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Carbon dioxide exchange processes over the grassland ecosystems in semiarid areas of China

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Based on the carbon fluxes measured over the grassland ecosystems in Inner Mongolia (UG79 site), Loess Plateau (SACOL site), and Tongyu, Jilin Province (TY site) in the semiarid areas from 2007 to 2008 with the eddy covariance method, we have investigated the carbon exchange processes over semiarid grassland ecosystem and its main affecting environmental variables. The precipitations at UG79 and TY sites in 2007 were below the historical average, especially for TY site, which was 50% below the historical average annual precipitation. The precipitation in SACOL site was close to average in 2007 but below average in 2008. The variation of monthly diurnal average NEE showed that the diurnal mean NEE decreased in the order of TY site, UG79 site, and SACOL site. However, a longer net carbon uptake period was observed at SACOL site. The diurnal course of NEE at UG79 site was similar between 2007 and 2008. The diurnal average NEE remained large during July and August in growing season (May to September) at UG79 site, with maximum values approaching 0.08 mg C m^{-2} s^{-1} in August of 2008. The diurnal average NEE of 2007 was larger than 2008 at SACOL site, with maximum values of 0.07 mg C m^{-2} s^{-1} in September of 2007. A shorter carbon uptake period was recorded in 2007 at TY site, lasting from July to August. A larger diurnal average NEE occurred in 2008 at TY site, with maximum values of 0.12 mg C m^{-2} s^{-1}. The ecosystem respirations of three sites were controlled by both soil temperature and soil volumetric water content (at a depth of 5 cm below the land surface). Both UG79 site and SACOL site acted as a carbon sink during the growing periods of 2007 and 2008. Annual NEE in the growing seasons of 2007 and 2008 ranged from −68 to −50 g C m^{-2} at UG79 site and from −109 to −55 g C m^{-2} at SACOL site. Alternation between carbon source and carbon sink was found at TY site, with respective values of annual NEE in the growing seasons of 0.32 g C m^{-2} and −73 g C m^{-2} in 2007 and 2008. The magnitude and duration of carbon uptake depended mainly on the amount and timing of precipitation and the timing of the first effective rainfall during the growing season in semiarid grassland ecosystems.

semiarid grassland ecosystem, carbon flux, eddy covariance method

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Grassland in middle-latitude region of semiarid area is a very important terrestrial ecosystem, and also a typical terrestrial landscape in China [1]. Typical steppe ecosystems under semiarid continental temperate climate condition cover about 10.5% of the national grassland area [2]. Grassland in semiarid area at middle latitudes is the climate-ecosystem transition zone, which is vulnerable to climate variability and human activities [3]. Overgrazing and poor

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farmland management in semiarid area have exacerbated the grassland degradation and desertification [4]. Land use change has influenced the global carbon and water cycle, and the variations of ecosystem's mass and energy exchanges between the land surface and the atmosphere induced a feedback on the regional and global climate change [5, 6]. Semiarid regions cover large areas in northern China and the land surface-atmosphere fluxes have a great impact on both global climate change and atmospheric circulation, and are also crucial to East Asia monsoon and northwest arid climate [7].

At present, most long-term carbon flux studies have focused on various temperate broadleaved forest [8], tropical rain forest [9], and boreal conifer forest ecosystems [10, 11]. Carbon exchange process studies of grassland ecosystems mainly conducted over Mediterranean grasslands [12], tall grass prairie [13], and tropical savanna [14]. The ecosystem in Mediterranean grassland could alternate between net carbon sources and sinks in different seasons due to the climate conditions. Seasonal variations in GPP followed closely to changes in leaf area index. Soil microbial respiration was well correlated with the precipitation. Large pulses of ecosystem respiration was observed after rain events and especially notable during the dry season when the grass was dead. The timing of rain events had more impact than the total amount of precipitation on ecosystem GPP and NEE for the Mediterranean grassland [12]. Change in soil moisture was the most important ecological factor controlling Carbon gain in northern temperate grassland in Canada. Gross photosynthesis was strongly correlated with changes in both LAI and canopy nitrogen (N) content [15]. Soil moisture was an important factor regulating CO_2 flux exchange over semiarid grasslands in Inner Mongolia under different grazing intensities. Decrease in soil water content can shift the positive absorption of carbon toward negative release into the atmosphere at the Leymus site and winter grazed site [16]. Improved understanding is required of carbon exchange processes over the grassland ecosystems in semiarid area and its main environmental drivers.

Based on the carbon dioxide fluxes measured over the grassland ecosystems in Inner Mongolia (UG79 site), Loess Plateau (SACOL site), and Tongyu, Jilin Province (TY site) in the semiarid areas from 2007 to 2008 with the eddy covariance method, we analyze the temporal and spatial variations of the net carbon exchange rate over different sites in semiarid areas, and investigate the main environmental variables controlling the carbon exchange processes at different time scales over grassland ecosystems in semiarid areas.

1 Experimental sites and data processing

1.1 Experimental sites

The grassland flux sites selected in this study are located in semiarid areas. The following are brief descriptions of three experiment sites.

The experimental site (UG79 site), which has been fenced and ungrazed since 1979, is located in the Xilin River Watershed of the Inner Mongolia Autonomous Region (43°33′N,116°40′E). The mean elevation is 1200 m. This site is exposed to a temperate, semiarid continental steppe climate with distinctive seasons. The average annual temperature is –0.4°C. A maximum of surface temperature is found in July and a minimum in January. The annual precipitation range is 350 mm, which falls primarily from June to August. The prevailing wind direction is southwest with an average wind velocity 4–5 m s^{-1}. The soil at the site is a dark chestnut, and soil humus depth is usually 30–45 cm. The content of the organic matter is 2.0%–4.0%. The hardy xeric herbaceous plants are the dominant communities. The xeric rhizomatous grass *Leymus chinensis* is the constructive species, and *Stipa grandis, Agropyron cristatum,* and *Cleistogenes squarrosa* are the dominant species. The heights of grass clusters are 50–60 cm [16].

Semiarid climate and environment observation of Lanzhou University (SACOL site) is located in the semiarid area on the China-Loess Plateau (35°57′N, 104°08′E), approximately 1965.8 m above sea level. The area has a semiarid continental temperate monsoon climate. The average annual temperature is –6.7°C. The average temperature in January and July is –8 and 19°C respectively. The annual precipitation range is 381.8 mm, a maximum of precipitation observed in August. The annual evaporation is 1528.5 mm and the relative humidity is 63%. The prevailing wind direction is southeast and northwest with an average wind velocity 1 m s^{-1}. The parent soil material is mainly Quaternary aeolian loess with the main soil type being sierozem. The terrain where the measurements are carried out is flat and covered with short grass. The dominated species within the immediate area are *Stipa bungeana* as well as *Artemisia frigida* and *Leymus secalinus* [17].

