Variations in diurnal and seasonal net ecosystem carbon dioxide exchange in a semiarid sandy grassland ecosystem in China’s Horqin Sandy Land

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Abstract

Grasslands are major terrestrial ecosystems in arid and semiarid regions, and play important roles in the regional carbon dioxide (CO$_2$) balance and cycles. Sandy grasslands are sensitive to climate change, yet the magnitudes, patterns, and environmental controls of their CO$_2$ flows are poorly understood. Here, we report the results from continuous year-round CO$_2$ observations in 5 years from a sandy grassland in China’s Horqin Sandy Land. The sandy grassland was a net CO$_2$ source at an annual scale, with a mean annual net ecosystem CO$_2$ exchange (NEE) of $48.88 \pm 8.10$ g C m$^{-2}$ yr$^{-1}$ in the years for which a complete dataset was available (2015, 2016, and 2018); total annual precipitation was the most important factor for NEE. At a seasonal scale, the sandy grassland showed net CO$_2$ absorption during the summer, but net CO$_2$ release in the other seasons. The main environmental factors that affected NEE were temperature and soil water content (SWC) in the spring, soil heat flux and solar radiation in the summer, soil heat flux and temperature in autumn, and SWC and temperature in winter. At the diurnal scale, net solar radiation was the most important factor for NEE in all seasons. The sandy grassland may have been a net annual CO$_2$ source at an annual scale because the study site is recovering from degradation, thus vegetation productivity is still low. Therefore, the ecosystem has not yet transitioned to a CO$_2$ sink and long-term observations will be necessary to reveal the true source or sink intensity and its response to environmental and biological factors.

Keywords: Net ecosystem CO$_2$ exchange (NEE); Gross primary productivity (GPP); ecosystem respiration ($R_{ec}$); Eddy covariance; Horqin Sandy Land

1 Introduction

Arid and semiarid ecosystems cover 30 to 40 % of the global terrestrial surface (Poulter et al., 2014). The extent and distribution of these areas are increasing in response to factors such as climate change, changes in wildfire frequency and intensity, and changes in land use (Asner et al., 2003; Hastings et al., 2010). These ecosystems are important because they account for 30 to 35 % of terrestrial net primary productivity (Gao et al., 2012; Liu et al., 2016a) and approximately 15 % of the global soil organic
affected implies causation, but the analysis only shows correlation

Could have it been because precipitation was below normal?
carbon pool (Lal, 2004; Liu et al., 2016a). Thus, the high potential carbon sequestration in arid and semiarid areas may have a greater impact on the future global carbon cycle than sequestration in tropical rainforest areas (Emmerich, 2003; Nosetto et al., 2006; Poulter et al., 2014), and arid and semiarid ecosystems will have significant effects on the global carbon cycle and carbon balance (Lal, 2004). However, arid and semiarid ecosystems have received much less attention than wetter ecosystems, and the lack of high-frequency continuous observations has led to a weak understanding of their role in global terrestrial net ecosystem CO$_2$ exchange (NEE) (Baldocchi et al., 2001; Hastings et al., 2010).

Desertification occurs in more than two-thirds of the area of arid and semiarid ecosystems (Lal, 2001). This may cause a serious imbalance in the structure and function of these ecosystems (Huenneke et al., 2002; Vest et al., 2011), especially in terms of whether the ecosystem functions as a carbon source or sink (Shachak et al., 1998; Gang et al., 2011). Grazing exclusion is a common method used to combat desertification in the world’s arid and semiarid areas (Mureithi et al., 2010; Sousa et al., 2012). For example, Sun et al. (2015) suggested that proper exclosures promoted the recovery of degraded sandy grassland and more sustainably use sandy grassland resources.

The Horqin Sandy Land is the largest sandy land in China, and nearly 80% of the area has been desertified (Li et al., 2019). The sandy land includes multiple overlapping ecotones, including transition zones between areas with different population pressures, between semi-humid and semiarid areas, and typical agro-pastoral ecotones. The ecological environment is fragile and extremely sensitive to climate change and human activities (Bagan et al., 2010; Zhao et al., 2015). The region’s sandy grassland grows on aeolian sandy soils or with sandy soils as the substrate, and is typical of the grassland vegetation that develops in sandy land. This grassland ecosystem is widespread in the Horqin Sandy Land (Munkhdalai et al., 2007; Zhao et al., 2007). Research showed that the restoration of degraded sandy grassland can increase its productivity and carbon sequestration, and that the ecosystem can begin to act as a carbon sink (Ruiz-Jaen and...
Drylands add up because of their vastness, but by themselves (on a per unit area basis) are not considered a potentially large area for long-term carbon sequestration.

From what has been shown, dryland C cycling contributes a lot of the interannual variability of global terrestrial C flux (fast response), but long term sequestration potential has not been borne out (slow response).

See Poulter et al. and studies that have followed that up over regions like Australia.

This is overlooking a large pool of work in the last 10 yrs. Some of which should certainly be mentioned and considered throughout this paper.

Please see (to name a few):

From Southwest US, which has a very similar summer monsoon climate that should be very apropos to your study.


Biederman papers, Scott, Litvak, Bowling, Wagle, Aussie papers

From Australia. See papers from Beringer, Cleverly, Eamus...

what is a sandy land?

citation?
Aide, 2005; Zhao et al., 2016). However, other studies showed that it was a carbon source (Li et al., 2012; Niu et al., 2018). There have been relatively few long-term studies of sandy grassland at the ecosystem level, so we do not yet fully understand the characteristic of NEE and its components, gross primary productivity (GPP) and ecosystem respiration ($R_{ec}$), at an ecosystem scale, particularly for sandy grassland protected by grazing exclosures, and more data are needed, particularly for semiarid sandy land (Barrett, 1968; Czobel et al., 2012).

Precipitation is one of the factors that most strongly affects NEE in arid and semiarid areas. It affects NEE mainly through its effects on GPP and $R_{ec}$ (Lal, 2004; Dasci et al., 2010; Hastings et al, 2010; Liu et al., 2016b). Previous research showed that reduced precipitation caused a continental-scale reduction in GPP, with concurrent decreases of $R_{ec}$ (Ciais et al., 2005). In contrast, other studies found that GPP was more sensitive than respiration to precipitation (Thomas et al., 2010; Shi et al., 2014). For instance, Delgado-Balbuena et al. (2019) have shown that GPP was more than twice as sensitive as $R_{ec}$ to precipitation in a semiarid grassland. The precipitation in the Horqin Sandy Land is low, with high temporal and spatial variation, and other water resources such as groundwater are small (Niu et al., 2015). Moreover, we found no reports on the response of ecosystem-scale NEE and its components to precipitation, and the response mechanisms are uncertain in the sandy grassland. Therefore, long-term data are required to fully understand how changes in annual precipitation influence the annual NEE, GPP, and $R_{ec}$ of sandy grassland.

