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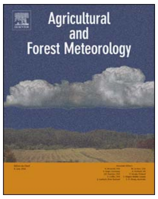

Research Paper

Permafrost affects carbon exchange and its response to experimental warming on the northern Qinghai-Tibetan Plateau

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ABSTRACT

Warming will increase the carbon flux in permafrost regions, and this process may be linked with permafrost via soil hydrothermal conditions. We measured the ecosystem respiration rates (ERRs) of alpine wet meadow, alpine meadow, and alpine steppe monthly during the growing seasons in 2014 and 2016 on the northern Qinghai-Tibetan Plateau (QTP). The results showed that the temperature sensitivity (Q_{10}) values of the ERR in alpine wet meadow and alpine meadow were higher than those in alpine steppe. The permafrost table is significantly correlated with soil temperature and moisture, thus, affects the ERRs in these ecosystems. After a 2-year warming experiment using open-top chambers (OTCs), the change rates of ERR (35.0–35.2%) were higher than those of gross primary production (GPP) (27.5–30.3%), while the absolute changes of GPP were greater than ERR. The average daytime NEE decreased by 16.5% to 21.3%, indicating more carbon assimilation was enhanced by the experimental warming. Our results show that ecosystem respiration rates in meadow and wet meadow are more sensitive to temperature increasing than those in steppe. The meadow and wet meadow ecosystems in permafrost regions on the northern QTP will assimilate more carbon than steppe in the growing seasons under climate warming scenarios.

1. Introduction

Northern permafrost regions contain abundant soil carbon—approximately double the amount of carbon in the atmosphere (Hugelius et al., 2014). Carbon emissions in these permafrost regions play an important role in driving global warming (Sierra et al., 2015; Zimov et al., 2006). Since temperature is one of the most important factors associated with ecosystem-level CO_2 emissions (Schaefer et al., 2009), climate warming will increase the CO_2 efflux of the ecosystem (Lu et al., 2013; Natali et al., 2012).

Numerous efforts have been made to understand the possible changes associated with ecosystem respiration in permafrost regions in the future. Most of those studies targeted two main questions: 1) what is the pattern of ecosystem CO_2 efflux in permafrost regions (Natali et al., 2012; Schuur et al., 2015; Schuur et al., 2009)? and 2) what is the response of ecosystem CO_2 efflux to warming (Biasi et al., 2008; Oberbauer et al., 2007; Peng et al., 2015)? These studies mainly focused on the processes related to CO_2 emissions, such as changes in the vegetation biomass and soil organic matter decomposition. Moreover, most of these studies selected a representative ecosystem, such as meadow, to investigate the CO_2 flux patterns under natural or warming conditions. Under natural conditions, permafrost degradation generally reflects an increase in the active layer thickness (Osterkamp, 2007) and results in ecosystem degradation (Wang et al., 2006). Thus, understanding the patterns of CO_2 efflux under different active layer thicknesses and in different ecosystems is a fundamental step in the evaluation of soil CO_2 emissions in the future.

The high-altitude alpine permafrost on the Qinghai-Tibetan Plateau (QTP), which accounts for approximately 75% of the global high-altitude permafrost area (Ran et al., 2012), has attracted increased attention in recent decades because its heterogeneous environments are vulnerable to climate change (Zhao et al., 2010). In recent decades, many studies have been conducted regarding the CO_2 exchanges of ecosystems on the QTP. It has been suggested that the alpine ecosystem acts as a carbon sink (Fawei et al., 2008; Kato et al., 2004). In the alpine meadows of both non-permafrost (Lin et al., 2011) and permafrost

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regions (Qin et al., 2015), the results of warming experiments showed that temperature had a strong effect on soil respiration, and warming promoted respiration in the alpine ecosystem. In non-permafrost regions, the contributions of different ecosystem components and their different responses to experimental warming were analyzed (Chen et al., 2016a). Although it has been demonstrated that warming can enhance the soil respiration, little is known about the changes of ecosystem carbon balance since the increased ERR could be offset by the plant growth in growing seasons in permafrost regions (Schuur et al., 2015).

The heterogeneities in alpine permafrost regions result in different vegetation types with various soil hydrothermal characteristics (Hoffmann et al., 2014), and the active layer on the QTP can range from 1 to 5 m or deeper (Hu et al., 2014; Wu et al., 2016). The permafrost region on the QTP has typical vegetation types of alpine steppe, alpine wet meadow, and alpine meadow with various soil temperatures and moistures (Genxu et al., 2002). The latter two ecosystems are rich in carbon pools and store approximately 64.9% of the total SOC in the permafrost regions of the QTP. In addition, the active layers in these two vegetation types are typically shallow (Hu et al., 2014; Mu et al., 2016b). Therefore, increasing temperatures likely have strong effects on the permafrost and consequently affect ecosystem respiration.

