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The abiotic contribution to total CO_2 flux for soils in arid zone

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Abstract

As an important component of ecosystem carbon budgets, soil carbon dioxide (CO_2) 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_2 flux, its relative importance has never been systematically assessed. In this study, the total soil CO_2 flux (R_{total}) was partitioned into biotic (R_{biotic}) and abiotic (R_{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_{abiotic} always contributed to R_{total} for the eight landscapes, but the degree of contribution varied greatly. In the cotton and hops fields, the ratio of R_{abiotic} to R_{total} was extremely low ($< 10\,\%$); whereas R_{abiotic} was dominant in the alkaline soil and dune crest. Statistically, $R_{\mathrm{abiotic}}/R_{\mathrm{total}}$ decreased logarithmically with rising R_{biotic}, suggesting that R_{abiotic} strongly affected R_{total} when R_{biotic} was low. This pattern confirms that soil CO_2 flux is predominantly biological in most ecosystems, but R_{abiotic} can dominate when biological processes are weak. On a diurnal basis, R_{abiotic} resulted in no net gain or loss of carbon but its effect on instantaneous CO_2 flux was significant. Temperature dependence of R_{total} varied among the eight landscapes, determined by the predominant components of CO_2 flux: with R_{biotic} driven by soil temperature and R_{abiotic} regulated by the rate of change in temperature. Namely, declining temperature resulted in negative R_{abiotic} (CO_2 went into soil), while rising temperature resulted in a positive R_{abiotic} (CO_2 released from soil). Furthermore, without recognition of R_{abiotic}, R_{biotic} would have been either overestimated (for daytime) or underestimated (for nighttime). Thus, recognition that abiotic component in total soil CO_2 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_2 exchange and not likely directly constitute a carbon sink, it can alter transient soil CO_2 flux significantly, either in magnitude or in its temperature dependency.

1 Introduction

As the primary path to release plant-fixed carbon dioxide (CO_2) back to the atmosphere (Ryan and Law, 2005), soil CO_2 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_2 flux can have a strong impact on the balance of atmosphere CO_2 concentration (Raich et al., 2002). Moreover, soil CO_2 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_2 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_2 flux, but large uncertainties remain (Davidson and Janssens, 2006; Carbone et al., 2008; Hardie et al., 2011). At the global scale, soil CO_2 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_2 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_2 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_2 goes into soil) (Parsons et al., 2004; Stone, 2008; Xie et al., 2009; Shanhun et al., 2012; Ma et al., 2013), uncertainty concerning soil CO_2 fluxes has increased, for there is an unstated hypothesis that biotic sources (including autotrophic and heterotrophic respiration) only release CO_2 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_2 on soil particles (Parsons et al., 2004), ventilation of subterranean cavities (Serrano-Ortiz et al., 2010) and changes in CO_2 solubility in soil water films (Karberg et al., 2005; Ma et al., 2013), were suggested to be related to total CO_2 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_2 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_2 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_2 flux, and quantified the magnitude of its impact on the total soil CO_2 flux over a variety of landscapes (Elberling et al., 2014), which represents a significant gap in our knowledge of soil CO_2 fluxes.

In the Gurbantunggut Desert, negative CO_2 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_2 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_2 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_2 in soil water. Additionally, we predicted that the contribution of abiotic flux to total soil CO_2 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 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.

To determine the potential abiotic contribution to total soil CO_2 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, 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 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_2 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 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 contribution to total soil CO_2 flux. The fluxes over sterilized and natural soil were considered abiotic (R_{abiotic}) and total flux (R_{total}), respectively, with the difference between the two representing the biotic flux (R_{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 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 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 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_2 flux was measured with an Automated Soil CO_2 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_2 flux from soil to atmosphere with positive values; thus, negative values indicate CO_2 moving from atmosphere into soil.

To evaluate the contribution of abiotic flux to the total soil CO_2 flux, ratios of R_{abiotic} to R_{total} were calculated for the eight sites when R_{abiotic} was positive:

$$\text{Ratio} = \left.\frac{R_{\text{abiotic}}}{R_{\text{total}}}\right|_{R_{\text{abiotic}}>0}$$

Cumulative CO_2 exchange of R_{biotic} and R_{abiotic} were calculated by numerical integration of R_{biotic} or R_{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_{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 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_2 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 (±0.38) $\mathrm{g\,kg\,soil^{-1}}$ in the hops field and a minimum of 0.57 (±0.07) $\mathrm{g\,kg\,soil^{-1}}$ in dune crest (Table 1). The average concentration of soil organic C content was 5.98 $\mathrm{g\,kg\,soil^{-1}}$. The eight sites differed in inorganic C contents ($F = 92.54$, $P < 0.001$), with an average of 5.08 $\mathrm{g\,kg\,soil^{-1}}$, 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 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 ($F = 79.24$, $P < 0.001$), with coefficient of variation of 89.36 %. Soil pH was high for all eight sites, with a minimum of 8.00 (±0.10), indicating that the soils were all strongly alkaline. EC, a proxy for soil salt concentration, was in the range of 0.09 (±0.01) to 14.23 (±0.87) $\mathrm{dS\,m^{-1}}$. In addition, the living root biomass, regarded as the most active contributor to CO_2 flux (Hanson et al., 2000), was low for all eight sites, with average of 18.78 $\mathrm{g\,m^{-2}}$, but with significant differences among sites. The maximum of living root biomass was 47.75 (±4.46) $\mathrm{g\,m^{-2}}$ in the cotton field; whereas there was little root biomass in alkaline soil, with 0.32 (±0.14) $\mathrm{g\,m^{-2}}$. 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_{biotic} and R_{abiotic}.