Tongyu degraded grassland observation site (TY site) is in Tongyu county, Baicheng City of Jilin Province (44°25′N, 122°52′E). The site is located in alluvial plain, and the terrain in this area is fairly open and flat, approximately 184 m a.s.l. The average annual temperature is 5.1°C. The annual precipitation range in the study area is 404.3 mm, with approximately 89% of annual rainfall occurring between May and September, which is the growing season. The annual evaporation is 1762.9 mm and the relative humidity is 58%. The average wind velocity of prevailing wind SSW is 4.2 m s^{-1}. The degraded grassland is situated in the middle and west marginal region of Song-Nen Plain. It has a semiarid continental monsoon climate of the mid-temperature zone. The soils of the degraded grassland are salty alkaline soil, meadow soil, and light chernozem. It is covered largely by *Chloris virgata* community and annual weed community. Grass can reach a maximum height of 10 cm in summer and 5 cm in winter and spring [18].

The observation in the surface layer includes the eddy covariance to measure turbulent fluxes, the meteorological elements profile observation system, the radiation observation system, and soil temperature and moisture measuring systems. Meteorological parameters include temperature, humidity, wind speed and direction. Radiation components contain incoming and outgoing solar radiation, incoming and outgoing long wave radiation. Eddy covariance measurements were measured by the ultra-sonic anemometer/thermometer (Campbell Scientific, CSAT3), moisture and an open-path infrared gas analyzer (LI -COR, CS7500). For a description of the full range of instrumentation at the three sites, see [16, 17, 19].

1.2 Data processing

Average 30 min turbulent fluxes were calculated using Edire software (John Moncrieff, School of Geosciences, University of Edinburgh). Steps for post-processing of the 10 Hz raw data are: (1) Out-of-range data due to instrument malfunction, weather, and system noise etc. are detected and removed in the subsequent calculation. (2) Data are rotated into streamwise coordinates using a double rotation procedure, and then 30 min block average, fluctuations, variance, covariance and other related variables are calculated to obtain initial fluxes. (3) Corrections to the initial flux values are made for high-frequency losses due to separation of sensors, path averaging, and sensor frequency response [20], and the correction for density effects is described in Webb et al. [21]. Data quality control includes the basic test for spike, the steady state test, and the integral turbulence characteristics test [22]. In the study, data quality of CO_2 was assessed by a standardized processing algorithms suggested by Papale et al. [23] based on the post-processing flux data.

Data gaps in the data record originating from instrument malfunction and quality control typically reach 30%–40% on an annual basis [13]. Gap-filling algorithms have been developed for examining the ecosystem carbon budget during the whole growing season. Short gaps (<2 hours) were filled by liner interpolation. Medium gaps (<2 days) were rebuilt based on the mean diurnal variation (MDV) on adjacent days [13]. Large gaps (>2 days) were filled by MDS (marginal distribution sampling) [24].

1.3 Ecosystem respiration model

Temperature and soil water availability are important environmental factors controlling ecosystem respiration [25]. It has been reported that ecosystem respiration tends to increase with increasing soil temperature when sufficient soil moisture is available [24]. The following functions are commonly used to express the relationship between ecosystem respiration (R_{eco}) and soil temperature:

Lloyd & Taylor model [26]:

$$R_{\text{eco}} = R_{10}\mathrm{e}^{\frac{E_a}{R}\left(\frac{1}{T_{\text{ref}}}-\frac{1}{T}\right)}; \tag{1}$$

Arrhenius model [26]:

$$R_{\text{eco}} = R_{10}\mathrm{e}^{E_0\left(\frac{1}{T_{\text{ref}}-T_0}-\frac{1}{T-T_0}\right)}; \tag{2}$$

Exponential model [26, 27]:

$$R_{\text{eco}} = a\cdot \mathrm{e}^{(b\cdot T_s)}; \tag{3}$$

Q_{10} model:

$$R_{\text{eco}} = R_{10}\cdot Q_{10}^{\frac{T-T_{\text{ref}}}{10}}, \tag{4}$$

where R_{eco} is the ecosystem respiration; R_{10} is the ecosystem respiration rate at the reference temperature (10°C); E_a and E_0 are activation energy, also called temperature sensitivity coefficients; R is gas constant; T_{ref} is the reference temperature; T is air temperature or soil temperature; T_0 is the temperature when ecosystem respiration is zero; T_s is soil temperature; Q_{10} is the corresponding ratio of the respiration at a given temperature to that at a temperature of 10°C. Arrhenius model is an improved model based on Lloyd & Taylor model. Q_{10} model is a transformation of exponential model and they are equivalent.

The following functions are commonly used to describe the relationship between ecosystem respiration (R_{eco}) and soil moisture/soil temperature:

Linear model:

$$R_{\text{eco}} = a\cdot \text{vwc} + b; \tag{5}$$

Multiplicative model:

$$R_{\text{eco}} = a\cdot \mathrm{e}^{(b\cdot T)}\cdot \text{vwc}^c, \tag{6}$$

where vwc is the volumetric soil water content; b and c are the fitting coefficients.

NEE between the plant and the atmosphere at night was equal to the ecosystem respiration. Eqs. (2), (3), (5), and (6) were used to describe the relationship between nocturnal ecosystem respiration and soil temperature and soil moisture. Only eqs. (2) and (3) were used for the fits at UG79 site because the soil volumetric water content data during May and August in 2007 was unavailable. Since the temperature sensitivity of ecosystem respiration was definitely temporally varying in an ecosystem [12], it was estimated for each month. Daytime respiration has been obtained by extrapolating the night-time fluxes to the rest of the day, using functional relationships with soil or air temperature [12]. Eq. (6), which integrated the effect of soil temperature and soil water content on ecosystem respiration, was finally applied to estimating daytime respiration.

Ecosystem respiration was defined as

$$R_{\text{eco}} = R_{\text{eco,night}} + R_{\text{eco,day}}, \tag{7}$$

where $R_{eco,night}$ is nighttime respiration, $R_{eco,day}$ is daytime respiration.

Gross ecosystem exchange was defined as

$$GEE=NEE-R_{eco}. \tag{8}$$

GEE is rightly negative to GEP. On the ecosystem level, it could be considered that GEP is right equal to GPP.

$$GPP=GEP=-GEE. \tag{9}$$

2 Results and discussions

2.1 Meteorological condition

Here we compared the seasonal courses of air temperature and soil temperature for 2007 and 2008 (Figure 1). The average air temperature (2 m) and soil temperature (5 cm) were higher in 2007 than in 2008 at UG site. The mean daily courses of air temperature and soil temperature showed no significant differences between the two years at SACOL site. The average air temperature and soil temperature were higher in 2008 than in 2007 at TY site. Average air temperature and soil temperature in SACOL site were highest during the two years, with values of 8.30 and 10.64°C respectively. The average air temperature and soil temperature were 7.72 and 5.27°C respectively during the two years at TY site. Average air temperature and soil temperature at UG site were the lowest, with values of 2.17 and 4.13°C respectively. The average air temperature at three sites was all higher than climate average.

