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RESEARCH ARTICLE

# Characteristics of net ecosystem carbon dioxide exchange (NEE) from August to October of Alpine meadow on the Tibetan Plateau, China

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**Abstract** The Alpine meadow is one of the vegetation types widely distributed on the Tibetan Plateau in China with an area of about 1.2 million square kilometers. The Damxung rangeland station, located in the hinterland of the Tibetan Plateau, is covered with an typical vegetation. The continuous carbon flux data (from August to middle October, 2003) measured with the open-path eddy covariance system was used to analyze the diurnal variation pattern of net ecosystem carbon dioxide exchange (NEE) and its relationship with the environmental factors, such as photosynthetically active radiation (PAR), precipitation, and temperature. Results showed that NEE presented obvious diurnal variation pattern with single-peak of diurnal maximum carbon assimilation at 11: 00–12: 00 (local time) with an average of −0.268 mg $CO_2 \cdot m^{-2} \cdot s^{-1}$, i.e., −6.08 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$. During the daytime, NEE fitted fairly well with PAR in a rectangular hyperbola function with the apparent quantum yield (0.020 3 μmol $CO_2$ $\mu mol^{-1}$ PAR) and maximum ecosystem assimilation (9.741 1 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$). During the night-time, NEE showed a good exponential relation with the soil temperature at 5 cm depth.

**Keywords** Tibetan Plateau in China, Alpine meadow, eddy covariance, carbon flux, environmental factors

## 1 Introduction

The global climate change induced by the increasing atmospheric concentration of greenhouse gases, such as $CO_2$, $CH_4$, is the focus and also one of the most serious challenges for our community. The Tibetan Plateau in China, named “the third pole in the world”, is regarded as the triggering zone of global climate change. It is one of the areas with the strongest radiation on earth (Zhang et al., 1996), and the environmental conditions are unique with a low air pressure, cool climate and low $CO_2$ concentration, which is less than two thirds of that on the plains. Because cool climate and low $CO_2$ concentration are main limiting factors for plant growth, the vegetation here will be more sensitive to the increase of air temperature and enrichment of $CO_2$ than the plant on plains. Hence, it is important to make a long-term measurement of the carbon flux between the vegetation and atmosphere on the Tibetan Plateau, which will not only predict the response degree of the vegetation under low air pressure to global climate change, but also provide the most immediate and powerful evidences for further research in this field on plains.

The Alpine meadow is one of the vegetation types widely distributed on the Tibetan Plateau with an area of about 1.2 million square kilometers, which amounts to 67% of the total area of Qinghai Province and the Tibetan Autonomic Region, China. It is not only one of the typical ecosystems in the Alpine area of Middle Asia, but also a representative ecosystem of the alpine areas in the world. Eddy covariance technique, which is a micrometeorological method to measure $CO_2$, water and heat flux between the atmosphere and vegetation directly, is superior to many other traditional methods. Its spatial and temporal monitoring scale is large, from several hundred miles to several kilometers, and also from several hours, days, seasons to even several years (Baldocchi et al., 2000). Consequently, eddy covariance technique was used rapidly and widely in measuring carbon flux between the terrestrial vegetation and atmosphere, and has become the main tool for measurement of FLUXNET, e.g., AsiaFlux, AmeriFlux, KoFlux and OzFlux. This paper analyzed the diurnal variation pattern of NEE as well as the relationship between NEE and the main environmental factors of the Alpine meadow ecosystem based on the carbon flux data measured with the open-path eddy covariance

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system in the Damxung rangeland station from August to October, 2003.