3.2 Partitioning R_{total} into R_{biotic} and R_{abiotic}

R_{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_{total} were 3.72, 2.03, 2.12, 1.28, 1.13, 0.53, 0.42 and 0.45 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ in cotton field, hops field, halophyte garden, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, respectively. In particular, R_{total} was negative during the night in sites of native saline desert, dune crest and alkaline soil, in which R_{biotic} was relatively low in the range of 0.001–0.364 $\mathrm{\mu mol\,m^{-2}\,s^{-1}}$ (Fig. 1f–h). By comparing CO_2 fluxes from soils after sterilization treatment with those in natural condition, R_{total} was partitioned into R_{biotic} and R_{abiotic} (Fig. 1). There were significant differences in R_{biotic} among the eight sites, either in flux rate or diurnal pattern. Maximum CO_2 flux rates decreased following the sequence of hops field, halophyte garden, hops field, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, with the average flux rate being 0.579 µmol m^{-2} s^{-1}. The diurnal patterns of R_{biotic} were all similar to those of R_{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_{total} had a significant relationship with $R_{abiotic}$, 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_{total}. For $R_{abiotic}$, diel variations were all of alternating positive and negative CO_2 fluxes over a day, and hourly flux rate fluctuated in the range of −0.67 to 0.538 µmol m^{-2} s^{-1} across the eight sites. For each site, the daily sum of hourly flux rate approximated zero (Fig. 1).

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

Total soil CO_2 fluxes were all linearly related to temperature (both for T_{soil} and $\Delta T/\Delta t$), but with intriguing differences in explanatory degree of the variation in total soil 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 CO_2 flux (Fig. 1), T_{soil} accounted for more than 60 % of the total soil 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 CO_2 flux than did T_{soil} (Table 2). Based on the above partitioning results, temperature dependence of biotic and abiotic components of the total soil CO_2 flux was separately analyzed (Table 2). For R_{biotic}, natural variation of T_{soil} accounted for most of daily R_{biotic} variation for most sites except alkaline soil and dune crest, where R_{biotic} was extremely low and with irregular variation (Fig. 1). Thus, the diel temperature cycle was the predominant physical control over R_{biotic}. For $R_{abiotic}$, variation in T_{soil} was significantly related to diel $R_{abiotic}$ variations, but explained far less of the variation in $R_{abiotic}$ than did $\Delta T/\Delta t$ (Table 2). The $\Delta T/\Delta t$ accounted for an average of approximately 71 % of the $R_{abiotic}$ variation across the eight sites. Moreover, the negative values of $R_{abiotic}$ 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_{abiotic} to R_{total}

To evaluate the contribution of R_{abiotic} to R_{total}, ratios of R_{abiotic} to R_{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 CO_2 release of R_{biotic} rose during the period of $R_{\text{abiotic}} > 0$ (Fig. 4). Thus, the contribution of R_{abiotic} to R_{total} was obviously negatively related to increasing R_{biotic}. It is noteworthy that the reason that we used cumulative CO_2 release of R_{biotic} as the target variable was that R_{abiotic} was balanced in a day – 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_{abiotic}, apparent R_{biotic} was overestimated during the period of $R_{\text{abiotic}} > 0$ (Fig. 5a). The overestimated ratio for R_{biotic} was within the range of 1.07–7.72, with an average of approximately 2. For example, the real value of cumulative CO_2 release from R_{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_{biotic} was obviously underestimated due to the abiotic part of the total soil CO_2 flux, and even to the extent of altering CO_2 transport direction (Fig. 5b) – despite R_{biotic} being always positive according to the conventional wisdom concerning soil respiration. For example, the real cumulative CO_2 exchange through R_{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_{biotic}, offset by negative R_{abiotic}, all became negative (indicating absorption) with −118.00, −29.82, −445.42 and −329.45 $\text{mg m}^{-2}\,\text{d}^{-1}$.