The precipitation had large seasonal and inter-annual differences (Figure 2). The precipitation at UG79 and TY sites in 2007 was both below the historical average. Precipitation at TY site was 50% below the long-term mean in 2007, but close to normal in 2008. Approximately 80% of annual rainfall fell in growing season (May-September) at UG79 site. Nearly 88% of annual rainfall was concentrated during May and September at TY site. The precipitation at SACOL site was close to normal in 2007, with 68% of annual rainfall occurring during May to September. The precipitation was below the average in 2008, with 80% of annual rainfall occurring during May to September.

Soil volumetric water content (5 cm) was closely related to the precipitation. The variation of soil volumetric water content closely followed the variation of precipitation. Soil

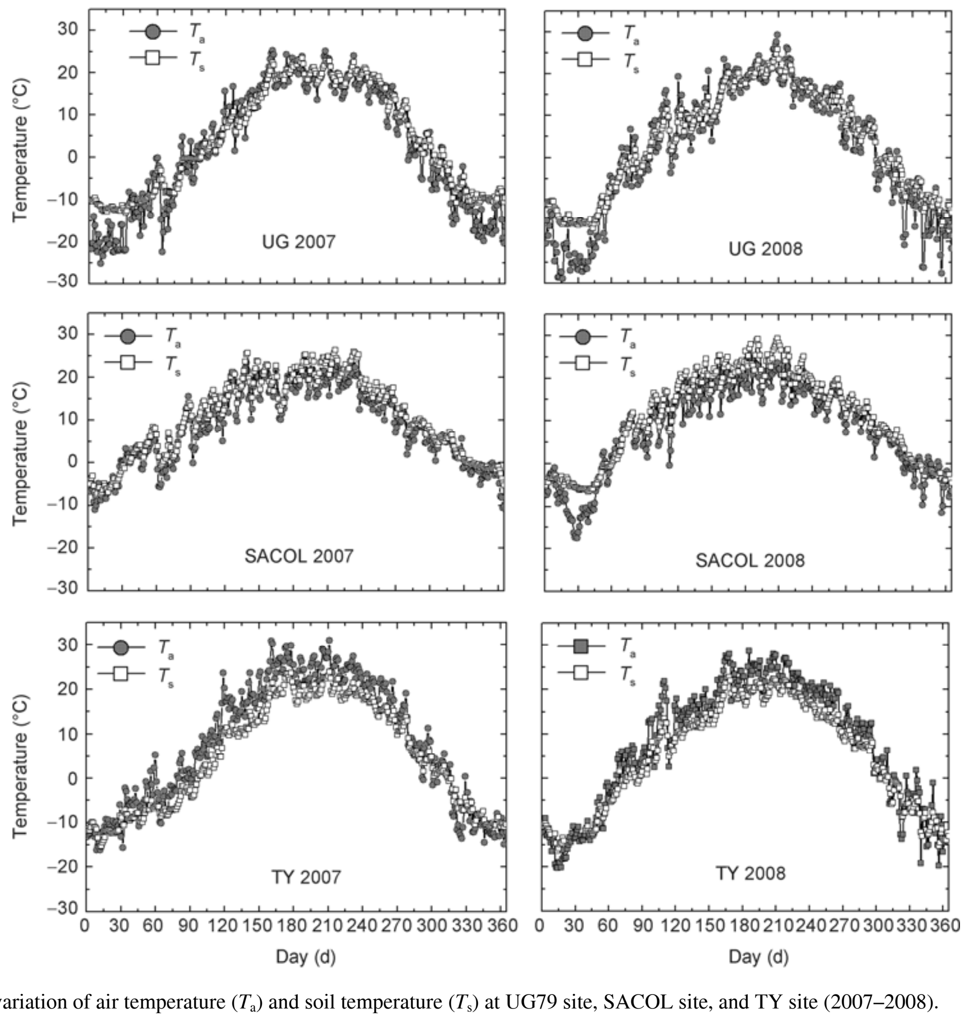

Figure 1 Seasonal variation of air temperature (T_a) and soil temperature (T_s) at UG79 site, SACOL site, and TY site (2007–2008).

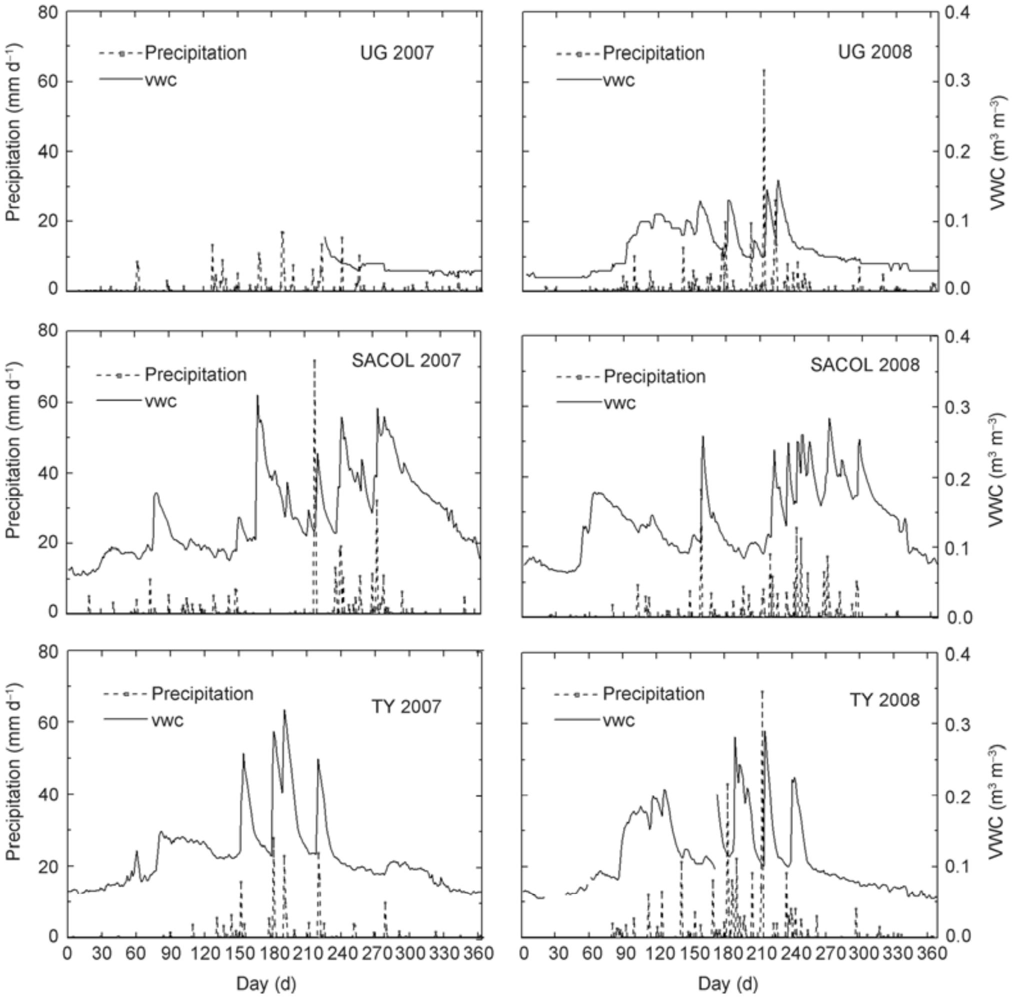

Figure 2 Seasonal variation of precipitation and soil volumetric water content (vwc) at UG 79 site, SACOL site, and TY site (2007–2008).

volumetric water content was similar in different years. The average soil volumetric water content at SACOL site remained 13.7% in 2007 and 2008, with a higher value of 15% in growing season. The average soil volumetric water content at TY site was 11%–12% during the two years, with a value of 14% in growing season. Soil volumetric water content was lower at UG79 site.