In this paper, we present the results from continuous (14 September 2014 to 31 December 2018) in situ monitoring of CO$_2$ dynamics in the Horqin Sandy Land’s sandy grassland using the eddy covariance technique, and quantified the temporal variation of NEE and the factors that control it. We had the following goals: (1) To quantify the diurnal, seasonal, and annual variation in NEE, GPP, and $R_{ec}$. (2) To identify the environmental factors that controlled NEE and its components at different temporal scales, and the possible underlying mechanisms in the sandy grassland. (3) To determine how annual precipitation affects the annual ecosystem NEE, GPP, and $R_{ec}$. 
can't tell from the reference list which papers these are because there are no years in the listing
citations to Scott et al. 2015, also Biederman et al. 2015
australian papers by cleverly, beringer
how is this in contrast with "concurrent decreases"?
see Scott et al., Biederman et al. 2015
of the "sandy grassland" in this region or grasslands underlain by sandy soils more globally?
Given these pretty goals limited to mainly data reporting. Ecosystem flux science has moved beyond this type of paper and into data interpretation and contextualization. It would be better to put these results into context of what is known already about the seasonal to interannual sensitivity elsewhere. This could be done either by bringing in these expectation learned from previous studies and testing those, or by pulling in data from other sites or syntheses like Fluxnet2015.
2 Materials and methods

2.1 Experimental site

Our study was conducted in a sandy grassland in the southern part of the Horqin Sandy Land, Inner Mongolia, China, at the Naiman Desertification Research Station of the Chinese Academy of Sciences (42° 55′ N, 120° 42′ E) (Fig. 1). The terrain is flat, and it evolved from reclamation of sandy grassland for agriculture to severe desertification, after which cultivation was abandoned and grazing exclosures were established to allow natural recovery of the vegetation, starting in 1985 (Zhao et al., 2007). Thus, the grassland had been recovering naturally for nearly 30 years when our study began. At an elevation of 377 m a.s.l., the study area has a continental semiarid monsoon temperate climate regime. The mean annual temperature is 6.8 °C, with mean monthly temperatures ranging from -9.63 °C in January to 24.58 °C in July. Average annual precipitation is approximately 360 mm, with 70% of the precipitation occurring during the growing season, between June and August. Annual mean potential evaporation is approximately 1973 mm. The annual frost-free period is 130 to 150 days. The zonal soil is a sandy chestnut soil, but most of the soil has been degraded by a combination of climate change and anthropogenic activity (unsustainable grazing or agriculture) into an aeolian sandy soil under the action of wind erosion (Zhao et al., 2007), with coarse sand, fine sand, and clay-silt contents of 92.7, 3.3, and 4.0 % in the topsoil to a depth of 20 cm. The contents of soil organic carbon and total nitrogen were 1.27 and 0.21 g kg$^{-1}$, respectively. Vegetation cover in the study area ranged from 50 to 70 %. The dominant plant species were annual herbs, including Artemisia scoparia, Setaria viridis, Salsola collina, and Corispermum hyssopifolium (Niu et al., 2018).

2.2 Eddy covariance observations

An eddy covariance flux tower (2.0 m high) was installed at the center of the observation field (Fig. 1b, c). We have continuously monitored CO$_2$, water, and heat fluxes at the tower using the eddy covariance system since late 2014. The fetch from all directions was more than 200 m. Calculations with a footprint model indicated that the fetch was well within the desired flux footprint (Schmid, 1994; Xu and Baldocchi,
Given the dominant controls of water in semiarid regions and that these P values and summer temps are very similar to the monsoon region in N. America, there is even more reason to bring in some of these results (found in the papers I listed above) in the Introduction and discussion.

You would want the fetch (region upwind of the flux tower that consists of "homogeneous" vegetation type and cover) to be greater than the flux footprint (See Schmid, H. P. "Experimental design for flux measurements: matching scales of observations and fluxes." Agricultural and Forest Meteorology 87.2-3 (1997): 179-200.)
The eddy covariance system consisted of an LI-7500 infrared gas analyzer (Li-Cor Inc., Lincoln, NE, USA), with a precision of 0.01 µmol m$^{-2}$ s$^{-1}$ and an accuracy within 1% of the reading for measurements at 30-min mean intervals, and a CSAT-3 three-dimensional ultrasonic anemometer (Campbell Scientific, Inc., Logan, UT, USA), with a precision of 0.1 °C and an accuracy of 1% for the readings at 30-min mean intervals. Raw 10-Hz data were recorded by a CR3000 datalogger (Campbell Scientific). The operation, calibration, and maintenance of the eddy covariance system followed the manufacturers’ standard procedures. The LI-7500 was calibrated every 6 months for CO$_2$, water vapor, and dew point values using calibration gases and dew point generator measurements supported by the China Land–Atmosphere Coordinated Observation System (Yun et al., 2018). We cleaned the mirror of the LI-7500 every 15 days to maintain the automatic gain control value below its threshold (55 to 65). All of the instruments were powered by solar panels connected to a battery.

2.3 Micrometeorological measurements

Along with the flux measurements obtained by the eddy covariance equipment, we measured standard meteorological and soil parameters continuously with an array of sensors. A propeller anemometer was installed at the top of the meteorological tower to measure the wind speed and direction. Net radiation (R$_n$, W m$^{-2}$) was measured by a four-component radiometer (CNR-1, Kipp and Zonen, Delft, the Netherlands) installed at 1 m above the ground. The air temperature (T$_{air}$, °C) and relative humidity (%) instruments (HMP45C, Vaisala Inc., Helsinki, Finland) were mounted at 2 m above the ground to measure the T$_{air}$, relative humidity, and atmospheric pressure (kPa). Precipitation (mm) measurements were obtained from a meteorological station 400 m from the study site.

We installed five CS109 temperature probes (Campbell Scientific) and five CS616 moisture probes (Campbell Scientific) in the soil at depths of 10, 20, 30, 40, and 50 cm to measure soil temperature (T$_{soil}$, °C) and soil water content (SWC, %). Two self-calibrating HFP01 soil heat flux (SHF, W m$^{-2}$) sensors (Hukseflux, Delft, the Netherlands) were buried 5 and 10 cm below the ground to obtain the SHF data. All of
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the environmental parameters were measured simultaneously with the eddy covariance measurements, and all data were recorded as 30-min mean values with a CR3000 datalogger.

2.4 Data quality and gap-filling method

We used the EddyPro 6.2.0 software (https://www.licor.com/env/products/eddy_covariance/software.html) to process the 10-Hz raw eddy covariance data. Processing included spike removal, lag correction, secondary coordinate rotation, Webb–Pearman–Leuning correction, and sonic virtual temperature conversion (Webb et al., 1980). We used the data processing method of Lee et al. (2004) to process the 30-min mean raw flux measurements to ensure their quality. Processed data were further corrected for weather effects and sensor uncertainty using the following procedure: (1) We removed data gathered during precipitation events, power failures, and sensor maintenance or malfunction. (2) We excluded unrealistic CO₂ flux data (values outside the range of −2.0 to 2.0 mg CO₂ m⁻² s⁻¹). (3) We rejected the data during stable atmospheric conditions at nighttime (friction velocity (u* < 0.1 m s⁻¹). Based on the Rₙ, NEE was classified as the daytime NEEₜₐ₅ (Rₙ ≥ 1 W m⁻²) or the night-time NEEₘᵦₕ (Rₙ < 1 W m⁻²). This screening resulted in the rejection of 20 to 30% of the flux data, depending on the period.