3.5 Predominant factors for R_{biotic} and R_{abiotic}

Once R_{biotic} and R_{abiotic} were partitioned, the predominant factors for R_{total} and the corresponding biotic and abiotic components were analyzed (Table 3). Root biomass was significantly correlated with R_{biotic}, and explained 91 % of R_{biotic} across the eight sites. Soil moisture was significantly correlated with R_{abiotic}, but explained less of the variance in abiotic flux than soil pH did. Thus, R_{abiotic} was determined by soil pH and soil moisture. While R_{abiotic} had an approximately zero sum over a diel cycle, daily cumulative CO_2 exchange from R_{total} equaled that for R_{biotic}. As a result, variation in R_{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_{total} and their biotic and abiotic components across the eight landscapes, we demonstrated that the view that R_{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; Shanhun et al., 2012), temperature was the most important factor influencing the diel cycle of R_{total} (Table 2). Natural temperature fluctuation coupled with $\Delta T/\Delta t$ explained > 90 % of R_{total} variation in all eight landscapes. However, the dominant factor (T_{soil} or $\Delta T/\Delta t$) for diel R_{total} variation was different, depending on which flux component was dominant (i.e. R_{abiotic} or R_{biotic}). When R_{total} was not significantly different from R_{biotic}, as observed in cotton and hops fields, soil temperature (T_{soil}) accounted for more than 60 % of diel R_{total} variation. Whereas, when R_{total} was dominated by R_{abiotic}, as in alkaline soil and dune crest, $\Delta T/\Delta t$ dominated diel R_{total} variation. Such variations suggested that soil temperature (T_{soil}) mainly controlled R_{biotic} while $\Delta T/\Delta t$ determined R_{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_{abiotic} in the eight landscapes, but R_{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 $< 40\,\text{mg}\,\text{kg}^{-1}$ 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_{biotic} at these two sites was low and temperature insensitivity of R_{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_{total} was basically the same as variation of R_{abiotic}; whereas, temperature dependence of R_{total} was a combined effect of both biotic and abiotic components. Although the diurnal variation of R_{total} with temperature is not unusual, it is intriguing that there was a change in the determination of temperature response.

R_{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_{abiotic} (Plummer and Busenberg, 1982; Karberg et al., 2005; Ball et al., 2009; Shanhun et al., 2012). Rising temperature allowed CO_2 to be dissolved in soil solution, and decreasing temperature induced CO_2 release on a daily basis (Fig. 2). Thus, there was a diel pattern of alternating positive and negative CO_2 fluxes with a zero sum in abiotic flux (Fig. 1). In a soil, the magnitude of R_{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 pH. A similar result was found in alkaline desert soils (Xie et al., 2009), where CO_2 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_{abiotic} resulted in no net gain or loss of C, its effect on instantaneous CO_2 flux was significant. When $R_{\text{abiotic}} > 0$, apparent R_{biotic} was clearly amplified compared to its real level (Fig. 4a); whereas, apparent R_{biotic} was significantly weakened when $R_{\text{abiotic}} < 0$, even to the extent of altering CO_2 transport direction (Fig. 4b). Without recognition of R_{abiotic}, R_{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_2 efflux and the oxygen influx) for three calcareous soil sites (Angert et al., 2015).

Such an abiotic effect on CO_2 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_2 flux (i.e. $R_{\text{abiotic}}/R_{\text{total}}$) is the key to discerning whether R_{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_2, which are not significantly affected by R_{abiotic}, making such correction unnecessary. However, in some extreme conditions, as in alkaline soil and dune crest, the effect of R_{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_{biotic} (Fig. 4), suggesting a strong effect of R_{abiotic} (over R_{total}) appeared when R_{biotic} was low. Conditions such as high soil pH, high moisture content, low soil organic C content and few living roots favored R_{abiotic} more than R_{biotic}, resulting in R_{abiotic} comparable to and even far exceeding R_{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_{abiotic} had no significant difference to the total soil CO_2 flux.

The information provided above shows that R_{total}, previously thought to be of purely biological origin, was actually a result of R_{biotic} being offset or intensified by R_{abiotic}. From this point of view, misestimates of biotic flux rates have potentially profound implications for quantifying the turnover time of the soil C pool, because biotic flux rate (conventional soil respiration) has been used to calculate the mean residence or turnover time of the soil C pool with the assumption that the contribution of living root respiration was a known proportion of total soil respiration (Raich and Schlesinger, 1992; Elberling et al., 2006). Additionally, influenced by abiotic processes, results relating soil CO_2 flux to certain environment factors often used in empirical models, such as temperature (Fang and Moncrieff, 2001; Vargas and Allen, 2008) and soil moisture (Yuste et al., 2003), would also be inaccurate. An example of such misuse is extrapolating entire year or entire region soil (or ecosystem) respiration from functions between respiration and temperature, derived from discontinuous measurement or even point observations (Bolstad et al., 2004; Lee et al., 2010), which would be either overestimated or underestimated depending on the time when dotted data were gotten.

In summary, the recognition that the abiotic component in the soil CO_2 flux is ubiquitous in alkaline soils has widespread consequences for the study of C cycling. When biotic processes are strong, the effect of the abiotic component is limited; however, if biotic processes are weak, the abiotic flux may dominate. While the abiotic flux will not change the sum or net value of daily soil CO_2 exchange and not likely directly constitute a C sink, it can significantly alter transient apparent soil CO_2 flux, either in magnitude or in temperature dependence.