2.2 Diurnal and seasonal variations of NEE

The mean diurnal variation of NEE at the three sites during growing season between 2007 and 2008 is shown in Figure 3. NEE at SACOL site and TY site showed an obvious diurnal variation between 2007 and 2008. The daytime NEE was higher in 2007 than in 2008 at SACOL site. NEE at TY site in 2007 was the lowest among the three sites, with a minimum value of –0.02 mg C m^{-2} s^{-1}. NEE in 2008 at TY site was close to the other two sites, with a maximum value of –0.04 mg C m^{-2} s^{-1}. The variation of NEE at UG 79 site between 2007 and 2008 was similar, with a maximum value approaching –0.04 mg C m^{-2} s^{-1}. The maximum value of NEE occurred at UG 79 site in 2007, with a rapid decline following a peak. The maximum value of NEE at SACOL site occurred later and decreased gently. After reaching the daily maximum value of NEE at 9:00–10:00, NEE gradually decreased until a balance at 18:00.

The monthly mean diurnal variation of NEE at the three sites between 2007 and 2008 was shown in Figure 4. The carbon emission was not obvious in non-growing season at UG79 site. The peak period of carbon uptake was from June to August, with a maximum value of NEE approaching 0.08 mg C m^{-2} s^{-1} in August of 2008 at UG 79 site. Low carbon uptake was observed at SACOL site in non-growing season, with a long carbon uptake period from April to October in 2008. The maximum value of NEE was recorded in September both in 2007 and 2008, with a maximum value approaching –0.07 mg C m^{-2} s^{-1} which was lower than the other sites. There was a short carbon uptake period in 2007 at TY site, with a net carbon uptake from July to September and a net carbon loss for the remainder of the year. The carbon uptake period from June to September in 2008 was longer than in 2007, with a maximum value of NEE 0.12 mg C m^{-2} s^{-1} in July.

The maximum values of the three sites were –0.07–0.11

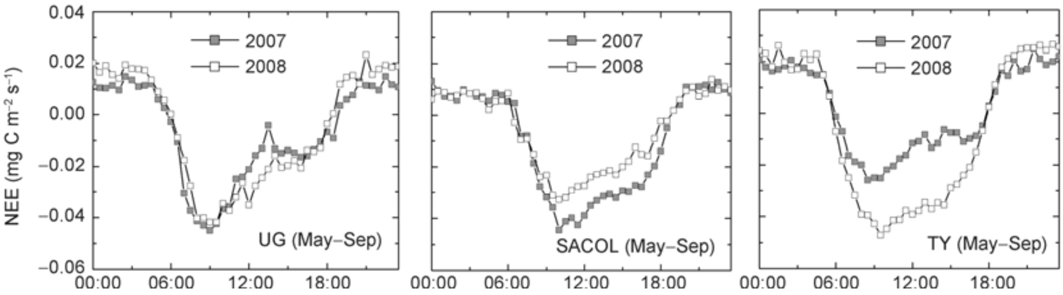

Figure 3 The mean diurnal variation of NEE in growing seasons at the three sites (2007–2008).

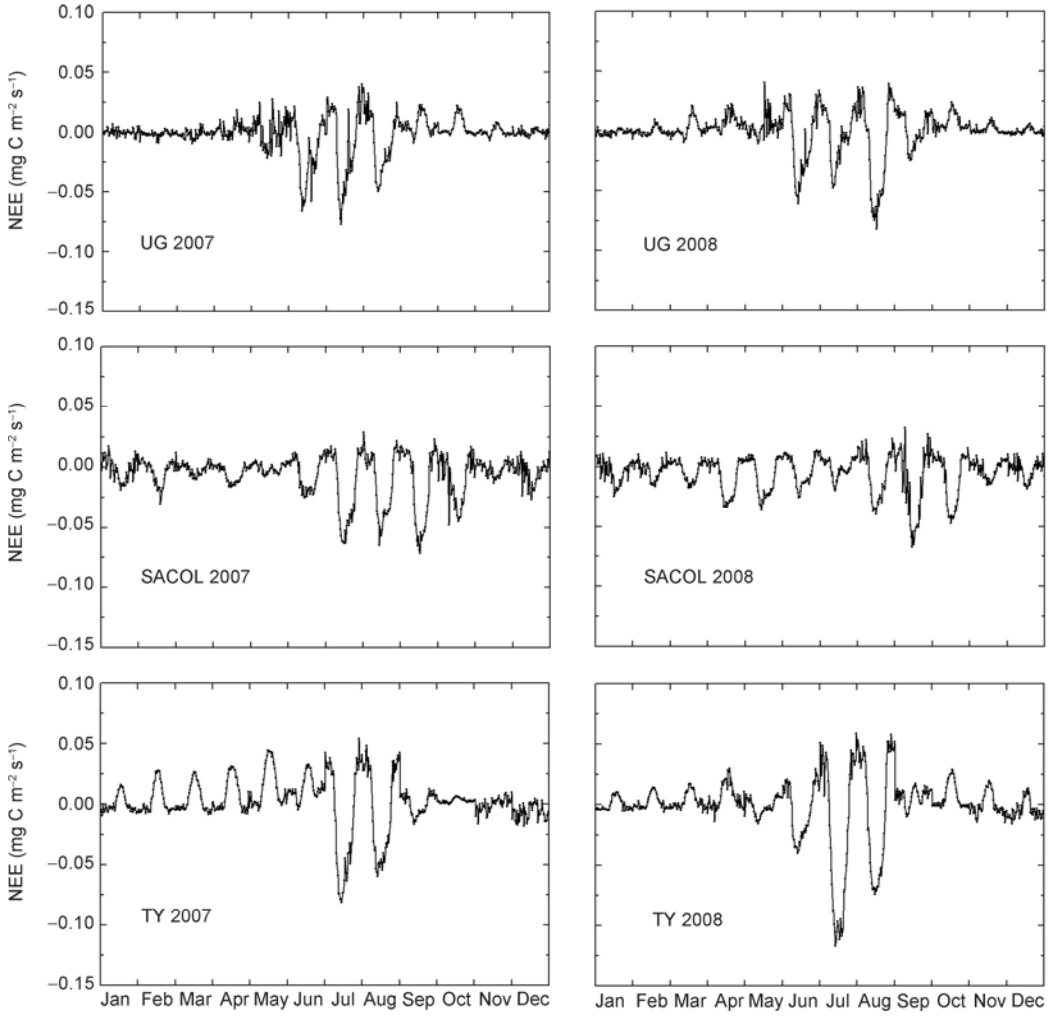

Figure 4 The monthly mean diurnal variaion of NEE at the three sites (2007–2008).

mg C m^{-2} s^{-1}. As compared to the other grassland ecosystems, maximum values of NEE for the three sites in our study were close to the 0.12 mg C m^{-2} s^{-1} reported for Inner Mongolia steppe during a dry year in 2005 [28], and the 0.06–0.17 mg C m^{-2} s^{-1} in northern temperate grassland in Canada during 1998–2000 [15].

