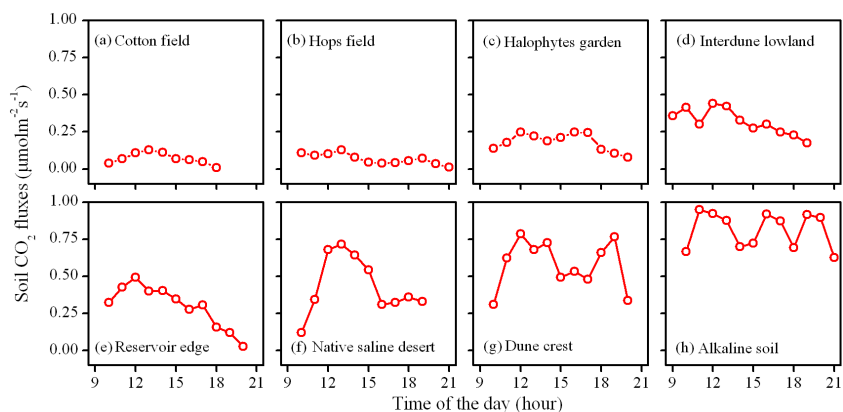
**Figure 1.** Partitioning the total soil CO<sub>2</sub> flux into biotic and abiotic parts across the eight sites. (a–h) represent the sites of cotton field, hops field, halophyte garden, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, respectively. The shaded parts indicate the periods during which  $R_{\text{abiotic}}$  was positive. Error bars represent standard errors of the mean.

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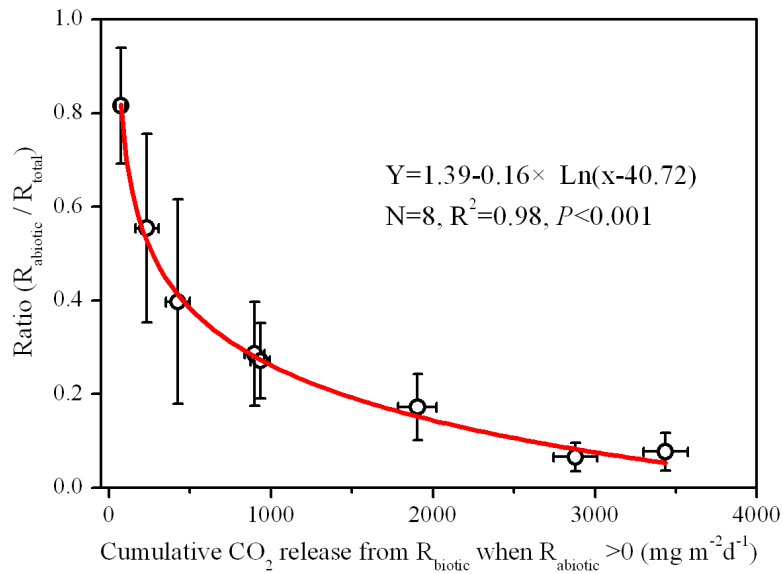
**Figure 2.** Temperature dependence for abiotic flux. Appearance of negative values of  $R_{\text{abiotic}}$  coincided with naturally declining soil temperature (the period of  $\Delta T/\Delta t < 0$ ), and positive values with rising soil temperature.

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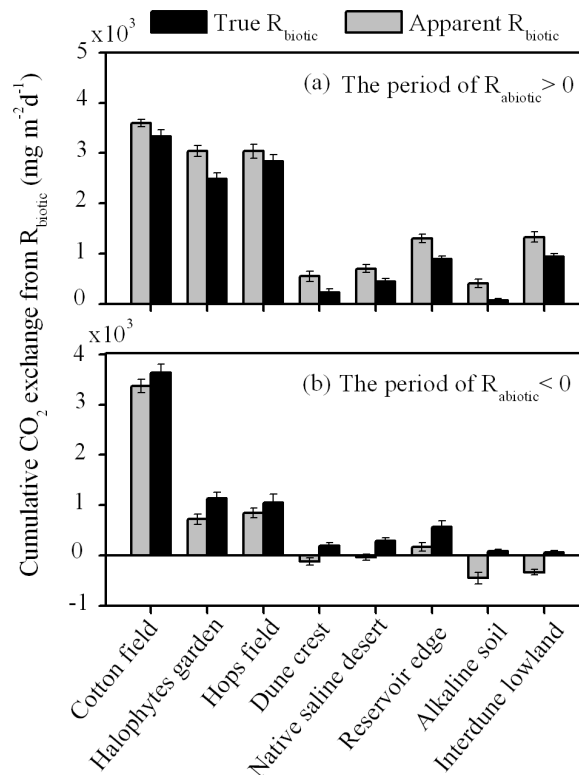
**Figure 3.** Ratio of  $R_{\text{abiotic}}$  to  $R_{\text{total}}$  during the periods of  $R_{\text{abiotic}} > 0$  for the eight sites.

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**Figure 4.** The average ratio of  $R_{abiotic}$  to  $R_{total}$  had an exponential relationship with cumulative  $CO_2$  release from  $R_{biotic}$ . Error bars represent standard errors of the mean.

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**Figure 5.** Cumulative apparent  $CO_2$  exchanges from  $R_{biotic}$  were significantly amplified compared to their real values during the period of  $R_{abiotic} > 0$  (a); whereas, the apparent  $R_{biotic}$  were weakened when  $R_{abiotic} < 0$  (b). Error bars represent standard errors of the mean.

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