Author contributions. All authors commented on manuscript at all stages. Y. Li designed the experiments and J. Ma carried them out; R. Liu has significant contribution in structuring and presenting the paper.

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References

Angert, A., Yakir, D., Rodeghiero, M., Preisler, Y., Davidson, E. A., and Weiner, T.: Using O_2 to study the relationships between soil CO_2 efflux and soil respiration, Biogeosciences, 12, 2089–2099, doi:10.5194/bg-12-2089-2015, 2015.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, Glob. Change Biol., 9, 479–492, 2003.

Ball, B. A., Virginia, R. A., Barrett, J. E., Parsons, A. N., and Wall, D. H.: Interactions between physical and biotic factors influence CO_2 flux in Antarctic dry valley soils, Soil Biol. Biochem., 41, 1510–1517, , 2009.

Barrett, J. E., Virginia, R. A., Parsons, A. N., and Wall, D. H.: Soil carbon turnover in the McMurdo Dry Valleys, Antarctica, Soil Biol. Biochem., 38, 3065–3082, 2006.

Bolstad, P. V., Davis, K. J., Martin, J., Cook, B. D., and Wang, W.: Component and whole-system respiration fluxes in northern deciduous forests, Tree Physiol., 24, 493–504, 2004.

Borken, W. and Matzner, E.: Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils, Glob. Change Biol., 15, 808–824, 2009.

Cable, J. M., Ogle, K., Lucas, R. W., Huxman, T. E., Loik, M. E., Smith, S. D., Tissue, D. T., Ewers, B. E., Pendall, E., Welker, J. M., Charlet, T. N., Cleary, M., Griffith, A., Nowak, P. S., Rogers, M., Steltzer, H., Sullivan, P. F., and Van Gestel, N. C.: The temperature response of soil respiration in deserts: a seven desert synthesis, Biogeochemistry, 103, 71–90, 2011.

Carbone, M. S., Winston, G. C., and Trumbore, S. E.: Soil respiration in perennial grass and shrub ecosystems: linking environmental controls with plant and microbial sources on seasonal and diel timescales, J. Geophys. Res.-Biogeo., 113, G02022, doi:10.1029/2007JG000611, 2008.

Crow, S. E., Sulzman, E. W., Rugh, W. D., Bowden, R. D., and Lajtha, K.: Isotopic analysis of respired CO_2 during decomposition of separated soil organic matter pools, Soil Biol. Biochem., 38, 3279–3291, 2006.

Davidson, E. A. and Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, Nature, 440, 165–173, 2006.

Davidson, E. A., Belk, E., and Boone, R. D.: Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest, Glob. Change Biol., 4, 217–227, 1998.

Elberling, B., Gregorich, E. G., Hopkins, D. W., Sparrow, A. D., Novis, P., and Greenfield, L. G.: Distribution and dynamics of soil organic matter in an Antarctic dry valley, Soil Biol. Biochem., 38, 3095–3106, 2006.

Elberling, B., Greenfield, L. G., Gregorich, E. G., Hopkins, D. W., Novis, P., and Sparrow, A. D.: Comments on "Abiotic processes dominate CO_2 flux in Antarctic soils" by Shanhun et al. Soil Biology & Biochemistry 53, 99–111 (2012), Soil Biol. Biochem., 75, 310–311, 2014.

Emmerich, W. E.: Carbon dioxide fluxes in a semiarid environment with high carbonate soils, Agr. Forest Meteorol., 116, 91–102, 2003.

Fang, C. and Moncrieff, J. B.: The dependence of soil CO_2 efflux on temperature, Soil Biol. Biochem., 33, 155–165, 2001.

Hanson, P. J., Edwards, N. T., Garten, C. T., and Andrews, J. A.: Separating root and soil microbial contributions to soil respiration: a review of methods and observations, Biogeochemistry, 48, 115–146, 2000.

Hardie, S. M. L., Garnett, M. H., Fallick, A. E., Rowland, A. P., Ostle, N. J., and Flowers, T. H.: Abiotic drivers and their interactive effect on the flux and carbon isotope (^{14}C and $\delta^{13}C$) composition of peat-respired CO_2, Soil Biol. Biochem, 43, 2432–2440, 2011.

Karberg, N. J., Pregitzer, K. S., King, J. S., Friend, A. L., and Wood, J. R.: Soil carbon dioxide partial pressure and dissolved inorganic carbonate chemistry under elevated carbon dioxide and ozone, Oecologia, 142, 296–306, 2005.

Lee, N. Y., Koo, J. W., Noh, N. J., Kim, J., and Son, Y.: Seasonal variation in soil CO_2 efflux in evergreen coniferous and broad-leaved deciduous forests in a cool-temperate forest, central Korea, Ecol. Res., 25, 609–617, 2010.