2.3 Ecosystem respiration

The relationship between nighttime NEE and soil temperature, soil water content in growing seasons of the three sites was presented in Figure 5. An exponential relationship existed between nighttime NEE and temperature at UG 79 site and TY site. The respiration rate increased rapidly during 15 and 20°C, and a maximum rate occurred when the soil temperature was around 20°C. When the soil temperature was above 20°C, the nighttime NEE began to decrease and the NEE points were more scattered. The relationship between nighttime NEE and soil temperature was not notable at SACOL site. Figure 5 shows that the temperature at

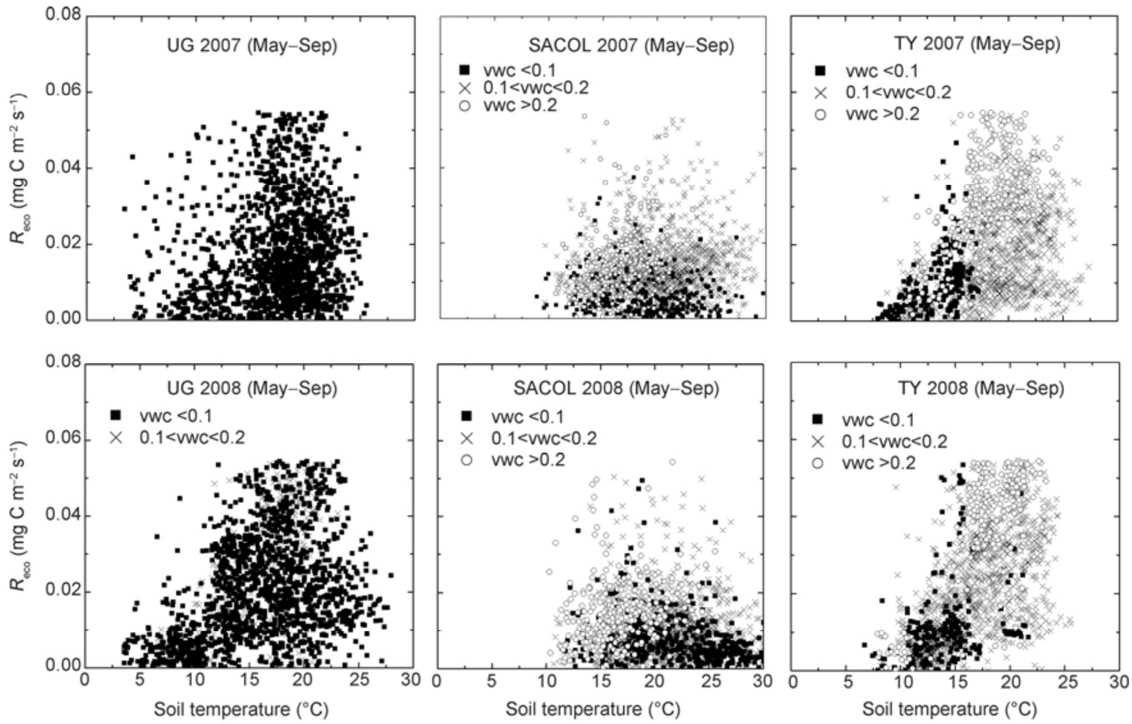

Figure 5 Relationship between nighttime NEE and soil temperature, soil volumetric water content (5 cm) in growing seasons for the three sites, but the data of soil volumetric water content at UG site was unavailable in 2007.

SACOL site remained high, more than 20°C during May and August. Ecosystem respiration was high under better soil water conditions. These results clearly indicated that ecosystem respiration depended on both soil temperature and available water content. Ecosystem respiration increased when temperature increased but only if available soil water was sufficient. The average soil temperature was 5°C higher than at the other two sites. Soil water content became the limiting factors controlling ecosystem respiration.

Figure 6 shows the estimated R_{eco} data derived from different ecosystem respiration equations. The seasonal dynamics of estimated R_{eco} was in agreement with the nighttime NEE in terms of phase and magnitude. The relative RMSE of estimated data is exhibited in Table 1.

Table 1 The relative RMSE of estimation results derived from different respiration equations

Site		2007				2008			
		Eq. (2)	Eq. (3)	Eq. (5)	Eq. (6)	Eq.(2)	Eq. (3)	Eq. (5)	Eq. (6)
UG	May	0.250	0.278			0.618	0.621	0.666	0.718
	Jun	0.280	0.326			0.305	0.321	0.399	0.442
	Jul	0.384	0.456			0.384	0.458	0.209	0.275
	Aug	0.404	0.453			0.141	0.144	0.320	0.275
	Sep	0.686	0.680			0.397	0.391	0.395	0.387
SACOL	May	0.370	0.478	0.332	0.440	0.317	0.337	0.322	0.424
	Jun	0.326	0.379	0.393	0.632	0.462	0.480	0.490	0.571
	Jul	0.229	0.311	0.187	0.265	0.335	0.535	0.423	0.443
	Aug	0.306	0.375	0.359	0.480	0.337	0.460	0.362	0.427
	Sep	0.216	0.234	0.169	0.244	0.269	0.345	0.271	0.337
TY	May	0.516	0.521	0.573	0.709	0.652	0.655	0.711	0.788
	Jun	0.452	0.547	0.399	0.440	0.429	0.428	0.306	0.293
	Jul	0.258	0.305	0.313	0.355	0.180	0.236	0.259	0.206
	Aug	0.338	0.362	0.310	0.323	0.258	0.264	0.273	0.264
	Sep	0.434	0.432	0.481	0.464	0.447	0.476	0.471	0.484

