How summer season precipitation affects net ecosystem carbon dioxide exchange over the grazing steppe in central Mongolia

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Introduction

Steppe covers 83% of territory in Mongolia (~1.3 ×10^6 km^2) (World Resources Institute, 2003). Due to its vastness in area, the steppe ecosystems in Mongolia play a critical role in regional and global carbon and water cycles. For the semiarid and arid ecosystems like Mongolian steppe, water stress is a limiting factor for plant growth, and vegetation productivity is tightly associated with the intra- and inter-seasonal variation in precipitation. Therefore, how the steppe ecosystems respond to moisture conditions is important for an improved understanding of the coupling among water and carbon cycling, steppe management, and climate change in Mongolia. The eddy covariance (EC) technique is now widely used for long-term continuous flux measurements across the world (Baldocchi, 2003). In this study, we used the EC technique to quantify whether the Mongolian steppe ecosystem is a carbon source or carbon sink and its sensitivity to summer precipitation.

Materials and Methods

The study site is located at Kherlenbayan-Ulaan (KBU), Hentiy province, Mongolia (47°12.838'N, 108°44.240'E) (Fig. 1). The climate in the region is temperate continental with mean annual air temperature of 1.2 °C and mean annual precipitation of 196 mm. The soil is the Chestnut soil. The vegetation is dominated by temperate C_3 plants.

We used the eddy covariance (EC) technique to measure net ecosystem carbon dioxide exchange (NEE) above the steppe. The EC system was set up and instrumented in March 2003. The system included a 3-D ultrasonic anemometer/thermometer (model SAT-550, Kaijo Sonic Co., Tokyo, Japan) and an open path CO_2/H_2O infrared gas analyzer (model Li7500, LICOR Inc., Lincoln, NE USA) for measuring CO_2 and water vapor fluxes. We also measured four components of net radiation (model CNR1, Kipp & Zonen BV, Delft, the Netherlands) at 2.5 m, air temperature and humidity (model HMP-45D, Vaisala Inc., Helsinki, Finland) at 2.5 m above the ground, soil temperature profile (5, 10, 20, 30, 50, 70, 100, and 150 cm) by platinum resistance thermometers (model C-PT, CLIMATEC Inc., Tokyo, Japan), soil heat flux (2 and 10 cm) by soil heat plates (model PHF-1.1, REBS, Inc., Seattle, WA, USA), soil moisture profile (10, 20, 30, 50, 70, 100 and 150 cm) by time domain reflectometry probes (model CS616, Campbell Scientific, Logan, UT, USA), and precipitation by a tipping bucket rain gauge (model CYG-52202, RM Young Company, Traverse City, MI, USA). Leaf area index was also measured monthly during the 2003 growing season. Details of information on the site and the measurements were reported in Li et al. (2005).

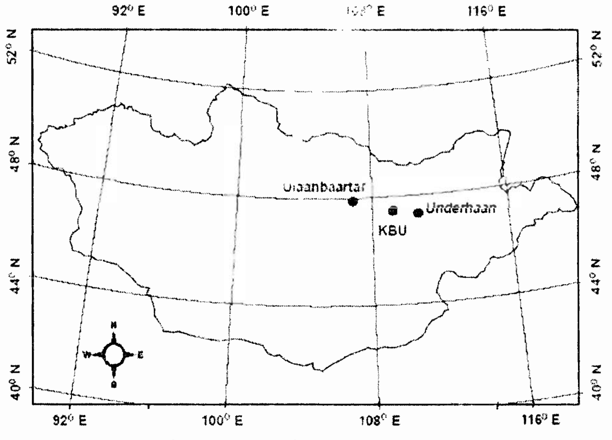

Fig. 1. Location of the site.