## 2 Study area and methods

### 2.1 Study area

The study area is located in the Damxung rangeland station, which is one of the key experimental sites of the Lhasa Plateau Ecosystem Research Station, Institute of Geographical Sciences and Natural Resources Research, CAS, China. The station (30º25′N, 91º05′E) is 1 km away from Damxung county with an elevation of about 4 333 m. The experimental site is categorized as plateau monsoon climate with characteristics of strong radiation, low air temperature, large diurnal variation, and small annual differences. Annual mean air temperature is 1.3°C, with minimum mean (–10.4°C) in January and maximum mean (10.7°C) in July. Mean daily variation temperature is 18.0°C, while the annual variation is 21.0°C. The average surface soil temperature is 6.5°C. Frozen soil duration is 3 months from November to next February. Annual mean precipitation is about 476.8 mm, with 85.1% in June and July. Annual evaporation is 1 725.7 mm and average wetness coefficient is 0.28. The annual average sunlight is 2 880.9 hours. And the amount of sun radiation is 7 527.6 $MJ·m^{-2}$, of which PAR is 3 213.3 $MJ·m^{-2}$.

The soil is classified as meadow soil with sandy loam. The soil has a depth of 0.3–0.5 m, with high gravel content of 30%. Organic matter content is 0.9%–2.97%, total nitrogen is 0.05%–0.19%, total phosphorous is 0.03%–0.07%, and pH is 6.2–7.7. The vegetation here is alpine steppe-meadow which is typical in the northern Tibetan Plateau, China. Three kinds of dominating species are *Stipa capillacea*, *Carex montis-everestii,* and *Kobresia pygmaea*, whose coverage is about 80%.

### 2.2 Methods

#### 2.2.1 Observation items

Fluxes of $CO_2$ and $H_2O$ between the vegetation and atmosphere were measured with an open-path eddy covariance system at a height of 2.1 m located in the Damxung observation site with the frequency of 10 Hz. The eddy covariance array sensors included a 3D sonic anemometer (CSAT3, Campbell Scientific Inc.) and an open-path $CO_2$ analyzer (Model LI7500, LI-Cor Inc.). Profiles of environmental factors, such as wind direction, wind speed, mean air temperature, mean air relative humidity, precipitation, atmospheric pressure, photosynthetically active radiation, net radiation, soil temperature (5, 10, 20, 50, 80 cm), and soil moisture (5, 10, 50 cm) were also measured. Measurement began from July 2003 up to present.

#### 2.2.2 Data processing

Data pretreatment was needed in order to adjust the flux data caused by sensor malfunction, which included spike removal (± 3$\sigma$), coordinate rotation and Webb-Pearman-Leuning revisal (Webb et al., 1980). The missing gap could be filled with the non-linear experiential function established between NEE and the environmental factors.

The daytime $CO_2$ flux ($NEE_d$) was fitted with the model of Michaelis-Menten (Falge et al., 2001) described as follows:

$$NEE_d = \frac{\alpha.PAR\ .\ \mathrm{NEE}_\infty}{\alpha.PAR + \mathrm{NEE}_\infty} - R$$

where $\alpha$ ($\mu mol\ CO_2·\mu mol^{-1}$ PAR) was the apparent quantum yield, denoting the maximum efficiency of light utilization in photosynthesis; PAR ($\mu mol·m^{-2}·s^{-1}$) was the photosynthetically active radiation; $NEE_\infty$ ($\mu mol\ CO_2·m^{-2}·s^{-1}$) was the maximum ecosystem assimilation and $R$ ($\mu mol\ CO_2·m^{-2}·s^{-1}$) was the respiration from soil and plant.

The nighttime $CO_2$ flux ($NEE_n$) was fitted with the following model based on soil temperature when the friction velocity $u^*$ was higher than 0.15 $m·s^{-1}$.

$$NEE_n = b_0 \exp\left(b_1 T_{\mathrm{soil}}\right)$$

where $b_0$, $b_1$ were the coefficient, $T_{\mathrm{soil}}$ the soil temperature at 5 am depth.