We used several strategies to compensate for missing data. We used linear interpolation to fill gaps that were shorter than 2 h. For longer gaps, we handled the gap in the NEEₜₐ₅ using the mean diurnal variation with a 7-day window (Falge et al., 2001), and handled the gap in the NEEₘᵦₕ using a temperature-dependent exponential model (Lloyd and Taylor, 1994):

\[
\text{NEE}_{\text{night}} = R_0 \exp (b T_{10}) \quad \text{Eq (1)}
\]

where \( R_0 \) is the base ecosystem respiration rate when the soil temperature is 0 °C, \( b \) an empirically determined coefficient, and \( T_{10} \) is the soil temperature at a depth of 10 cm. Daytime ecosystem respiration can be estimated by extrapolation from the parameterization derived from Eq. (1). We did not attempt to fill in gaps longer than 7 days, and treated those gaps as missing data. Gross primary productivity (GPP) was
Atmospheric stability depends on more than other factors besides $u^*$.

How were these parameters obtained and how often? A moving window of ~1 week should be used. See for example, Reichstein et al. 2005.
obtained as follows:

\[ GPP = NEE - R_{ec} \]  

Eq (2)

We evaluated the data quality based on the degree of energy closure (sensible heat + latent heat – net radiation – soil heat flux). The energy closure values for the sandy grassland from 2015 to 2018 were 86.5, 82.1, 57.7, and 85.2 %, respectively.

2.5 Statistical analyses

We performed correlation analysis (Pearson’s r) and principal-components analysis (PCA) using version 22 of the SPSS software (IBM, Armonk, NY, USA). Unless otherwise noted, we defined statistical significance at \( p < 0.05 \). Pearson’s r was applied to confirm the strength of the relationships between parameters. PCA was used to identify the main environmental factors that affected NEE and its components at different temporal scales. Before performing PCA, we tested for collinearity (using a variance inflation factor of \( 0 < VIF < 10 \)) using the Kaiser–Meyer–Olkin (KMO) test and Bartlett’s sphericity test. Collinearity was used to repartition the \( T_{soil} \) and SWC data. We considered KMO values > 0.50 and \( p < 0.05 \) for Bartlett’s sphericity test to indicate acceptable data (Hair et al., 2005). Our data were suitable for PCA, with the KMO value ranging from 0.52 to 0.78 and \( p < 0.001 \) for all Bartlett’s sphericity test results.

3 Results

3.1 Meteorological conditions

We recorded \( T_{air} \) in the sandy grassland between September 2014 and December 2018 (Fig. S1). The mean annual \( T_{air} \) was 7.38 °C, with minimum and maximum \( T_{air} \) of \(-17.82 \) and 27.15 °C, respectively. Average \( R_n \) was 74.13 W m\(^{-2}\), with average minimum and maximum values for the 5 years minimum and maximum \( R_n \) of \(-13.09 \) and 166.32 W m\(^{-2}\), respectively (Fig. S2). The diurnal- scale SHF values at depths of 5 and 10 cm were 0.65 and \(-0.21 \) W m\(^{-2}\), respectively (Fig. S3), with maximum values of 34.43 and 26.88 W m\(^{-2}\) (both on 28 April 2018), and the minimum values were \(-36.26 \) and \(-23.77 \) W m\(^{-2}\) (both on 4 October 2016).

The annual mean \( T_{soil} \) values at depths of 10, 20, 30, 40, and 50 cm were 9.49, 9.66, 9.85, 10.22, and 10.65 °C (Fig. S4a). The average minimum diurnal values for the 5
These should be used to estimate $G$, the soil heat flux at $z=0$. 
years diurnal $T_{\text{soil}}$ at all depths were $-18.08$, $-16.33$, $-14.17$, $-12.56$, and $-11.26 \, ^{\circ}\text{C}$, respectively, and the average maximum diurnal values for the 5 years diurnal $T_{\text{soil}}$ were $33.45$, $32.31$, $31.30$, $30.49$, and $29.76 \, ^{\circ}\text{C}$, respectively. The annual mean SWC values at depths of 10, 20, 30, 40, and 50 cm were 3.5, 3.6, 4.2, 4.8, and 5.7 %, respectively (Fig. S4b). The average minimum diurnal values for the 5 years minimum diurnal SWC at all depths were 1.5, 1.6, 1.6, 2.4, and 2.7 %, respectively, and the average maximum diurnal values for the 5 years diurnal SWC were 10.8, 7.9, 11.0, 12.1, and 13.6 %, respectively.

The site was windy, with an annual average wind speed of $3.19 \, \text{m s}^{-1}$ from 2015 to 2018, and the principal direction of the strongest winds was from the northeast sector (Fig. S5). In spring, the average wind speed was $2.25 \, \text{m s}^{-1}$. In summer, the average wind speed was about $2.51 \, \text{m s}^{-1}$, predominantly driven by the north wind.

The annual precipitation totaled 212.3 mm in 2015, 276.8 mm in 2016, 312.8 mm in 2017, and 350.8 mm in 2018 (Fig. S4b). The mean annual precipitation was 288.2 mm, which was less than the mean annual precipitation of 360.0 mm from 1960 to 2014. During the spring (March, April, and May), precipitation was relatively abundant, with mean precipitation of about 41.9 mm, which accounted for 12 to 20 % of the total annual precipitation. The majority of the precipitation (about 65 %) occurred in the summer (June, July, and August), with mean precipitation of about 197.1 mm. The autumn (September, October, and November) precipitation was similar to that in spring, with a mean precipitation of about 48.6 mm, which accounted for 14 to 23 % of the annual total. During the winter (December, January, and February), the mean precipitation of 0.6 mm accounted for only 1 to 6 % of the annual total.

Annual, seasonal, and diurnal variability of NEE, GPP and $R_{\text{ec}}$.

Figure 2 suggests that the sandy grassland was a net CO$_2$ source, with an annual mean NEE, GPP, and $R_{\text{ec}}$ of $48.88 \pm 8.10$, $351.78 \pm 20.97$, and $302.87 \pm 28.96 \, \text{g C m}^{-2} \, \text{yr}^{-1}$ in the years for which a complete dataset was available (2015, 2016, and 2018). (We omitted 2017 from this calculation because of large gaps in the data, described below.) NEE ranged from 34.99 C m$^{-2}$ yr$^{-1}$ in 2018 to 63.05 g C m$^{-2}$ yr$^{-1}$ in 2015, whereas GPP
All of this extreme detailed reporting of numeral results is unnecessary. Use figures and tables to report only what is necessary to your analysis.

This could be why the NEE was positive, not just grassland recovery trajectory as mentioned in the abstract and discussion. See Scott et al. 2010, 2015

Too much reporting of the values already shown in the figures and really the figures all convey essentially the same data, just at different time scales.