According to the EC technique, half-hourly net ecosystem CO_2 exchange (NEE; in ìmol m^{-2} s^{-1})

can be estimated from (e.g. Baldocchi, 2003):

$$\mathrm{NEE}=\overline{w'c'}, \qquad (1)$$

where primes are deviations from the time-averaged mean (e.g. $c'=c-\bar{c}$). The overbar indicates a time-averaged mean. Negative fluxes signify a net carbon gain of the canopy from the atmosphere. Post data processing included (1) the cospectral correction for CO_2 and water vapor fluxes using the algorithm proposed by Eugster & Senn (1995), and (2) the correction of the scalar fluxes for the density effect following the algorithm described by Webb *et al.* (1980). We also used the methods proposed by Falge et al. (2001) to fill the data gaps caused by sensor malfunction, rain events, sensor maintenance, power failure, etc.

We modeled NEE using a Michaelis-Menten function (Falge *et al.*, 2001):

$$\mathrm{NEE}=\frac{\alpha\times\mathrm{NEE}_{\mathrm{sat}}\times\mathrm{PAR}}{\alpha\times\mathrm{PAR}+\mathrm{NEE}_{\mathrm{sat}}}+R, \quad (2)$$

(3) We used NEE data to estimate gross ecosystem production (GEP):

where *á* is the apparent quantum yield or the initial slope of the light response curve (ìmol CO_2 per ìmol of photons); PAR is the photosynthetically active radiation, and NEE_{sat} is the saturation value of NEE at an infinite light level. *R* is a bulk estimate of ecosystem respiration (R_{eco}).

We used NEE to estimate gross ecosystem productivity (GEP) by:

$$\mathrm{NEE}=-\mathrm{GEP}+R_{eco}, \qquad (3)$$

where R_{eco} was estimated from nighttime NEE data when u_* ³ 0.2 m s^{-1} using an exponential function.

Results and Discussion

The magnitudes and day-to-day variability of NEE, GEP and R_{eco} differed depending on growth status of grasses and weather conditions during the measurements (Fig. 2). Several peaks of the NEE were triggered primarily by rain pulses. There were twelve rain events >5 mm from April 23 to October 21. The first rain event (12.2 mm from DOY 132-135) enhanced R_{eco} more than GEP resulting in an increase in NEE from –0.14 g C m^{-2} d^{-1} (averaged over day of year, DOY 129-131) prior to the rain to 0.07 g C m^{-2} d^{-1} (averaged over DOY 136-138) after the rain. This respiration enhancement effect was even larger during the rain period itself (NEE = 0.66 g C m^{-2} d^{-1} averaged over DOY 132-135). The second rain event (13.2 mm on DOY 147) also brought about a positive increase in NEE during and immediately after the rains. The following three rains event (17.7 mm, DOY 170 to 172; 24.2 mm, DOY 175-180; 14.3 mm, DOY 182-184 were separated by only one or two rainless days, so NEE after these rains was compared with that before DOY 170. NEE decreased from –0.17 g C m^{-2} d^{-1} (averaged over DOY 167-169) to –1.17 g C m^{-2} d^{-1} (averaged over DOY 185-193), which indicates a much stronger positive effect on GEP than on R_{eco}. By now, soil moisture (14.3% at 10 cm depth) obviously has increased above the threshold that appeared to limit microbial activity before the early season rain events. This order of magnitude decrease in NEE corresponds with the rapid increase of green LAI from 0.2 to 0.5 m^2 m^{-2}. The following rain event from DOY 196-200 (29.3 mm) again made NEE more negative. The period from late July (around DOY 201) to late August (around DOY 230) was a peak growing season with LAI exceeding 0.5. The largest carbon uptake (NEE = –2.3 g C m^{-2} d^{-1}) occurred in late July (DOY 207). On the same day, GEP reached its maximum of 3.5 g C m^{-2} d^{-1}. Although several minor rain events (totaling 1.7 mm) occurred from DOY 208 to 225, a rapid depletion of SWC. Carbon uptake followed that decrease in SWC, and the steppe switched from a net sink to a net source on DOY 222, suggesting the onset of water stress. The stress disappeared after the following two strong rain events: 17.3 mm from DOY 226-228 and 21.6 mm on DOY 232, which stimulated a temporal increase in carbon uptake (Fig. 2). With the onset of grass senescence (around DOY 240), NEE began to decline. The seasonal decline of solar radiation, temperature, and reduced photosynthetic capacity further accelerated this decline. The rain events during the senescence period primarily enhanced the carbon release from the canopy, but this effect was smaller than earlier in the growing season. From about mid October, the steppe entered the dormancy period which is a source of CO_2.