## 3 Results

### 3.1 Averaged diurnal variation of NEE during the growing season

The averaged diurnal variation pattern of NEE from August to September was illustrated in Fig. 1 (NEE was positive, donating carbon release; NEE was negative, donating carbon uptake). During night-time, the ecosystem behaved as a carbon source with the peak 0.094 mg $CO_2·m^{-2}·s^{-1}$, i.e., 2.13 $\mu mol\ CO_2·m^{-2}·s^{-1}$. During daytime, the whole ecosystem turned into a carbon sink usually at 8：00, and reached the maximum at about 12:00, which was about −0.268 mg $CO_2·m^{-2}·s^{-1}$, i.e., 6.08 $\mu mol\ CO_2·m^{-2}·s^{-1}$.

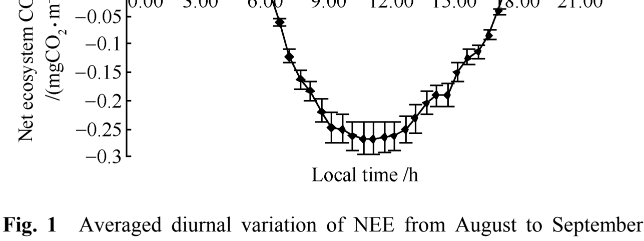

**Fig. 1** Averaged diurnal variation of NEE from August to September, 2003 in Damxung, China

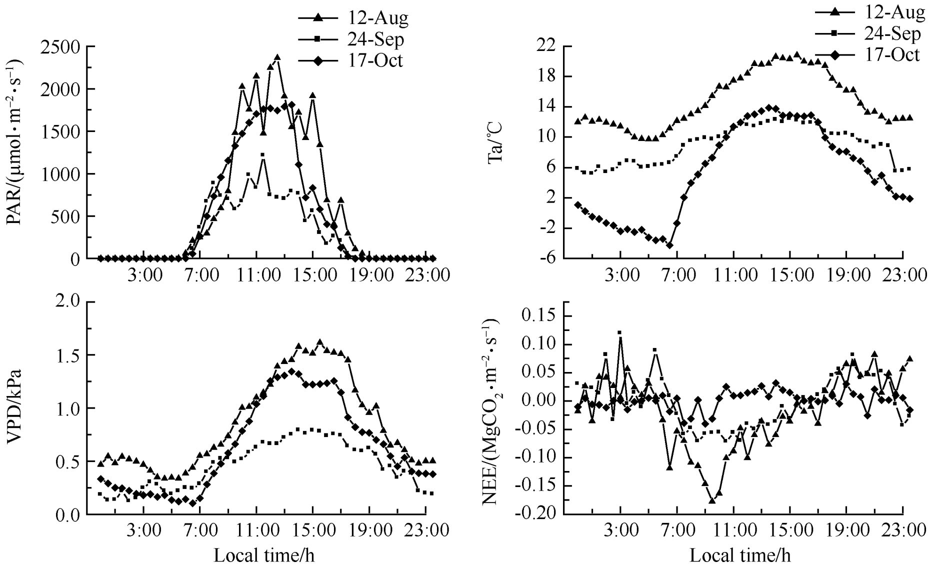

**Fig. 2** Comparison of PAR, Ta, VPD, NEE on typical clear days from August to October

Several representative clear days (August 12th, September 24th, and October 12th) were chosen in order to analyze the relationship between NEE and the environmental factors. Figure 2 showed the variation patterns of the environmental factors on these days, including the photosynthetically active radiation (PAR), air temperature ($T_a$), the water vapor pressure deficient (VPD) and NEE. As the PAR was concerned, it was highest in August (2 300 μmol $m^{-2}{\cdot}s^{-1}$), and lowest in September (1 200 μmol $m^{-2}{\cdot}s^{-1}$). The reason for the low radiation in September might be that there was too much precipitation (97.2 mm), which was close to that in August (104.2 mm). As for the $T_a$, it fluctuated within 10ºC–20ºC in August, 5ºC–15ºC in September, and fell below zero degree in October. The VPD in August was highest with the maximum 1.6 kPa, while the peak in September was lowest (only 0.8 kPa). The diurnal variation patterns of NEE during the three days were similar, which showed carbon release during night-time and turned into carbon uptake during daytime with photosysnthesis