Here and elsewhere non-significant figures are being reported. Do we really believe that precip is accurate down to the nearest 10th of a mm, fluxes down to the 100th of a g?
ranged from 255.99 g C m\(^{-2}\) yr\(^{-1}\) in 2015 to 355.77 g C m\(^{-2}\) yr\(^{-1}\) in 2018 and \(R_{ec}\) ranged from 319.04 g C m\(^{-2}\) yr\(^{-1}\) in 2015 to 390.85 g C m\(^{-2}\) yr\(^{-1}\) in 2018. The eddy covariance tower was set up in mid-August 2014, and the instrument was allowed to stabilize for 1 month before we began collecting data, from 15 September to 23 December 2014; during that period, we measured a cumulative carbon release of 46.67 g C m\(^{-2}\), with cumulative GPP and \(R_{ec}\) of 24.80 and 71.47 g C m\(^{-2}\), respectively. From 15 February to 26 April 2017 and from 14 October to 6 November 2017, approximately 3 months of data were missing due to instrument maintenance and calibration, and the cumulative NEE, GPP, and \(R_{ec}\) were 63.33, 273.67 and 337.00 g C m\(^{-2}\) for the remaining 9 months of the year. Note that the periods covered by the data are therefore not identical.

We also observed clear seasonal variations in the total seasonal NEE, GPP, and \(R_{ec}\) (Fig. 3) and their diurnal cycles (Fig. 4). In spring, the sandy grassland was an atmospheric CO\(_2\) source in all years, with NEE, GPP, and \(R_{ec}\) averaging 0.15 ± 0.05, 0.63 ± 0.03, and 0.78 ± 0.03 g C m\(^{-2}\) d\(^{-1}\), respectively (Fig. 3a). The diurnal NEE cycle was characterized by a single absorption peak from around 07:30 to around 16:30 (Fig. 4a). Note that although all times in China are reported as the Beijing time, the study site was not sufficiently far east of Beijing for this to affect the physiological meaning of these times. The rest of the day was characterized by weak carbon absorption. The average diurnal GPP was also characterized by a single peak from around 05:00 to around 19:30, and the diurnal \(R_{ec}\) was characterized by an approximately horizontal line at about 0.78 g C m\(^{-2}\) d\(^{-1}\). The maximum and minimum average diurnal values for NEE were 0.78 (20:00) and −0.81 (12:00) g C m\(^{-2}\) d\(^{-1}\), respectively, versus 1.57 (12:00) and 0.58 (4:30) g C m\(^{-2}\) d\(^{-1}\) for GPP and 1.01 (18:00) and 0.05 (17:30) g C m\(^{-2}\) d\(^{-1}\) for \(R_{ec}\).

In summer, the sandy grassland was a CO\(_2\) sink in all years, with NEE, GPP, and \(R_{ec}\) averaging −0.58 ± 0.05, 2.44 ± 0.05, and 1.86 ± 0.03 g C m\(^{-2}\) d\(^{-1}\), respectively (Fig. 3b). The diurnal cycles of NEE and GPP were also characterized by a single peak, between 05:00 and 19:30 (Fig. 4b), and the ecosystem CO\(_2\) uptake reached its peak from around 10:30 to 12:00. The diurnal \(R_{ec}\) pattern was similar to the spring, but at a higher level (about 1.86 g C m\(^{-2}\) d\(^{-1}\)). The maximum and minimum diurnal NEE averaged 2.67
Round off to the nearest 1.

Unusual...the thing should work right out of the box. Do you really mean this?
(21:30) and −4.60 (11:30) g C m\(^{-2}\) d\(^{-1}\), respectively, versus 6.02 (11:30) and 0.09 (19:30)
g C m\(^{-2}\) d\(^{-1}\) for GPP and 2.77 (21:30) and 1.19 (8:00) g C m\(^{-2}\) d\(^{-1}\) for R\(_{ec}\).

In autumn, the sandy grassland was a net source of atmospheric CO\(_2\) in all years, with NEE, GPP, and R\(_{ec}\) averaging 0.50 ± 0.02, 0.27 ± 0.02, and 0.76 ± 0.02 g C m\(^{-2}\) d\(^{-1}\), respectively (Fig. 3c). The diurnal dynamics of NEE, GPP, and R\(_{ec}\) in autumn (Fig. 4c) were similar to those in spring (Fig. 4a), but the magnitudes of NEE and GPP in autumn were lower than in the spring. The diurnal R\(_{ec}\) was similar to the spring, at about 0.76 g C m\(^{-2}\) d\(^{-1}\). The maximum and minimum average diurnal NEE were 0.88 (19:00) and 0.02 (11:30) g C m\(^{-2}\) d\(^{-1}\), respectively, versus 0.89 (17:30) and 0.63 (4:00) g C m\(^{-2}\) d\(^{-1}\) for GPP and 0.74 (12:00) and 0.01 (5:00) g C m\(^{-2}\) d\(^{-1}\) for R\(_{ec}\).

In winter, the grassland ecosystem functioned as a net CO\(_2\) source in all years, with an average seasonal NEE of 0.58 ± 0.01 g C m\(^{-2}\) d\(^{-1}\) (Fig. 3d). It should also be noted that since the investigation started on 14 September 2014 and ended on 31 December 2018, the 2017 to 2018 winter was only about one-third of the usual length (i.e., it did not include data from January and February 2019). The diurnal dynamics of the winter NEE differed from the other seasons (Fig. 4d), with a minimum release value of 0.38 g C m\(^{-2}\) d\(^{-1}\), and with two emission peaks: at 0.81 g C m\(^{-2}\) d\(^{-1}\) (08:00) and 0.89 g C m\(^{-2}\) d\(^{-1}\) (16:30).

3.3 Response of NEE, GPP and R\(_{ec}\) to changes in environmental factors

We analyzed the effects of environmental factors on NEE and its components at different temporal scales. The analysis methods for the diurnal scale (Pearson’s \(r\) and PCA) were the same as the methods used at a seasonal scale, so to avoid repetition, we have only described the relationship between the seasonal-scale NEE and its components and the associated environmental factors. At the diurnal scale, \(R_n\) was the main factor that affected NEE, GPP and R\(_{ec}\) in all four seasons (data not shown). NEE was significantly negatively correlated with \(R_n\), whereas GPP and R\(_{ec}\) were positively correlated with \(R_a\), indicating that the ecosystem’s carbon sequestration capacity increased with increasing \(R_n\).

Seasonal-scale NEE, GPP, and R\(_{ec}\) were significantly correlated with many
I’d like to see some plots like GEP or Reco vs. ppt (yearly or monthly or seasonal), et, or soil moisture. Water availability should be a dominant control. If it isn’t, you need to tell us why.

This is not an in-depth analysis. We already know that the diurnal scale is not only controlled, but also defined, by the fluctuations in energy input.

Is this across seasons or within season?
environmental factors (Table S1). We found extremely weak and non-significant relationships between NEE, GPP, and \( R_{ec} \) and two climate variables (relative humidity and atmospheric pressure), so we excluded those variables from our subsequent analysis. NEE was negatively correlated with most environmental factors in all seasons except the autumn, when most correlations were positive, and GPP and \( R_{ec} \) were positively correlated with most environmental factors (Table S1).