Li, X. D., Fu, H., Guo, D., and Wan, C. G.: Partitioning soil respiration and assessing the carbon balance in a *Setaria italica* (L.) Beauv. cropland on the Loess Plateau, Northern China, Soil Biol. Biochem., 42, 337–346, 2005.

Liu, Q., Edwards, N. T., Post, W. M., Gu, L., Ledford, J., and Lenhart, S.: Temperature-independent diel variation in soil respiration observed from a temperate deciduous forest, Glob. Change Biol., 12, 2136–2145, 2006.

Luo, Y. and Zhou, X. H.: Soil Respiration and Environment, Academic/Elsevier, San Diego, 2006.

Ma, J., Wang, Z.-Y., Stevenson, B., Zheng, X.-J., and Li, Y.: An inorganic CO_2 diffusion and dissolution process explains negative CO_2 fluxes in saline/alkaline soils, Sci. Rep., 3, 2025, doi:10.1038/srep02025, 2013.

Marland, G., Boden, T. A., and Andres, R. J.: Global, regional, and national fossil fuel CO_2 emissions, in: Trends: a Compendium of Data on Global Dioxide Information Analysis Center, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, USA, 2008.

Mielnick, P., Dugas, W. A., Mitchell, K., and Havstad, K.: Long-term measurements of CO_2 flux and evapotranspiration in a Chihuahuan desert grassland, J. Arid Environ., 60, 423–436, 2005.

Parsons, A. N., Barrett, J. E., Wall, D. H., and Virginia, R. A.: Soil carbon dioxide flux in Antarctic dry valley ecosystems, Ecosystems, 7, 286–295, 2004.

Plummer, L. N. and Busenberg, E.: The solubilities of calcite, aragonite and vaterite in CO_2-H_2O solutions between 0 °C and 90 °C, and an evaluation of the aqueous model for the system $CaCO_3$-CO_2-H_2O, Geochim. Cosmochim. Ac., 46, 1011–1040, 1982.

Raich, J. W. and Schlesinger, W. H.: The global carbon-dioxide flux in soil respiration and its relationship to vegetation and climate, Tellus B, 44, 81–99, 1992.

Raich, J. W., Potter, C. S., and Bhagawati, D.: Interannual variability in global soil respiration, 1980–94, Glob. Change Biol., 8, 800–812, 2002.

Ryan, M. G. and Law, B. E.: Interpreting, measuring, and modeling soil respiration, Biogeochemistry, 73, 3–27, 2005.

Serrano-Ortiz, P., Roland, M., Sanchez-Moral, S., Janssens, I. A., Domingo, F., Godderis, Y., and Kowalski, A. S.: Hidden, abiotic CO_2 flows and gaseous reservoirs in the terrestrial carbon cycle: review and perspectives, Agr. Forest Meteorol., 150, 321–329, 2010.

Shamir, I. and Steinberger, Y.: Vertical distribution and activity of soil microbial population in a sandy desert ecosystem, Microbial. Ecol., 53, 340–347, 2007.

Shanhun, F. L., Almond, P. C., Clough, T. J., and Smith, C. M. S.: Abiotic processes dominate CO_2 fluxes in Antarctic soils, Soil Biol. Biochem., 53, 99–111, 2012.

Stevenson, B. A. and Verburg, P. S. J.: Effluxed CO_2-^{13}C from sterilized and unsterilized treatments of a calcareous soil, Soil Biol Biochem., 38, 1727–1733, 2006.

Stone, R.: Ecosystems – have desert researchers discovered a hidden loop in the carbon cycle?, Science, 320, 1409–1410, 2008.

Tang, J. W., Baldocchi, D. D., and Xu, L.: Tree photosynthesis modulates soil respiration on a diurnal time scale, Glob. Change Biol., 11, 1298–1304, 2005.

Vargas, R. and Allen, M. F.: Environmental controls and the influence of vegetation type, fine roots and rhizomorphs on diel and seasonal variation in soil respiration, New Phytol., 179, 460–471, 2008.

Xie, J.-X., Li, Y., Zhai, C.-X., Li, C.-H., and Lan, Z.-D.: CO_2 absorption by alkaline soils and its implication to the global carbon cycle, Environ. Geol., 56, 953–961, 2009.

Yuste, J. C., Janssens, I. A., Carrara, A., Meiresonne, L., and Ceulemans, R.: Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest, Tree Physiol., 23, 1263–1270, 2003.