strengthening. The peak of carbon uptake was usually reached at noon, which was highest in August (−0.18 mg $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$), and that in September was −0.072 mg $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$. In October, the whole ecosystem was almost a carbon source with the beginning of plant perishing. It was shown that water was not the main controlling factor in August. Although the VPD was highest, enough radiation and optional temperature made the peak carbon uptake maximal. In October, the plant began to perish thoroughly with the air temperature dropping below zero in the morning, and the whole ecosystem almost became a carbon source in spite of the radiation being stronger than that in September. In addition, the precipitation in October was only 9.6 mm, which might also be a limiting factor.

### 3.2 Relationship between NEE and the environmental factors during the growing season

As shown in Fig. 3, the daytime NEE fitted fairly well with PAR in a rectangular hyperbola function with the averaged apparent quantum yield 0.020 3 μmol $CO_2{\cdot}\mu mol^{-1}$ PAR, the apparent maximum ecosystem assimilation 9.741 1 μmol $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$ and the respiration from soil and plant 1.615 9 μmol $CO_2{\cdot}m^{-2}{\cdot}s^{-1}$. Liu et al. (2000) have studied the apparent quantum yield of winter wheat on the Tibetan Plateau, and concluded that the *α* of plant on the Plateau was only two thirds of that on the plain. However, the *α* referred to was on the leaf level, which greatly differed with *α* on the ecosystem scale.

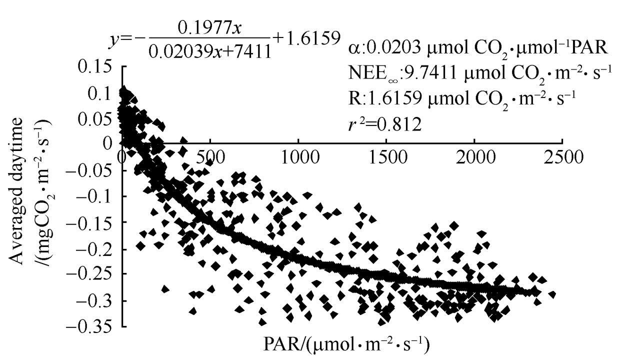

**Fig. 3** Relationship between daytime NEE and PAR from August to September in Damxung, China

The night-time NEE was fitted with the soil moisture at 5 cm depth when the friction velocity ($u$*) was higher than 0.15 $m{\cdot}s^{-1}$, and results showed that there was a good exponential relationship (Fig. 4).