In spring, \( T_{soil} \) at all depths, and \( T_{air}, R_{n} \), and SWC at all depths were negatively correlated with NEE (Table S1). In the PCA, principal component 1 (PC1) explained 57% of the NEE variation (Table 1), and was dominated by temperature (\( T_{soil} \) at all depths and \( T_{air} \)). PC2 explained about 25% of the NEE variation, and was dominated by SWC at depths of 0 to 10 cm. The first two PCs explained about 82% of the NEE variation. GPP was positively correlated with most environmental factors. PC1 explained 39% of the GPP variation, and temperature and SWC at depths of 10 to 50 cm were the dominant factors (Table 2). PC2 explained about 33% of GPP variation, and was dominated by SHF at all depths. The first three PCs explained about 89% of the GPP variation. \( R_{ec} \) was positively correlated with all environmental factors except for wind speed. PC1 explained 42% of the \( R_{ec} \) variation (Table 3) and was dominated by SWC at depth of 20 to 50 cm, \( T_{soil} \) at all depths, \( T_{air} \), and \( R_{n} \). PC2 explained about 30% of the \( R_{ec} \) variation, and was dominated by SHF at all depths. The first three PCs explained about 89% of the \( R_{ec} \) variation.

In summer, PC1 explained 42% of the NEE variation, and was dominated by SHF at all depths and \( R_{n} \) (Table 1). PC2 explained 29% of the NEE variation, and was dominated by air and soil temperatures. The first three PCs explained about 88% of the NEE variation. For GPP, PC1 explained 36% of the variation and was dominated by SHF at all depths and \( R_{n} \) (Table 2). PC2 explained 25% of the variation, and was dominated by air and soil temperatures. The first three PCs explained about 86% of the GPP variation. For \( R_{ec} \), PC1 explained 31% of the variation and was dominated by SWC at all depths and by precipitation (Table 3). PC2 also explained 31% of the variation, but was dominated by air and soil temperatures. The first three PCs explained
Should use VPD

This type of analysis isn't getting to the heart of the matter. It is related to the seasonality or phenology at the site because it matches the timing of rainfall input (covariation), but it is water, not energy, which is a first order control on carbon cycling in these regions.

What's the relationship between GPP and ground heat flux?

This is a great example of why this analysis is not useful. The diurnal cycle is dominated by energy. You need to look beyond this first order constraint on the diurnal variability to what is controlling the seasonal strength or weakness of GPP and Rec. Again, if that isn’t water, then why not?

These results of within season empirical PC analysis provide no useful insight into the controls on grassland C flux that the rest of the community could find useful.
about 78% of the $R_{ec}$ variation.

In autumn, PC1 explained 46% of the NEE variation and was dominated by $T_{air}$, SWC at depth of 10 cm, $T_{soil}$ at all depths, and $R_n$ (Table 1). PC2 explained 34% of the variation and was dominated by SWC at depths of 0 to 30 cm. The first two PCs explained about 80% of the NEE variation. For GPP, PC1 explained 33% of the variation and was dominated by SHF at all depths and $T_{air}$ (Table 2). PC2 explained 28% of the variation and was dominated by SWC and $T_{soil}$ at all depths and $R_n$. The first four PCs explained about 85% of the GPP variation. For $R_{ec}$, PC1 explained 36% of the variation and was dominated by SHF at all depths and $T_{air}$ (Table 3). PC2 explained 32% of the variation and was dominated by SWC and $T_{soil}$ at all depths and by $R_n$. The first three PCs explained about 82% of the $R_{ec}$ variation.

In winter, the NEE were equal to $R_{ec}$. PC1 for NEE ($R_{ec}$) explained 39% of the variation and was dominated by SWC at depths of 20 to 30 cm and $T_{soil}$ at all depths (Table 1 and Table 3). PC2 accounted for 25% of the variation and was dominated by SHF at a depth of 10 cm and $T_{air}$. For GPP, there was no photosynthesis during the winter, so no data is provided in Table 2.

In summary, the dominant control factors for NEE, GPP, and $R_{ec}$ differed among the seasons.

4 Discussion

4.1 Annual and seasonal mean and diurnal variability

Our results suggested that the sandy grassland ecosystem in China’s Horqin Sandy Land was a net CO$_2$ source, with an annual mean NEE of 48.88 ± 8.10 g C m$^{-2}$ yr$^{-1}$ in the years for which a complete dataset was available (2015, 2016, and 2018). This result was similar to that obtained for a semi-desert sandy grassland near Vácrátót, Hungary (where the dominant species were Festuca vaginata and Stipa capillata), but the Hungarian annual NEE was higher, at 131.48 g C m$^{-2}$ yr$^{-1}$ in 2001 (Balogh et al., 2005).

In contrast, many other arid and semiarid dry ecosystems with similar climate and geographical conditions were a significant net sink for CO$_2$. For example, in the Mojave Desert ecosystem in the United States, where the dominant species were evergreen
Recommend comparing your results to comparable ecosystems in comparable climates. Missing Scott et al., Biederman 2018, Pietrie et al. Studies from Australia or S. Africa.
shrubs, drought-deciduous shrub species, and perennial grasses, the annual NEE was 
−102 ± 67 and −110 ± 70 g C m⁻² yr⁻¹ in 2005 and 2006, respectively (Wohlfahrt et al., 
2008). China’s Tengger Desert, where the dominant vegetation was xerophytic shrubs 
planted in 1956, had annual NEE of −13.87 and −23.36 g C m⁻² yr⁻¹ in 2009 and 2010, 
respectively (Gao et al., 2012). The southern edge of China’s Mu Us desert, which is 
dominated by a mixture of deciduous shrub species, had an annual NEE of −77 g C m⁻² 
² yr⁻¹ in 2012 (Jia et al., 2014). China’s Gurbantonggut Desert, which is dominated by 
shrubs and grasses, had an annual NEE of −5 and −40 g C m⁻² yr⁻¹ in 2006 and 2007, 
respectively (Liu et al., 2016). The reason for these differences from the present study 
may be differences in the carbon sequestration ability of the dominant vegetation. 
Zheng et al. (2007) showed that the average carbon sequestration of terrestrial higher 
plants was higher for shrubs than for herbs. The dominant vegetation of our study area 
comprised annual herbs, which would have lower carbon sequestration capacity than in 
a shrub-dominated ecosystem.

The sandy grassland ecosystem in the present study was a net CO₂ source at an annual 
scale. On the one hand, this is because the dominant plants were annual plants, with a 
low carbon sequestration capacity. On the other hand, the site is still recovering from 
severe degradation, and has relatively low vegetation productivity (e.g., the mean 
anual GPP (351.78 ± 20.97 g C m⁻² yr⁻¹) in our study was lower in China’s Mu Us 
desert (456 ± 20.97 g C m⁻² yr⁻¹) (Jia et al., 2014)), and the restoration of degraded 
sandy grassland ecosystems is a long process (Li et al., 2019). Therefore, the ecosystem 
has not yet reached the threshold at which it will change into a CO₂ sink, and it will be 
necessary to study NEE for a longer period to reveal when that change occurs and the 
ecosystem’s long-term response to environmental and biological factors (Su et al., 2003; 
Niu et al., 2018).

We believe that seasonal variation of environmental factors also explained the 
seasonal differences in NEE, GPP, and Rec at our site. In spring, the sandy grassland 
was a net CO₂ source in all years (Fig. 3a). Before the growing season, plants begin to 
germinate, and both GPP and Rec increased with increasing temperature, solar radiation,
Certainly not a proven result and there are contradictory, site-specific results. See Scott et al. 2015, Kurc and Small 2007, Pietrie et al. ...