2.4 Seasonal variation of carbon exchange

The seasonal variations in daily NEE, GPP and R_{eco} were shown in Figure 7 over the course of this study. A net carbon uptake period was observed from June to August at UG 79 site. The low precipitation and severe plant water deficits in the middle growing season resulted in a rapid decrease of photosynthesis in July of 2007 and 2008. The maximum of daily total NEE was approaching –5 g C m^{-2} d^{-1}. At SACOL site, while it showed a quite different pattern of seasonal variations in carbon exchange in 2007 and 2008. GPP increased over R_{eco} from June in 2007, making the ecosystem a carbon sink. The ecosystem continued to sequester carbon with the maximum in July and started to decline in September. Due to the early rain in March and May at SACOL site, the grass germinated earlier. GPP was higher than R_{eco} in May, causing a negative NEE. NEE decreased gradually as a result of few precipitations in June and July. The rain subsequently caused the grassland ecosystem to be a carbon sink until the end of September. We also observed the inter-annual variation in carbon exchange at TY site between 2007 and 2008. The precipitation in 2007 was 50% below the climate average and the grass germinated later. The plant photosynthesis increased gradually from June

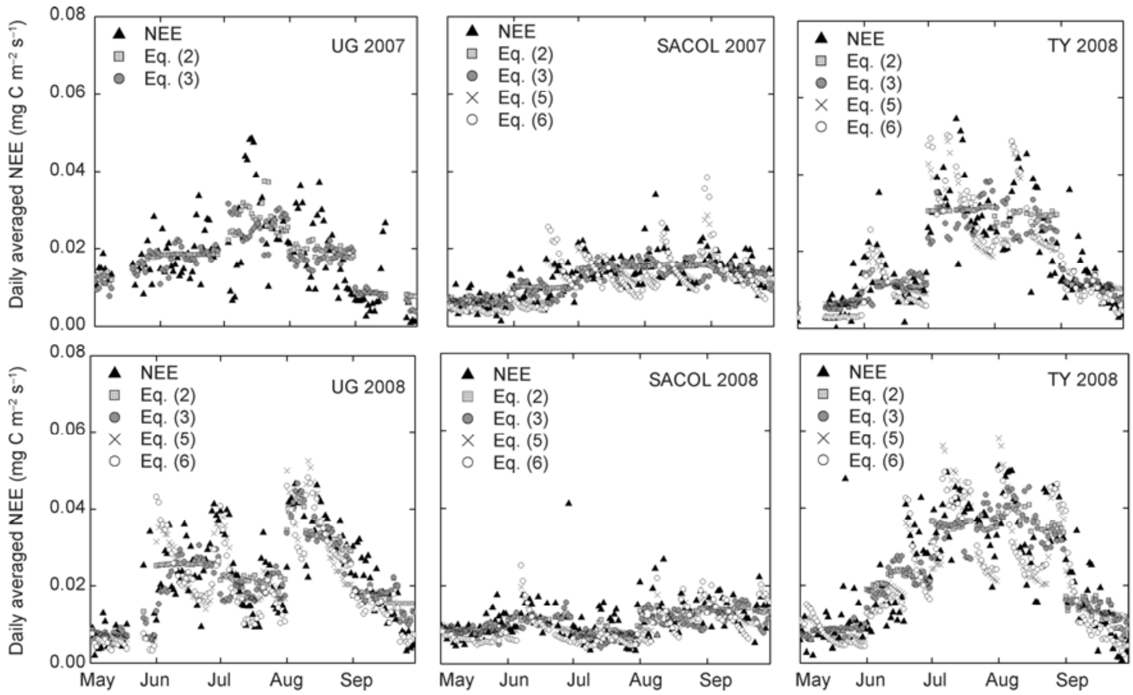

Figure 6 Average diurnal variation of nighttime NEE (observed vs. predicted).

and NEE became negative. Due to the low soil moisture content in August, the carbon uptake rate plummeted to near zero. The carbon uptake period continued to September. The ecosystem functioned as a strong carbon sink in 2008 and the daily maximum NEE reached up to –5 g C m^{-2} d^{-1} (same as TY site).

Figure 8 shows the relationship between ecosystem respiration (R_{eco}) and gross primary production (GPP). Ecosystem respiration was positively correlated with GPP. The slope of linear regression was less than one and regression intercept was not equal to zero. Since terrestrial ecosystems function cumulatively as an effective sink of atmospheric CO_2, the average of the ratio R_{eco}/GPP should be less than one across multiple ecosystem types [29]. R_{eco}/GPP is equivalent to the ratio of dR_{eco}/dGPP if heterotrophic respiration is zero. Theoretically, autotrophic respiration reduces to zero when GPP=0. The regression intercepts for the three sites were significantly non-zero, and the regression intercepts would be equal to a "background" of annual autotrophic respiration if vegetation was absent [30]. The positive ratio of dR_{eco}/dGPP for the three sites indicated that R_{eco} increased with increasing GPP. The dR_{eco}/dGPP at UG79 site between 2007 and 2008 was 0.49 and 0.57 respectively. The dR_{eco}/dGPP at SACOL site between 2007 and 2008 was 0.36 and 0.37 respectively. The dR_{eco}/dGPP at TY site was 0.67 and 0.58 respectively. The results illustrated that the ecosystem capacity in carbon balance for one grassland ecosystem varied as environmental factors fluctuated. The low precipitation and the late growing season at TY site in 2007 resulted in higher heterotrophic respiration. The GPP in May, June and September was lower than ecosystem respiration. Although the precipitation occurring in July and August changed the system into a sink of carbon, the ecosystem was a slight carbon source in the whole growing season. The capacity and variation in carbon balance for the degraded grassland in semiarid area was highly correlated with the amount and timing of precipitation.

Figure 9 shows the cumulatively GPP, R_{eco} and NEE at the three sites between 2007 and 2008. The integrated NEE at UG79 site between 2007 and 2008 was –68 and –50 g C m^{-2} , respectively. The seasonal variation of carbon exchange was similar in 2007 and 2008 with maximum value of integrated GPP 270 and R_{eco} 218 g C m^{-2}, respectively. The dominance of GPP over R_{eco} from June resulted in a net carbon sink at UG79 site. The GPP at UG79 site during July and August increased slowly in 2008 as compared to 2007 and reached up the maximum value in September. A strong carbon sink was recorded at SACOL site in 2007. The variation of ecosystem respiration was similar between 2007 and 2008, increasing steadily in the whole growing season with maximum value of 109 g C m^{-2}. The GPP at SACOL site between 2007 and 2008 was 245 and 163 g C m^{-2}, respectively, and NEE was –109 and –55 g C m^{-2}, respectively. In agreement with the diurnal variation of NEE for growing season, the daily average NEE was lower. It was noted from the variation of integrated NEE that the carbon uptake was still increasing in September with a longer carbon uptake period. It was an effective carbon sink at SACOL site. The carbon exchange process in 2007 and 2008 showed a large difference at TY site. The NEE for the two growing seasons was 0.32 and –73 g C m^{-2}, respectively. The scarce rain in 2007 resulted in a low net