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

	Soil organic C (g kg^{-1})	Soil inorganic C (g kg^{-1})	pH	EC (dS m^{-1})	Root biomass (g m^{-2})	Moisture (%, g g^{-1})
Cotton field	7.20^{b} (0. 47)	4.41^{e} (0.11)	8.13^{c} (0.09)	3.83^{b} (0.92)	47.75^{a} (4.46)	13.02^{a} (0.52)
Halophyte garden	8.00^{b} (0.68)	5.96^{c} (0.11)	9.20^{a} (0.06)	14.23^{a} (0.87)	24.19^{c} (3.18)	7.60^{b} (0.42)
Hops field	15.85^{a} (0.38)	4.67^{e} (0.23)	8.00^{c} (0.10)	1.09^{c} (0.21)	38.19^{b} (4.77)	7.94^{b} (0.39)
Dune crest	0.57^{f} (0.07)	1.24^{g} (0.05)	8.93^{b} (0.03)	0.09^{e} (0.01)	0.95^{f} (0.24)	0.26^{f} (0.04)
Reservoir edge	5.38^{c} (0.98)	8.24^{b} (0.20)	8.76^{b} (0.15)	1.23^{c} (0.33)	17.51^{cd} (0.64)	8.25^{b} (0.42)
Alkaline soil	2.96^{e} (0.09)	5.38^{d} (0.12)	9.17^{a} (0.17)	0.23^{d} (0.05)	0.32^{g} (0.14)	0.40^{e} (0.03)
Native saline desert	3.25^{e} (0.60)	9.25^{a} (0.18)	8.60^{b} (0.09)	4.76^{b} (0.82)	5.09^{e} (0.32)	1.63^{d} (0.11)
Interdune lowland	4.62^{d} (0.50)	1.52^{f} (0.09)	8.90^{b} (0.10)	0.11^{e} (0.03)	16.23^{d} (0.64)	2.50^{c} (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_2 flux and the corresponding biotic and abiotic components at different landscapes.

Landscape			Total soil CO_2 flux					Biotic flux		
	Model R^2	Variable	Parameter estimate	F	Partial R^2	Model R^2	Variable	Parameter estimate	F	Partial R^2
Cotton field	0.938	Intercept	−3.411 ± 0.213	–	–	0.914	Intercept	−2.985 ± 0.225	–	–
		T_{soil}	0.211 ± 0.008	464.435	0.912		T_{soil}	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	–	–
		T_{soil}	0.118 ± 0.004	67.617	0.600		T_{soil}	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	212
Hops field	0.946	Intercept	−1.234 ± 0.12	–	–	0.928	Intercept	−0.908 ± 0.11	–	–
		T_{soil}	0.09 ± 0.005	53.077	0.541		T_{soil}	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	–	–	–
		T_{soil}	0.02 ± 0.002	89.550	0.224		T_{soil}	–	–	–
		$\Delta T/\Delta t$	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	–	
		T_{soil}	0.013 ± 0.003	24.117	0.028		T_{soil}	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	–	–	–
		T_{soil}	0.033 ± 0.002	289.151	0.379		T_{soil}	–	–	–
		$\Delta T/\Delta t$	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	–	–
		T_{soil}	0.018 ± 0.003	42.804	0.136		T_{soil}	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	–	–
		T_{soil}	0.051 ± 0.004	191.614	0.218		T_{soil}	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		Abiotic flux			
	Model R^2	Variable	Parameter estimate	F	Partial R^2
Cotton field	0.898	Intercept	-0.338 ± 0.042	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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	–	–
		T_{soil}	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_2 flux and the corresponding biotic and abiotic components across the eight landscapes. The model R^2 for total soil CO_2 flux, biotic flux and abiotic flux were 0.91, 0.91 and 0.89, respectively, and all $P < 0.005$.

Total soil CO_2 flux				
Variable	Parameter estimate	F	P	Partial R^2
Intercept	−203.43 ± 433.44		0.65	N.A.
Root biomass	131.78 ± 17.47	56.86	< 0.001	0.91
Biotic flux				
Variable	Parameter estimate	F	P	Partial R^2
Intercept	−202.31 ± 400.10		0.63	N.A.
Root biomass	128.10 ± 16.13	63.05	< 0.001	0.91
Abiotic flux				
Variable	Parameter estimate	F	P	Partial R^2
Intercept	−2157.71 ± 396.65		0.003	N.A.
pH	278.58 ± 43.97	9.324	0.001	0.61
Soil moisture	15.03 ± 4.22	12.691	0.016	0.28