What about below-average precipitation? Again, our expectation is that water is the dominant control so this should be examined.

This doesn’t convey any useful information.
and precipitation (Niu et al., 2011; Rey et al., 2011). However, $R_{ec}$ was more responsive than GPP to precipitation. Liu et al. (2016a) showed that precipitation before the growing season had an important impact on NEE in arid and semiarid regions. After the winter drought, the spring precipitation greatly promoted the respiration of soil microbes (Zhang et al., 2016). As a result, $R_{ec}$ increased significantly. Precipitation also promoted GPP to some extent, but the carbon uptake was relatively small during plant germination. Therefore, the ecosystem was a net CO$_2$ source.

In summer, the sandy grassland was a CO$_2$ sink in all years (Fig. 3b). Our results agree with previous results for the study area (Li et al., 2015), as well as with results for a semiarid savanna in Australia (Hutley et al., 2005) and a grassland in California (Ma et al., 2007). GPP and $R_{ec}$ increased because of the favorable temperature and moisture conditions. However, because photosynthesis is greater than respiration during the peak of the growing season, the ecosystem became a net CO$_2$ sink (Kemp, 1983; Liu et al., 2016a; Niu et al., 2018).

In the autumn and winter, the sandy grassland was a net CO$_2$ source in all years (Fig. 3c,d). At the end of the growing season (in autumn), annual plants began to die and photosynthesis weakened (Fang et al., 2014). As a result, the ecosystem gradually transformed from a carbon sink to a carbon source (Keenan et al., 2009; Kiely et al., 2009).

At the diurnal scale, NEE in the spring, summer, and autumn showed CO$_2$ uptake during the day (06:00-18:00), and CO$_2$ emission during the night (Fig. 4a, b, c). The NEE increased with increasing light intensity during the day, reached its peak value around noon, then decreased until sunset, when the ecosystem changed from net carbon absorption to carbon release (Wagle and Kakani, 2014; Jia et al., 2014).

In winter, the sandy grassland ecosystem showed CO$_2$ emission throughout the day (Fig. 4d). At a diurnal scale, the ecosystem showed carbon “uptake”, at a level too small to display in Fig. 4d. This phenomenon may have resulted from heating effects in the open-path infrared gas analyzer (Burba et al., 2008). We recently created a Li-Cor LI-8150 gas analyzer system with six long-term monitoring chambers in the footprint of
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eddy covariance to test whether that hypothesis is correct.

4.2 Impacts of the environment on NEE, GPP, and $R_{\text{ec}}$

Our results demonstrated the important roles of the environmental factors in regulating the direction and amount of NEE between the atmosphere and the ecosystem in a sandy grassland in the Horqin Sandy Land. The most important environmental factors differed among the different scales.

At the diurnal scale, NEE in the four seasons was mainly explained by the $R_n$, which agrees with results for a study of the Mojave Desert ecosystem (Wohlfahrt et al., 2008). Our study area was located at a relatively high latitude, which means that solar radiation may be a limiting factor on many ecosystem processes such as GPP (Li et al., 2005; Liang et al., 2012).

At the seasonal scale, the carbon cycle processes were affected by many environmental factors, including soil and air temperatures, SWC, solar radiation ($R_n$ and SHF), and precipitation. Our results showed that the dominant environmental factors that affected NEE differed among the seasons. Our PCA analysis (Tables 1, 2 and 3) showed that in the spring, the main environmental factors that affected NEE, GPP, and $R_{\text{ec}}$ were temperature and SWC. After experiencing the winter cold and drought, the effect of temperature and SWC on soil thawing and vegetation greenup were greater than those of other environmental factors (Chu et al., 2013; Wolf et al., 2016).

In summer, the most important environmental factors for NEE and GPP were solar radiation and SHF. This result agreed with previous studies, which demonstrated that solar radiation was the main environmental factor that affected photosynthesis during the peak of the growing season (Saigusa et al., 2008; Hinko-Najera et al., 2017). However, SWC was the most important factor for $R_{\text{ec}}$, and the variation of SWC was mainly controlled by precipitation (Fig. S4b). Studies have suggested that the burst-type precipitation could strongly stimulate $R_{\text{ec}}$ during the growing season in semiarid areas (Hunt et al., 2002; Saetre and Stark, 2005).

In autumn, SHF and air and soil temperatures were the dominant environmental
This is the main result?

The daily scale is by definition regulated by radiation input.

I would expect to see WATER here.

Because your study relies upon simple empirical correlation analysis to tell you what’s going on without any input from what is already know from the science, your result here is overly simplistic with no links to physical processes. For example, why would SHF ever be relevant to GPP?
factors for NEE, GPP, and $R_{ec}$. The ecosystem was dominated by $R_{ec}$ during the later stages of the growing season, and studies have shown that $R_{ec}$ was strongly affected by soil temperature (Wang et al., 2012; Niu et al., 2018), and that the changes of soil temperature depended on SHF (Gao et al., 2010; Guo et al., 2011). Therefore, SHF and temperature were the most important environmental factors for the autumn NEE, GPP, and $R_{ec}$.

In winter, the annual plants had withered, so there was no GPP and the entire ecosystem was characterized by carbon emission. Our results showed that SWC and soil temperature were the most important factors that affected NEE, and that NEE increased with decreasing SWC and temperature. Previous studies found that when SWC decreases sufficiently to create water stress, it may replace temperature as the main factor that controls soil respiration in arid and semiarid areas, and as a result, soil respiration decreased with decreasing SWC (Wu et al., 2010; Escolar et al., 2015). Our results were inconsistent with these previous studies. This may be due to drought, since precipitation during the winter amounted to between 1 and 6% of the annual precipitation, and this would be exacerbated by strong winter winds in the Horqin Sandy Land (Fig. S5; Wang et al., 2005; Liu et al., 2016b). The soil organic matter and nutrients would also be lost faster when SWC decreases and the wind strengthens, resulting in increased carbon emission (Lai, 2004; Munodawafa, 2011).

We also analyzed the relationship between annual NEE, GPP, and $R_{ec}$ in the years for which a complete dataset was available (2015, 2016, and 2018) and the environmental factors (Table S1). We found that the total annual precipitation was the most important factor that limited NEE, GPP, and $R_{ec}$. NEE was negatively correlated with annual precipitation, GPP was positively correlated with it, and the correlation between $R_{ec}$ and precipitation was not significant. Taken together, these results indicated different sensitivity of GPP and $R_{ec}$ to annual precipitation.

Previous studies suggested that GPP was limited by the availability of water and was strongly correlated with total annual precipitation in arid and semiarid ecosystems (Webb et al., 1987; Sala et al., 1988). GPP of annual herbaceous plants was especially...
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strongly affected by precipitation, which could change the composition and community structure of plants, thereby affecting GPP (Nackley et al., 2014; Wang et al., 2016). Our result was consistent with these previous studies. However, the correlation between $R_{ec}$ and precipitation was not significant in our study. This may be because of the relatively high latitude of our study area, since $R_{ec}$ was affected by multiple environmental factors that would be affected by latitude, such as temperature and solar radiation. However, we must improve our understanding of the responses of the ecosystem to precipitation and the underlying mechanisms that control whether it will be a carbon source or sink. To accomplish this, it will be necessary to observe the ecosystem continuously for a longer period of time.