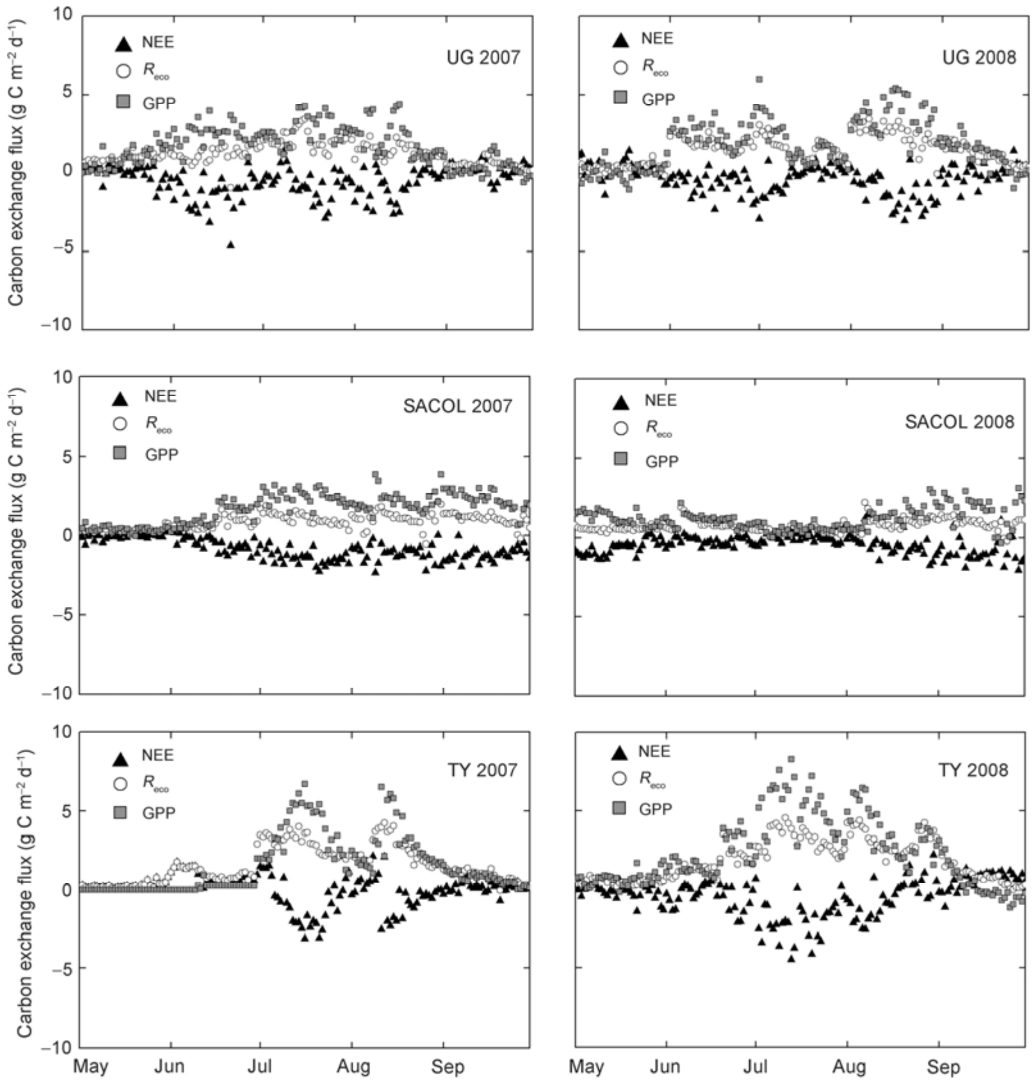

Figure 7 Seasonal variation of daily total GPP, R_{eco} and NEE in growing seasons between 2007 and 2008 at the three sites.

carbon exchange and a short carbon uptake period. The ecosystem was a slight carbon sink during June and August in the growing season in 2007. The R_{eco} was also low in 2007 but the difference between 2007 and 2008 in R_{eco} was less than GPP, with integrated GPP value of 218 and 354 g C m^{-2} respectively. The lower carbon uptake and a short carbon uptake period caused the grassland ecosystem at TY site to be a weak carbon source in 2007. It became a carbon sink in the growing season of 2008. The study on a savanna and open grassland showed that the annual NEE from 2000 to 2006 ranged from –144 to –35 g C m^{-2} a^{-1} and from –6 to 189 g C m^{-2} a^{-1} at the savanna and nearly grassland, respectively [30]. The grassland ecosystem was an effective carbon sink except for the extreme drought year. The GPP in the savanna and open grassland ecosystem ranged from 600 to 1500 g C m^{-2} a^{-1}. The GPP in the grassland ecosystem in semiarid areas was rather low as compared to the savanna and open grassland ecosystem.

The common slope R_{eco} vs. GPP was usually less than one. Obvious annual variation in carbon exchange process was observed. The grassland could shift from carbon sink to carbon source attributed to the climate fluctuations. Such alternations between carbon sink and carbon source have been reported for a Canadian cool temperate grassland [15] and European grassland [31]. Alternations between carbon sink and carbon source are not rare, especially when a ecosystem encounters extreme climatic events or disturbances [32]. Due to the variation in precipitation, the ecosystem changed from a weak carbon source in 2007 to a strong carbon sink in 2008. The carbon sequestration potential was highly correlated with the length of the carbon uptake [33]. The length of growing season depends on the plant physiological characteristic, which was influenced by the environmental factors [34]. The timing of precipitation determined the beginning and length of the growing season [12]. The late precipitation in 2007 at SACOL and TY site caused a late onset of carbon uptake in the growing season.