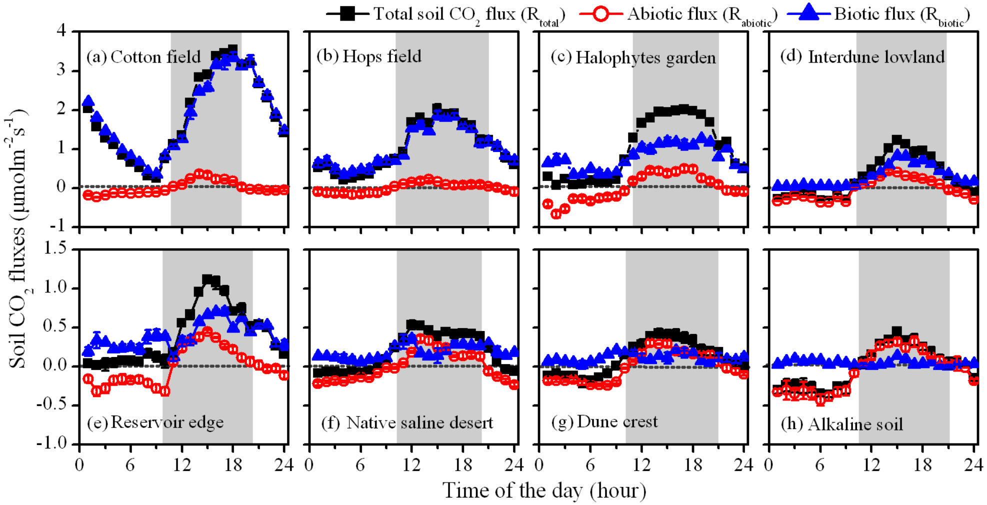

Figure 1. Partitioning the total soil CO_2 flux into biotic and abiotic parts across the eight sites. **(a–h)** represent the sites of cotton field, hops field, halophyte garden, interdune lowland, reservoir edge, native saline desert, dune crest and alkaline soil, respectively. The shaded parts indicate the periods during which $R_{abiotic}$ was positive. Error bars represent standard errors of the mean.

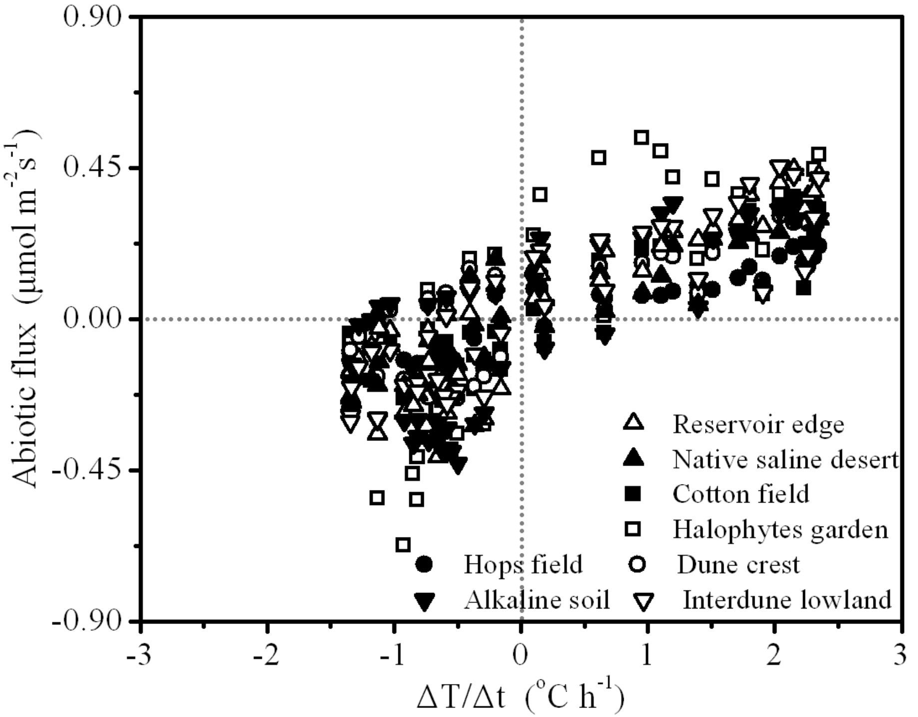

Figure 2. Temperature dependence for abiotic flux. Appearance of negative values of R_{abiotic} coincided with naturally declining soil temperature (the period of $\Delta T/\Delta t < 0$), and positive values with rising soil temperature.

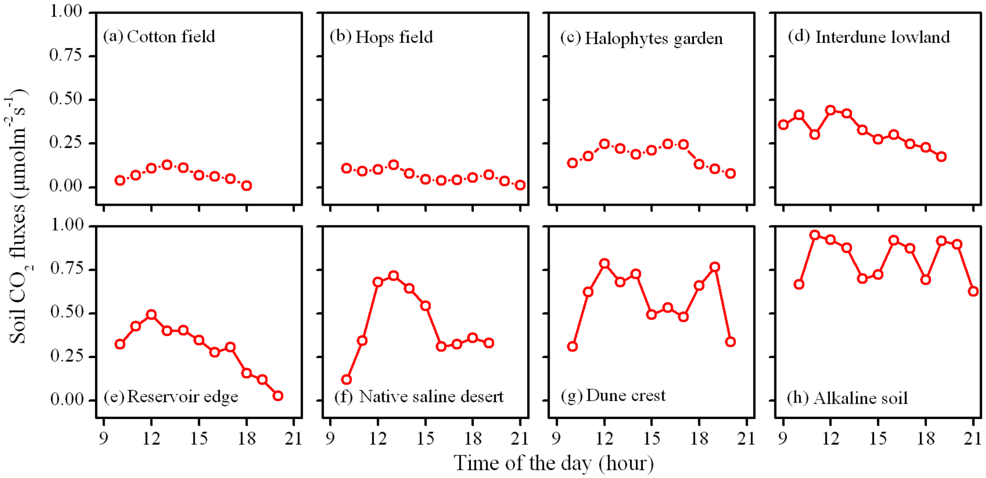

Figure 3. Ratio of R_{abiotic} to R_{total} during the periods of $R_{\text{abiotic}} > 0$ for the eight sites.