5 Conclusions

Our field data indicated that the sandy grassland has functioned as a CO$_2$ source at an annual scale, with a mean annual NEE of 48.88 ± 8.10 g C m$^{-2}$ yr$^{-1}$. At the seasonal scale, the sandy grassland showed net CO$_2$ absorption during the summer, but net CO$_2$ release in the other seasons. At the diurnal scale, the ecosystem showed a strong single daytime absorption peak in the spring, summer, and autumn, but strong CO$_2$ emission at night. In winter, the ecosystem was characterized by CO$_2$ emission all day, as there was no GPP.

At the daily scale, NEE in all four seasons was controlled by $R_n$. At the seasonal scale, NEE was mainly affected by temperature and SWC in the spring, solar radiation in the summer, SHF and temperature in the autumn, and SWC and temperature in the winter. At the annual scale, the total annual precipitation was the most important factor for NEE. Our findings demonstrated the importance of long-term, high-frequency field monitoring in sandy land to improve our understanding of CO$_2$ cycling and its likely responses to a changing climate. However, it will be necessary to study the NEE for a longer period to reveal its long-term response to environmental and biological factors.

Data availability. In agreement with the FAIR Data standards, the data used in this article are archived, published, and available in a dedicated repository: [http://doi.org/10.4121/uuid:35deeb02-8165-49b7-af8d-160d537ae15a](http://doi.org/10.4121/uuid:35deeb02-8165-49b7-af8d-160d537ae15a).
Where is this result shown?

This dataset appears to have all the data to remake the figures. What would really be useful is to know where the community can access the 30 min met and flux data? This "raw" data is exactly what others could use to generate comparisons and include with future studies. I strongly suggest this data is shared in a flux archive like ChinaFlux/Fluxnet. This will only increase the use of this data and benefit this studies authors.
Competing interests. The authors declare that they have no conflict of interest.

Author contributions. YQL, YYN, HBY, XYW, and YLD designed the study; YYN, XWG, and JL performed the experiments. YYN and HBY analyzed the data. YYN drafted the manuscript. All co-authors had a chance to review the manuscript and contributed to discussion and interpretation of the data.

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References


This page contains no comments
of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, Bulletin of the American Meteorological Society., 82, 2415–2434.


This page contains no comments
M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F., Sanz, M.


Escolar, C., Maestre, F. T, and Rey. A.: Biocrusts modulate warming and rainfall
This page contains no comments


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Hutley, L. B., Leuning, R., Beringer, J., and Cleugh, H. A.: The utility of the eddy
This page contains no comments


This page contains no comments


This page contains no comments


This page contains no comments


This page contains no comments


Saetre, P., and Stark, J. M.: Microbial dynamic sand carbon and nitrogen cycling following rewetting of soils beneath two semi-arid plant species, Oecologia,
This page contains no comments


This page contains no comments


Wang, X. Y., Li, Y. L., Zhao, X. Y., Mao, W., Cui, D., Qu, H., Lian, J., and Luo, Y. Q.: Responses of soil respiration to different environment factors in semi-arid and
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Wu, X., Yao, Z. N., Brüggemann, N., and Shen, Z. Y.: Effects of soil moisture and temperature on CO₂ and CH₄ soil atmosphere exchange of various land
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Figure captions

Fig. 1. Locations of the Horqin Sandy Land and the Naiman station. (b) and (c) are the covariance site at the Naiman station during the growing and dormant seasons, respectively.

Fig. 2. Annual patterns of daily net ecosystem CO$_2$ exchange (NEE), gross primary productivity (GPP), and ecosystem respiration ($R_{ec}$) from 2014 to 2018. Positive NEE values indicate net CO$_2$ release, whereas negative values indicate net CO$_2$ uptake by the ecosystem. Note that the initial measurements were from 15 September to 23 December 2014, so no data are available for the first part of 2014.

Fig. 3. Seasonal mean net ecosystem CO$_2$ exchange (NEE), gross primary productivity (GPP), and ecosystem respiration ($R_{ec}$) from 2014 to 2018: (a) spring (March, April, and May), (b) summer (June, July, and August), (c) autumn (September, October, and November), and (d) winter (December, January, and February). Note that the initial measurements were from 15 September to 23 December 2014, so no data are available for the first part of 2014.

Fig. 4. Diurnal changes in mean net ecosystem CO$_2$ exchange (NEE), gross primary productivity (GPP), and ecosystem respiration ($R_{ec}$) from 2014 to 2018: (a) spring (March, April, and May), (b) summer (June, July, and August), (c) autumn (September, October, and November), and (d) winter (December, January, and February). Note that the initial measurements were from 15 September to 23 December 2014, so the spring and summer data do not include the period before 15 September. The final measurements were obtained on 31 December 2018, so the winter period from 2017 to 2018 was only about one-third of the usual length (i.e., it did not include data from January and February 2019).
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Fig. 1.

![Map of land use and other features](image1)

Fig. 2.

![Graphs showing CO₂ rates](image2)

**Land use**
- cropland
- woodland
- grassland
- water body
- urban and rural area
- sandy land
- other

**Legend**
- NEE
- $R_{\text{nu}}$
- GPP

**Day of year (Julian day)**
- 2014
- 2015
- 2016
- 2017
- 2018

0 30 60 90 120 150 180 210 240 270 300 330 360
Labels are too small on all axes of all figures.
Fig. 3.
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The convention for these types of diurnal plots is to use micromol CO$_2$ m$^{-2}$ sec$^{-1}$. 
Table 1. Principal-components analysis (PCA) for the relationships between the net ecosystem CO$_2$ exchange (NEE) and the environmental factors at a seasonal scale. PC, principal component; $T_{\text{air}}$, air temperature; $R_n$, net solar radiation; SHF, soil heat flux; SWC, soil water content; $T_{\text{soil}}$, soil temperature.

<table>
<thead>
<tr>
<th>Component</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{air}}$</td>
<td>0.910</td>
<td>0.188</td>
<td>0.423</td>
<td>-0.017</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.739</td>
<td>0.034</td>
<td>0.781</td>
<td>0.018</td>
</tr>
<tr>
<td>SHF at 5 cm</td>
<td>0.920</td>
<td>0.198</td>
<td>-0.036</td>
<td></td>
</tr>
<tr>
<td>SHF at 10 cm</td>
<td>0.929</td>
<td>0.202</td>
<td>0.047</td>
<td>0.870</td>
</tr>
<tr>
<td>SWC at 0-10 cm</td>
<td>0.112</td>
<td>0.978</td>
<td>0.238</td>
<td>0.824</td>
</tr>
<tr>
<td>SWC at 10-30 cm</td>
<td>0.133</td>
<td>0.845</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWC at 10-50 cm</td>
<td>0.780</td>
<td>0.510</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWC at 20-30 cm</td>
<td>0.868</td>
<td>0.053</td>
<td>-0.144</td>
<td></td>
</tr>
<tr>
<td>SWC at 30-40 cm</td>
<td>0.949</td>
<td>-0.011</td>
<td>0.161</td>
<td></td>
</tr>
<tr>
<td>SWC at 40-50 cm</td>
<td>0.025</td>
<td>-0.052</td>
<td>0.998</td>
<td>0.880</td>
</tr>
<tr>
<td>$T_{\text{soil}}$ at 0-50 cm</td>
<td>0.935</td>
<td>0.140</td>
<td>-0.009</td>
<td>0.961</td>
</tr>
<tr>
<td>Cumulative</td>
<td>57.227</td>
<td>82.566</td>
<td>41.639</td>
<td>70.785</td>
</tr>
</tbody>
</table>