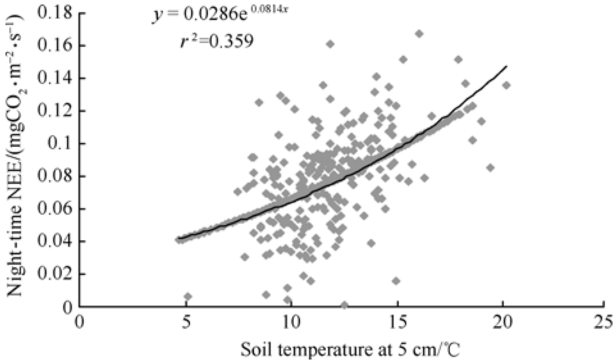

**Fig. 4** Relationship between night-time NEE and soil temperature at 5cm from August to September in Damxung, China

## 4 Discussion

The maximal diurnal carbon uptake rate of the alpine meadow ecosystem in Damxung on the Tibetan Plateau, China, was only −0.268 mg $CO_2$·$m^{-2}$·$s^{-1}$, i.e., −6.08 μmol $CO_2$·$m^{-2}$·$s^{-1}$, which was much lower than that in other grassland ecosystems. For example, the maximal $CO_2$ exchange during the growing season in the North American prairie grassland could reach −1.3 mg $CO_2$·$m^{-2}$·$s^{-1}$ (30 μmol $CO_2$·$m^{-2}$·$s^{-1}$) (Kim and Verma, 1990), −1.2 μmol $CO_2$·$m^{-2}$·$s^{-1}$ (27.2 μmol $CO_2$. $m^{-2}$. $s^{-1}$) (Dugas et al., 1999). The reason for this may be that all these sites had much higher leaf area index of around 4–5 $m^2$·$m^{-2}$, and often included drought-tolerant $C_4$ species (Hunt et al., 2002). Precipitation would influence the carbon exchange greatly. Lawrence et al. (2002) have observed the carbon exchange of $C_3$ temperate grassland in north Canada continuously for three years. They reported that the peak of net diurnal carbon uptake could reach −14 μmol $CO_2$·$m^{-2}$·$s^{-1}$ with enough soil moisture. But when a drought prevailed, it was only −5μmol $CO_2$·$m^{-2}$·$s^{-1}$. The leaf area index (LAI) was another key factor. Andrew et al. (2001) observed that in a tall grass prairie in north-central Oklahoma, USA, the maximal diurnal carbon uptake rate was −0.25 mg $CO_2$·$m^{-2}$·$s^{-1}$ (5.7 μmol $CO_2$·$m^{-2}$·$s^{-1}$) with the LAI being 0.6 in late April, increasing to −1.4 mg $CO_2$·$m^{-2}$·$s^{-1}$ (31.8 μmol $CO_2$·$m^{-2}$·$s^{-1}$) with LAI 2.8 in mid July, and dropping to −0.9 mg $CO_2$·$m^{-2}$·$s^{-1}$ (20.4 μmol $CO_2$·$m^{-2}$·$s^{-1}$) when plant began to perish in September. The vegetation in Damxung is composed of $C_3$ plant species, which are merely 3–5 cm high with low above ground biomass and low LAI as a result of cold climate and precipitation shortage in the north Tibetan Plateau. It might explain why the maximal diurnal carbon uptake rate of the alpine meadow in Damxung was so low. Furthermore, from late August to September, the photosynthetic ability of plant on the Tibetan Plateau began to fall with the onset of sense- cence as a result of mean air temperature dropping and pre- cipitation decreasing, which would also influence the result. It can be concluded that the alpine meadow has the carbon uptake potential, but how big the carbon sink is deserves further research.

The averaged apparent quantum yield of the alpine meadow ecosystem from August to September was 0.020 3 μmol $CO_2$·$\mu mol^{-1}$ PAR. Whereas Andrew et al. (2001) observed $\alpha$ of a tall grass prairie was 0.034 8 μmol $CO_2$·$\mu mol^{-1}$ PAR with enough precipitation during peak growth. When moisture stress conditions prevailed, $\alpha$ dropped to 0.023 4 μmol $CO_2$·$\mu mol^{-1}$ PAR. When plant was in the senescence period, $\alpha$ was only 0.011 4 μmol $CO_2$·$\mu mol^{-1}$ PAR. Ruimy et al. (1995) suggested an upper limit of 0.044 1 μmol $CO_2$·$\mu mol^{-1}$ PAR for $C_3$ and $C_4$ grasslands during peak growth, which agreed with the value observed in this study. Xu et al. (1988) thought that the drop of $CO_2$ partial pressure with the increase of altitude might be the primary reason that caused the decrease of photosynthesis and $\alpha$ for the same kind of species. The altitude of Damxung was 4 300 m, so high altitude and low $CO_2$ partial pressure would be likely to explain the lowness of $\alpha$ on the Tibetan Plateau alpine meadow ecosystem. Furthermore, the perishing of plants in September might also had some influences on $\alpha$.

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