



Seasonal and inter-annual variations in CO₂ fluxes over 10 years in an alpine shrubland on the Qinghai-Tibetan Plateau, China



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ABSTRACT

Alpine ecosystems play an important role in the global carbon cycle, yet the long-term response of *in situ* ground-based observations of carbon fluxes to climate change remains not fully understood. Here, we analyzed the continuous net ecosystem CO₂ exchange (NEE) measured with the eddy covariance technique over an alpine *Potentilla fruticosa* shrubland on the northeastern Qinghai-Tibetan Plateau from 2003 to 2012. The shrubland acted as a net CO₂ sink with a negative NEE ($-74.4 \pm 12.7 \text{ g C m}^{-2} \text{ year}^{-1}$, Mean \pm S.E.). The mean annual gross primary productivity (GPP) and annual ecosystem respiration (RES) were 511.8 ± 11.3 and $437.4 \pm 17.8 \text{ g C m}^{-2} \text{ year}^{-1}$, respectively. The classification and regression trees (CART) analysis showed that aggregated growing season degree days (GDD) was the predominant determinant on variations in monthly NEE and monthly GPP, including its effect on leaf area index (LAI, satellite-retrieved data). However, variations in monthly RES were determined much more strongly by LAI. Non-growing season soil temperature (T_s) and growing season length (GSL) accounted for 59% and 42% of variations in annual GPP and annual NEE, respectively. Growing season soil water content (SWC) exerted a positive linear influence on variations in annual RES ($r^2 = 0.40$, $p = 0.03$). The thermal conditions and soil water status during the onset of the growing season are crucial for inter-annual variations of carbon fluxes. Our results suggested that an extended growing season and warmer non-growing season would enhance carbon assimilation capacity in the alpine shrubland.

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1. Introduction

The cold and relatively humid climate in alpine ecosystems may facilitate soil carbon storage (Yang et al., 2010; Marcolla et al., 2011) and these ecosystems play an important role in the global carbon cycle with large proportion of labile carbon (Budge et al., 2011). Alpine ecosystems are also considered to be very sensitive to ongoing global warming (Wookey et al., 2009) and are coupled to the local climate system through various feedbacks (Piao et al., 2008; Barichivich et al., 2013; Ueyama et al., 2013; Shen et al., 2015a). Recent short-term observational studies have reported that the role of alpine ecosystems fluctuates between carbon sink, car-

bon neutral and carbon source, with large interannual variability and confounding abiotic and biotic effects (Kato et al., 2006; Li et al., 2006; Zhao et al., 2006; Reverter et al., 2010). However, their long-term carbon balance is still unclear because of non-linear metabolism processes and ecosystem plasticity responses to climate variability (Ma et al., 2007; Wohlfahrt et al., 2008a; Marcolla et al., 2011). Informed knowledge on the inter-annual variations in ground-based carbon fluxes for such ecosystems would improve our predictions of their potential responses to climate change (Piao et al., 2008, 2012).

The site-level temporal variations in a temperature-limited ecosystem carbon balance are believed to be regulated by thermal conditions (Kato et al., 2006; Zhao et al., 2006), water status (Yu et al., 2003; Marcolla et al., 2011), and vegetation phenology (Griffis et al., 2000; Ma et al., 2007; Shen et al., 2011), especially growing-season length (GSL) and aggregated growing degree days (GDD) (Groendahl et al., 2007; Barichivich et al., 2013; Ueyama

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et al., 2013), rather than some other single factors (Wohlfahrt et al., 2008a; Marcolla et al., 2011) or vegetation types (Kato et al., 2006; Street et al., 2007). In addition, pre-growing-season precipitation and temperature also played an important role in nutrient supply (Lafleur and Humphreys, 2007), vegetation phenology (Shen et al., 2015b), and vegetation photosynthetic performance during the following growing season (Griffis et al., 2000; Li et al., 2014). However, previous analyses of carbon balance have been limited to short-term observations (Kato et al., 2006; Zhao et al., 2006) or satellite measurements (Yu et al., 2003). Therefore, research based on multi-year *in situ* measurements could further our understanding of CO₂ fluxes in alpine ecosystems (Griffis et al., 2000; Marcolla et al., 2011).

Observational and manipulated studies in alpine regions have shown that warming advances the snow-melt date and green-up date, prolongs the growing season (Groendahl et al., 2007; Zhang et al., 2013), and promotes CO₂ assimilation and vegetation production in alpine ecosystems (Street et al., 2007; Li et al., 2015; Shen et al., 2015a). On the other hand, climate warming could enhance micro-organism activity and/or labile substrate availability, thereby stimulating soil C emissions, and depressing plant photosynthesis rate by limiting the soil water supply (Piao et al., 2008; Reverter et al., 2010; Chen et al., 2016). The balance between these opposing biological mechanisms determines how alpine ecosystems affect the climate system, but little observational evidence exists to assess their effects. The related long-term *in situ* ground-based flux data are useful (Griffis et al., 2000; Marcolla et al., 2011), while few data on alpine ecosystems over the Qinghai-Tibetan Plateau (QTP) are available (Yang et al., 2010). The QTP has experienced substantial warming in recent decades (Piao et al., 2011; Shen et al., 2015a) and knowledge of the long-term ecosystem carbon balance response of alpine shrubland remains limited (Li et al., 2006; Zhao et al., 2006). It is possible that a warmth-induced expansion in the range of alpine shrubland could cause changes in soil carbon storage and regional CO₂ budgets (Sturm et al., 2005). Therefore, in this study we present 10 years of continuous flux data, obtained using the eddy covariance (EC) technique in alpine shrubland on the northeastern QTP, from January 2003 to December 2012. The objectives of this study were: (1) to quantify the seasonal and inter-annual variability of net ecosystem CO₂ exchange (NEE), ecosystem respiration (RES), and gross primary production (GPP); and (2) to clarify the major environmental factors controlling the variations in seasonal and annual CO₂ fluxes. We hypothesized that seasonal CO₂ fluxes would be controlled by thermal conditions while inter-annual CO₂ fluxes would be regulated by growing season length (Kato et al., 2006; Ueyama et al., 2013).