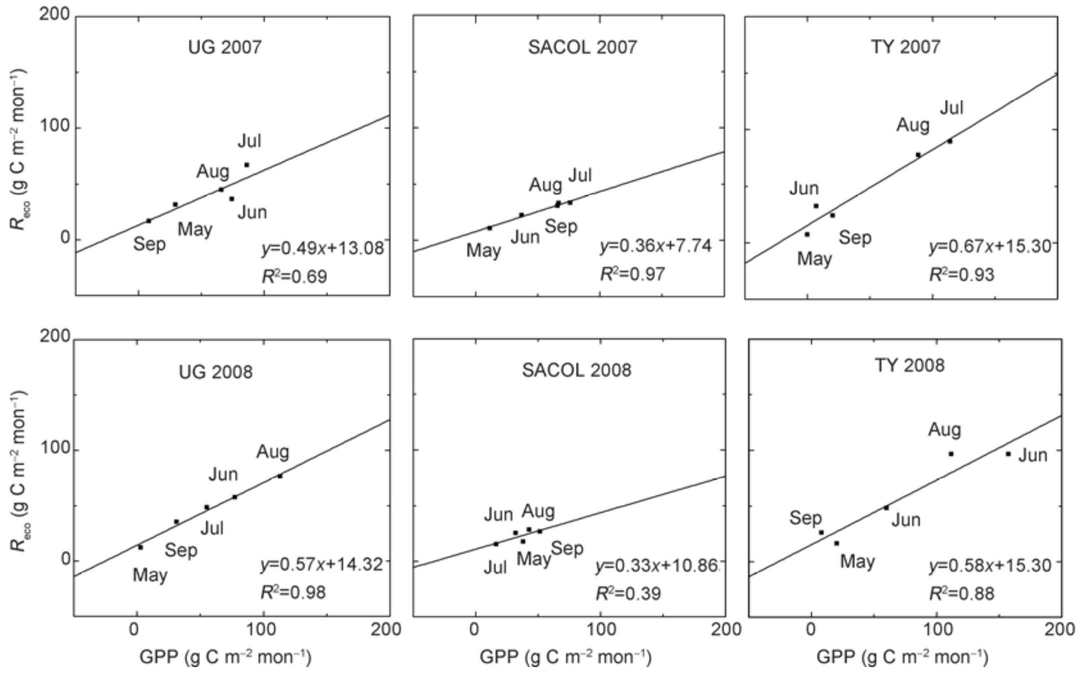

Figure 8 Linear relationships between R_{eco} and GPP in growing seasons between 2007 and 2008 at the three sites.

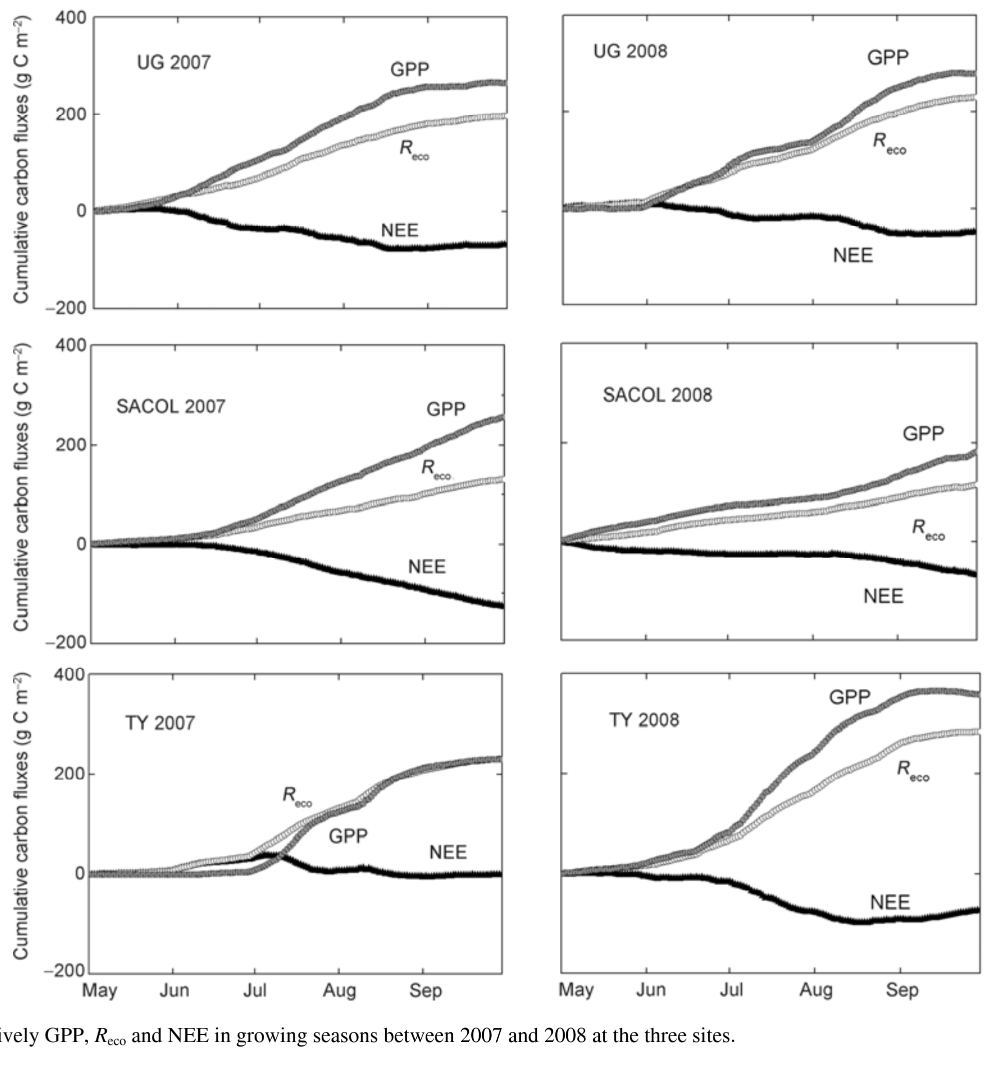

Figure 9 Cumulatively GPP, R_{eco} and NEE in growing seasons between 2007 and 2008 at the three sites.

3 Conclusions

We have investigated the carbon exchange processes and its main environmental drivers in the three grassland ecosystems (UG79 site, SACOL site and TY site) in semiarid areas based on the eddy covariance data. The results showed that there were large temporal and spatial variations in the carbon exchange processes in the three grassland ecosystems. The maximum of NEE occurred usually in diurnal 09:00–10:00 and in July-September over the whole growing season. The integrated GPP and R_{eco} at TY site was the highest between 2007 and 2008, with respective value of 286 and 249 g C m^{-2}. The second was UG79 site, with integrated GPP 270 and R_{eco} 209 g C m^{-2}, respectively. SACOL site was the lowest, with integrated GPP 208 and R_{eco} 109 g C m^{-2}.

The amount and timing of precipitation had a strong effect on carbon exchange processes for grassland ecosystem in semiarid area. The scarce precipitation at TY site in 2007, approximately 50% lower than the historical average, caused the ecosystem to be a weak carbon source over the whole carbon sink. The ecosystem started to sequester carbon in July due to the late precipitation. The precipitation at TY site in 2008 was close to the normal, and the ecosystem became an effective carbon sink from May in the growing season. The carbon uptake was low at SACOL site between 2007 and 2008 but with a longer carbon uptake period, and the ecosystem was a strong carbon sink in both years. The low precipitation and severe plant water deficits in the middle growing season inhibited the carbon uptake, and the ecosystem could be a slight carbon source. The carbon exchange processes all showed a "double peaks" at UG79 site and TY site between 2007 and 2008. GPP was more sensitive than R_{eco} to the variation of precipitation. The low precipitation at SACOL site in 2008 resulted in a lower GPP than 2008, but with a smaller difference between R_{eco}. The large difference in precipitation at TY site between 2007 and 2008 caused the GPP in 2008 to be 130 g C m^{-2} higher than 2007, and R_{eco} 60 g C m^{-2} higher than 2007. The dR_{eco}/dGPP for three sites was all less than one. The inter- annual variation and regional difference of dR_{eco}/dGPP depended on both the climate fluctuation and the characteristic of soil and plant at the site. The carbon, water and energy exchange were closely correlated, and more studies are needed to investigate the relation between carbon, water and energy fluxes.

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