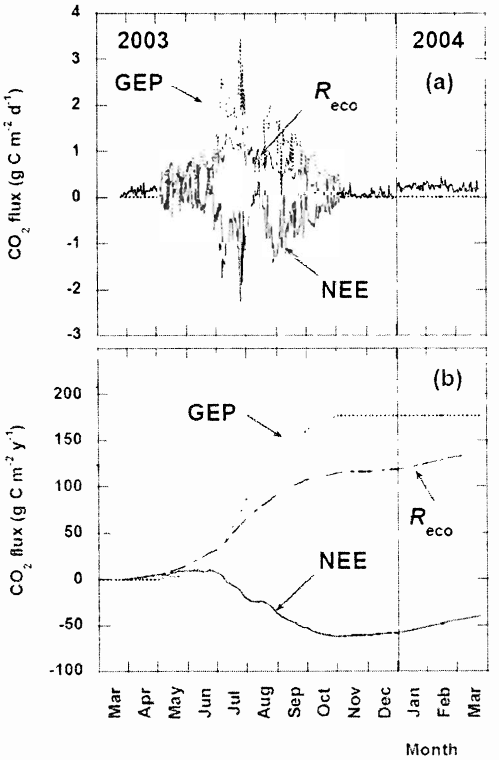

Fig. 2. (a) Time series of NEE, GEP and R_{eco}, and (b) Cumulative values of NEE, GEP and R_{eco} from 25 March of 2003 to 24 March of 2004.

The maximal daily-integrative NEE (–2.3 g C m^{-2} d^{-1}) for Mongolian steppe lies in the lower half of the maximum NEE range (–1.9 to –9.3 g C m^{-2} d^{-1}) reported in the literature. Integration of NEE data from March 25 of 2003 to March 24 of 2004 yielded a total annual net carbon uptake of –41 g C m^{-2} y^{-1}, which can be partitioned into 179 g C m^{-2} y^{-1} of GEP and 138 g C m^{-2} y^{-1} of R_{eco}, respectively. Our results suggest that the central Mongolian steppe is a weak sink for atmospheric CO$_2$.

Biologically, NEE is sensitive to LAI (Fig. 3). NEE responded to LAI in a linear manner (NEE = –1.57×LAI + 0.12, n = 182, adjusted r^2 = (Fig. 3).

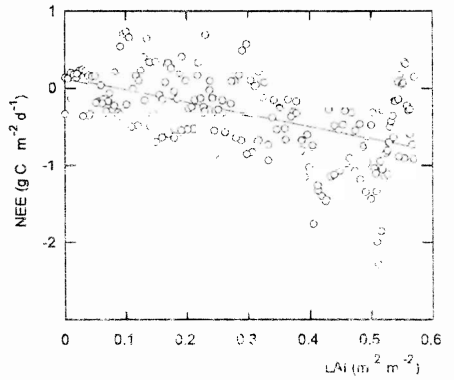

Fig. 3 The NEE-LAI relationship during the growing period from 23 April to 21 October of 2003.

Daytime NEE depended on incident PAR (Eqn. (2)) in the 30-min resolution during the growing season (Fig. 4). NEE saturated (NEE$_{sat}$ = –2.04 ìmol m^{-2} s^{-1}) at PAR = 1330 ìmol m^{-2} s^{-1} (Fig. 4).

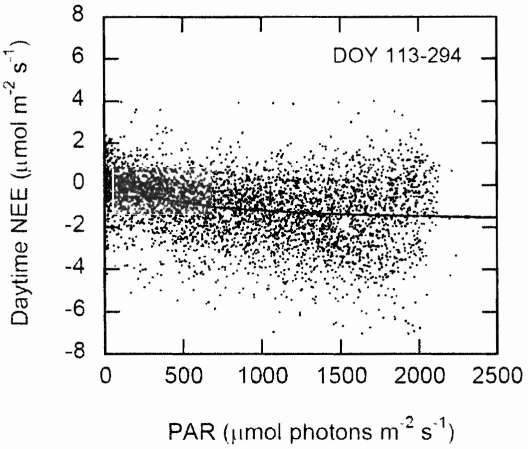

Fig. 4 The light response curves. A hyperbolic function (Eqn. (3)) was used to fit the data.