2. Materials and methods

2.1. Site description

The study site is located in an alpine *Potentilla fruticosa* shrubland, near the Haibei National Field Research Station for Alpine Grassland, Qinghai (37°36'N, 101°19'E, 3200 m a.s.l.), on the northeastern QTP in a region of alpine permafrost. This region has a plateau continental climate with evident cold-dry (from November to following April) and warm-wet (from May to October) seasons. Based on meteorological data from 1980 to 2010, the mean annual air temperature (T_a) is about -1.0°C ; the warmest monthly T_a is approximately 10°C in July and the coldest is approximately -15°C in January. Mean annual precipitation is approximately 580 mm, of which 80% is concentrated in the warm-wet season (Li et al., 2006; Zhao et al., 2006). The depth of permafrost in the studied region

is about 6 m and overall is in a state of degradation (Wang et al., 2015).

The vegetation canopy of the alpine *Potentilla fruticosa* shrubland ecosystem consists of two layers with shrubs and grasses. The primary layer is mainly formed by *Potentilla fruticosa* shrubs. The canopy height and shrub coverage is approximately 30–60 cm and 60%–80%, respectively. The secondary layer of grass is composed of dominant species *Kobresia humilis*, *Stipa aliena*, *Poa orinosa*, *Helictotrichon tibeticum*, *Elymus nutans*, *Aster flaccidus*, *Polygonum viviparum*, and *Leontopodium nanum*, with approximately 8–16 cm vegetation canopy height and 70%–80% plant coverage fraction during peak growing season (July and August). Soil is a clay loam and classified as Mollic Gric Cambisols, featuring high levels of organic matter and low levels of available nutrients (soil organic matters up to 106.7% and available nitrogen 0.039% in the 0–10 cm soil layer: personal observational data). According to the phenology of most of flora in alpine shrublands, the growing season (from a flux data processing perspective) is defined as April 20–October 10 (Zhao et al., 2006). Meanwhile, based on a plant-centric year rather than the calendar year (Robinson et al., 2013; Li et al., 2015), last October 11–April 19 is classified as the non-growing season of the current year. However, the non-growing season in 2003 only covered January 1–April 19 due to a lack of data. The study sites are lightly (3.75 sheep ha^{-1}) grazed by yak and Tibetan sheep during the non-growing season.

2.2. Flux and climatic factors measurements

An open-path eddy covariance (EC) system was installed in the center of a fairly flat (slope $< 1\%$), open (5 km minimum distance from mountain base) and homogenous vegetated area (average shrub coverage 70%) covering about 12 km². The EC system consisted of a three-dimensional ultrasonic anemometer (CSAT3, Campbell, USA) and an open-path infrared CO₂/H₂O gas analyzer (LI-7500, LI-Cor, USA), both fixed at a height of 2.2 m above the ground. The raw data (wind speed, sonic virtual temperature, and CO₂ and H₂O concentrations) were sampled at 10 Hz. The 30-min fluxes were calculated, adjusted by WPL (Webb, Pearman and Leuning) density correlation, and logged with a data logger (CR5000, Campbell, USA). The CO₂/H₂O gas analyzer was calibrated during the end of each April. Zero points, CO₂ span and water span were established using dry N₂ gas (99.999%, National Institute of Metrology, China), standard CO₂ gas (450 mg/kg, National Institute of Metrology, China) and a dew-point generator (LI-610, LI-Cor, USA), respectively.

The routine meteorological factors were measured synchronously. Air temperature (T_a) and relative humidity were monitored by a temperature and humidity probe (HMP45C, Vaisala, Finland) at both 1.5 m and 2.5 m, and were used to estimate vapor pressure deficit (VPD). Wind speed and direction were sampled by a cup anemometer (034A-L, RM Young, USA) and a dogvane (014A, RM Young, USA) at a height of 2.5 m. Shrub canopy temperature was measured via infrared thermocouple sensor (IRTS-P, Apogee, UT) at 1.5 m. Radiation (including downward long-wave and short-wave, upward long-wave and short-wave radiation) and photosynthetic photon flux density (PPFD) were monitored with 4 radiometers (CM11, Kipp & Zonen, Netherlands) and a quantum sensor (LI-190SB, LI-Cor, USA), respectively, at 1.5 m height. Precipitation was collected with a rain gauge (52203, RM Young, USA) installed at 0.5 m above ground level. Using thermocouple probes (105T, Campbell, USA), soil temperature was measured at depths of 5, 10, 20, 40, and 80 cm. Volumetric soil water content was monitored by time-domain reflectometry (CS616, Campbell, USA) at 10 and 20 cm depths. The soil heat flux was measured with heat plates (HFT-3, Campbell, USA) buried at three different points at 1 cm below the soil surface. Thirty-minute averages of meteorological

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