$^a$ Before the PCA, SWC was divided into six depth ranges (0 to 10, 10 to 30, 10 to 50, 20 to 30, 30 to 40, and 40 to 50 cm) according to the results of a collinearity test for the four seasons. $T_{\text{soil}}$ was divided into a single range (0 to 50 cm) according to the results of a collinearity test for the different seasons.
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Table 2. Principal-components analysis (PCA) for the relationships between the gross primary productivity (GPP) and the environmental factors at the seasonal scale. Because there was no plant photosynthesis in winter, we did not perform the PCA for that season. PC, principal component; T_{air}, air temperature; R_n, net solar radiation; SHF, soil heat flux; SWC, soil water content; T_{soil}, soil temperature.

<table>
<thead>
<tr>
<th>Component</th>
<th>Spring PC1</th>
<th>Spring PC2</th>
<th>Spring PC3</th>
<th>Spring PC4</th>
<th>Summer PC1</th>
<th>Summer PC2</th>
<th>Summer PC3</th>
<th>Summer PC4</th>
<th>Autumn PC1</th>
<th>Autumn PC2</th>
<th>Autumn PC3</th>
<th>Autumn PC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{air}</td>
<td>0.849</td>
<td>0.410</td>
<td>0.108</td>
<td>0.849</td>
<td>0.736</td>
<td>0.594</td>
<td>0.178</td>
<td>-0.004</td>
<td>0.023</td>
<td>-0.001</td>
<td>0.011</td>
<td>0.980</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.023</td>
<td>-0.001</td>
<td>0.011</td>
<td>-0.007</td>
<td>0.126</td>
<td>0.103</td>
<td>0.416</td>
<td>-0.017</td>
<td>0.000</td>
<td>0.146</td>
<td>0.962</td>
<td>0.008</td>
</tr>
<tr>
<td>R_n</td>
<td>0.511</td>
<td>0.550</td>
<td>0.136</td>
<td>0.781</td>
<td>0.920</td>
<td>0.173</td>
<td>-0.134</td>
<td>0.928</td>
<td>0.057</td>
<td>-0.091</td>
<td>-0.007</td>
<td>0.071</td>
</tr>
<tr>
<td>SHF at 5 cm</td>
<td>0.138</td>
<td>0.967</td>
<td>-0.059</td>
<td>0.920</td>
<td>0.173</td>
<td>-0.134</td>
<td>0.928</td>
<td>0.057</td>
<td>-0.091</td>
<td>-0.007</td>
<td>0.071</td>
<td>0.007</td>
</tr>
<tr>
<td>SHF at 10 cm</td>
<td>0.191</td>
<td>0.951</td>
<td>0.032</td>
<td>0.932</td>
<td>0.185</td>
<td>-0.052</td>
<td>0.943</td>
<td>0.096</td>
<td>-0.063</td>
<td>0.071</td>
<td>0.007</td>
<td>0.007</td>
</tr>
<tr>
<td>SWC at 0-10 cm</td>
<td>0.184</td>
<td>-0.006</td>
<td>0.974</td>
<td>-0.073</td>
<td>-0.256</td>
<td>0.890</td>
<td>0.133</td>
<td>0.758</td>
<td>0.244</td>
<td>0.071</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>SWC at 10-50 cm</td>
<td>0.836</td>
<td>0.103</td>
<td>0.416</td>
<td>0.101</td>
<td>-0.017</td>
<td>0.933</td>
<td>0.000</td>
<td>0.848</td>
<td>-0.071</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.055</td>
<td>0.146</td>
<td>0.962</td>
<td>0.008</td>
<td>-0.131</td>
<td>0.685</td>
<td>0.206</td>
<td>-0.131</td>
<td>0.685</td>
<td>0.206</td>
<td>-0.131</td>
<td>0.685</td>
</tr>
<tr>
<td>T_{soil} at 0-50 cm</td>
<td>0.974</td>
<td>0.126</td>
<td>0.029</td>
<td>-0.003</td>
<td>0.950</td>
<td>-0.170</td>
<td>0.558</td>
<td>0.685</td>
<td>0.206</td>
<td>-0.131</td>
<td>0.685</td>
<td>0.206</td>
</tr>
<tr>
<td>Cumulative</td>
<td>38.847</td>
<td>72.205</td>
<td>88.735</td>
<td>35.926</td>
<td>60.984</td>
<td>85.673</td>
<td>32.594</td>
<td>60.441</td>
<td>72.558</td>
<td>84.518</td>
<td>84.518</td>
<td>84.518</td>
</tr>
</tbody>
</table>

a Before the PCA, SWC was divided into two depth ranges (0 to 10, and 10 to 50) according to the results of a collinearity test for the four seasons. T_{soil} was divided into a single range (0 to 50 cm) according to the results of a collinearity test for the different seasons.
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Table 3. Principal-components analysis (PCA) for the relationships between the ecosystem respiration ($R_{ec}$) and the environmental factors at the seasonal scale. PC, principal component; $T_{air}$, air temperature; $R_n$, net solar radiation; SHF, soil heat flux; SWC, soil water content; $T_{soil}$, soil temperature.

<table>
<thead>
<tr>
<th>Component*</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
<td>PC2</td>
<td>PC3</td>
<td>PC1</td>
</tr>
<tr>
<td>$T_{air}$</td>
<td>0.844</td>
<td>0.429</td>
<td>0.040</td>
<td>-0.064</td>
</tr>
<tr>
<td>Wind speed</td>
<td>0.010</td>
<td>0.030</td>
<td>0.995</td>
<td>0.057</td>
</tr>
<tr>
<td>$R_n$</td>
<td>0.162</td>
<td>0.952</td>
<td>-0.197</td>
<td>0.928</td>
</tr>
<tr>
<td>SHF at 5 cm</td>
<td>0.811</td>
<td>-0.312</td>
<td>-0.091</td>
<td>0.123</td>
</tr>
<tr>
<td>SHF at 10 cm</td>
<td>0.916</td>
<td>0.061</td>
<td>0.054</td>
<td>0.949</td>
</tr>
<tr>
<td>SWC at 10-50 cm</td>
<td>41.703</td>
<td>72.155</td>
<td>88.606</td>
<td>30.642</td>
</tr>
</tbody>
</table>

*Before the PCA, SWC was divided into six depth ranges (0 to 10, 10 to 50, 20 to 30, 20 to 50, 30 to 40, and 40 to 50 cm) according to the results of a collinearity test for the four seasons. $T_{soil}$ was divided into a single range (0 to 50 cm) according to the results of a collinearity test for the different seasons.
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