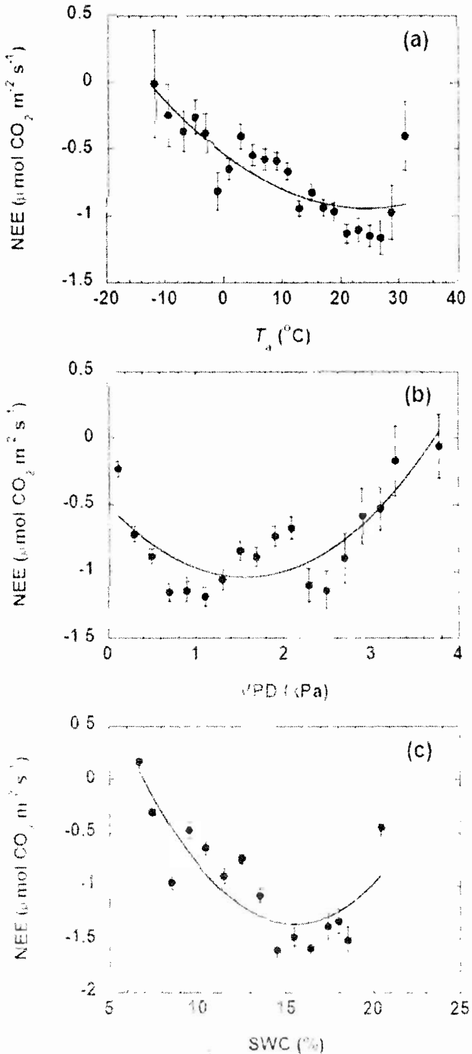

Fig. 5. The responses of NEE to (a) air temperature (T_a), (b) air water vapor pressure deficit (VPD), and (c) soil water content at 10 cm depth (SWC). NEE was bin-averaged. Curves are best fits by the quadratic polynomial function

The model-derived quantum yield (*á*) was –0.0046 ìmol CO_2 ìmol^{-1} photons. The *á* value for the Mongolian steppe was particularly low as compared with the range (–0.008 ~ –0.465) found in the literature for grasslands and crops (e.g. Ruimy *et al.*, 1995), suggesting the steppe is not very productive in terms of light use efficiency.

In addition, NEE was sensitive to air temperature (T_a), atmospheric water vapor deficit (VPD) and soil water content (SWC). To illustrate this sensitivity, we compiled the daytime NEE data (from Fig. 4) using bins of T_a, VPD and SWC. Bin width was 2 °C for T_a, 0.2 kPa for VPD, and 1% for SWC, respectively. Regardless of PAR, the NEE data were averaged over each bin, and were plotted against T_a, VPD and SWC in Fig. 5, respectively.

Carbon uptake (NEE gets more negative) almost linearly increased with increasing T_a, (Fig. 5a). Carbon uptake appeared to increase with VPD before VPD reached 1.5 kPa, and thereafter decreased with further increase of VPD (Fig. 5b). At higher VPD there is a reduction in NEE due to stomatal closure under drought conditions. Both SWC and VPD affect the hydraulic status of plants and determine to a large degree gas exchange between the plants and the ambient air via leaf stomatal conductance. Thus, water shortage from the soil might aggravate VPD-induced decrease in carbon uptake. Carbon uptake increased with increasing SWC up to 15% (Fig. 5c). Further increase in SWC may be more advantageous to ecosystem respiration, and thus carbon uptake decreased when SWC exceeded 15% (Fig. 5c).

Conclusions

One full year measurements of carbon dioxide flux were conducted over a typical steppe in central Mongolia. The steppe was a weak sink for the atmospheric CO_2. And the strength of the sink was sensitive to canopy development and variation in such environmental factors as air temperature, water vapor pressure deficit and soil moisture. We argue the strength is likely subject to anthropogenic disturbances such as overgrazing. This point deserves clarification in our future study.

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