Based on the above information, it is extremely important to study the ecosystem respiration rates (ERRs) of different vegetation types and link their changes with the active layer thickness. Additionally, the carbon exchange response in alpine wet meadow and alpine meadow areas must be clarified. Specifically, are there differences in ERR among vegetation types in alpine permafrost regions? What effects do hydrothermal conditions have on alpine ecosystem respiration? How are CO_2 releases and exchanges (in the form of ERR and NEE) affected by rising temperatures in different ecosystem types? To address these questions, the ERRs in different ecosystems in the permafrost regions (Supplementary Fig. 1, Supplementary Table 1) on the northern QTP were measured *in situ* during the growing season from 2014 to 2016. The effects of rising temperature on ERR and NEE in the alpine meadow and alpine wet ecosystems were studied using OTCs. These results can improve our understanding of the responses of alpine permafrost ecosystems to climate changes, as well as provide important data for regional and even global development and validation of permafrost carbon cycle models.

2. Materials and methods

2.1. Study area

The study area was located in the upper reaches of the Heihe River Basin on the northern QTP (Supplementary Fig. 1). The annual air temperature of the basin is approximately 1 °C (Peng et al., 2013), and the mean annual evaporation is approximately 1080 mm (Mu et al., 2014). There are three typical vegetation types: alpine wet meadow, alpine meadow, and alpine steppe.

In this study, ten monitoring sites cover three vegetation ecosystems with different permafrost conditions (Supplementary Table 1). The sampling sites are located on both eastern (EBO sites) and western tributaries (YNG) of the Heihe River (Supplementary Fig. 1). The SFG1, SFG2, and SFG3 sites are characterized by alpine steppe vegetation and are located at the boundary between permafrost areas and seasonal frozen ground.

2.2. Experimental design

Ecosystem respiration in the three vegetation types was monitored at ten sites in June, July, August, and September from 2014 to 2016. For the above ground biomass (ABG) measurement, each site contained a 50 × 50 m quadrat with one monitoring point every 10 m. The ABG of each site was measured by harvesting the vegetation approximately once each month during the growing season. In the plots with warming experiments, the ABG was calculated based on the height of the grass using a linear regression, which was established from the control plots. In our study, the linear regression for the biomass height was as follows:

$$y = 0.008x - 0.004 \tag{1}$$

where y is the ABG (g cm^{-2}) and x is the mean height of the grass (cm). This equation was obtained using a linear regression with 12 samples in September 2016. The R^2 value for this equation was 0.86 at $p < 0.01$. Then, this equation was used to calculate the ABG values of the warming plots in September 2016.

Six open-top chambers (OTCs) were randomly established in alpine wet meadow (EBO #A) and alpine meadow (EBO #B and PT5) areas. To exclude differences in vegetation and micro-relief, areas were relatively flat, and no areas with patchy vegetation distributions were selected. We fenced 20 × 20 m blocks in 2012 to exclude ungulate grazers. Within these blocks, we applied a paired design with replicated three times. Six 3 m × 3 m plots were arranged in a 2 × 3 matrix. The distance between the adjacent plots was 2 m. The OTC installations were completed in May 2013. In addition, the CO_2 fluxes in the OTC installation areas were measured, and the results were compared to those from control plots to ensure that the conditions were similar (the differences among the plots were less than 10% in July 2012) prior to the warming experiment. The OTCs were hexagonal open-top greenhouses made of Lexan plastic. The trapezoidal walls of the OTCs were angled inward at $\sim 60^\circ$ and 30 cm tall, encompassing a total area of 1 m^2. The distance between each OTC was approximately 5 m, which ensured that all the plots had similar slopes and aspects.

To quantify the environmental factors affected by the OTCs, soil hydrothermal recording systems were established in the control and warming plots during OTC construction. Soil temperature (at 10 cm depth) and moisture (at 20 cm depth) were measured using soil temperature and moisture sensors (CS616 and 109-L, Campbell, USA), with data logged every 30 min.

2.3. Ecosystem CO_2 emissions

The CO_2 emission rate was monitored using a dark chamber to determine the ERR. The NEE in the warming and control plots was measured since the growing season in 2015.

All the ERR and NEE were measured three cycles and then produced mean values for each plot. ERRs were measured using the LI-8100 Automated Soil CO_2 Flux System (Li-Cor Inc., Lincoln, NE, USA). To measure the ecosystem CO_2 flux, PVC collars with a diameter of 20 cm were permanently inserted approximately 3.0 cm into the ground at each monitoring point in early May 2014. The ecosystem CO_2 fluxes on the QTP between 08:30 and 11:30 a.m. on clear days were considered representative of a one-day average flux according to the measurements of diurnal gas flux variation (Lu et al., 2013). Our measurements also showed that the ecosystem emissions at 10:00 a.m. were similar to the mean diurnal values from 8:00 to 20:00 in the three vegetation types (Supplementary Fig. 2). Therefore, the CO_2 flux was measured randomly from 9:00 to 11:00 a.m., and a measurement in a control plot was always followed by a measurement in the adjacent warming plot. At each site, the system was run in five-minute segments. Ecosystem CO_2 emissions in each chamber were measured continuously for three cycles, and the three measurements were averaged to produce a mean flux value.

The NEE was measured immediately after the measurement of ERR at each site. We used a light sensor connected with EGM-4 (PP systems, Amesbury, MA, USA) to monitor the solar radiation to ensure the NEE was measured under similar radiations during a round of field observation. When the solar radiation decreased rapidly due to sudden appearance of clouds, the measurement would be break off until the radiation recovered. For the measurement of NEE, acrylic glass frames