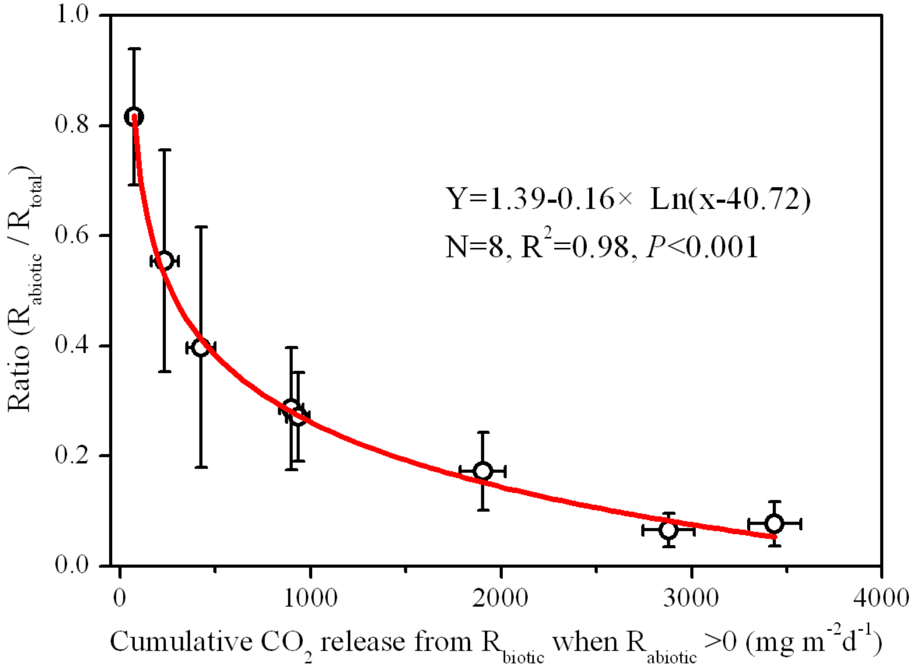

Figure 4. The average ratio of $R_{abiotic}$ to R_{total} had an exponential relationship with cumulative CO_2 release from R_{biotic}. Error bars represent standard errors of the mean.

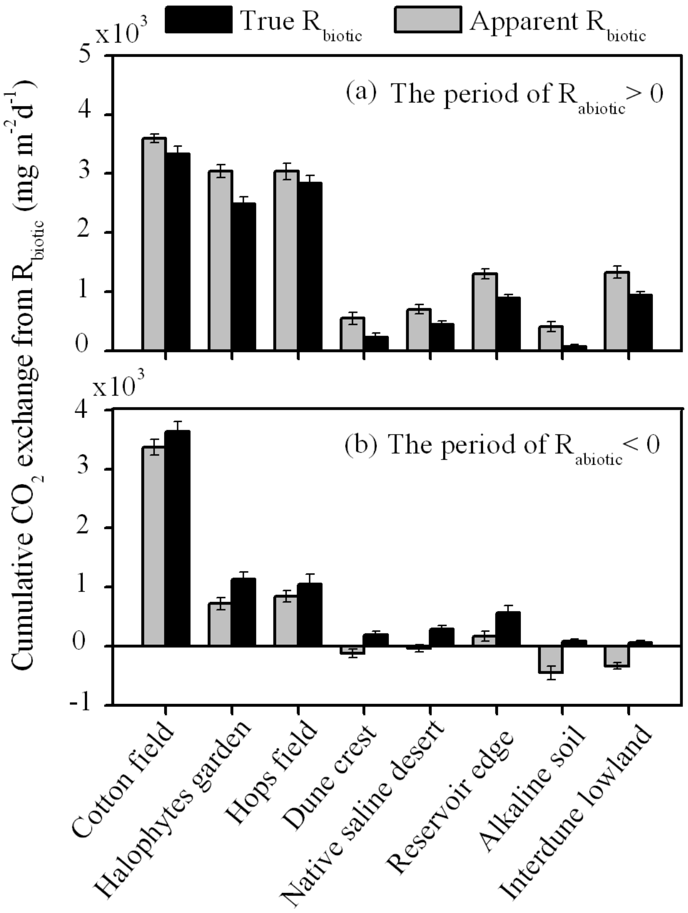

Figure 5. Cumulative apparent CO_2 exchanges from R_{biotic} were significantly amplified compared to their real values during the period of $R_{\mathrm{abiotic}} > 0$ **(a)**; whereas, the apparent R_{biotic} were weakened when $R_{\mathrm{abiotic}} < 0$ **(b)**. Error bars represent standard errors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