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Plant production, and carbon and nitrogen source pools, are strongly intensified by experimental warming in alpine ecosystems in the Qinghai-Tibet Plateau

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ABSTRACT

The aim of this study was to assess initial effects of warming on the nutrient pools of carbon and nitrogen of two most widespread ecosystem types, swamp meadow and alpine meadow, in the Qinghai-Tibet Plateau, China. The temperature of the air and upper-soil layer was passively increased using open-top chambers (OTCs) with two different temperature elevations. We analyzed air and soil temperature, soil moisture, biomass, microbial biomass, and nutrient dynamics after 2 years of warming. The use of OTCs clearly raised temperature and decreased soil moisture. The aboveground plant and root biomass increased in all OTCs in two meadows. A small temperature increase in OTCs resulted in swamp meadow acting as a net carbon sink and alpine meadow as a net source, and further warming intensified this processes, at least in a short term. On balance, the alpine ecosystems in the Fenghuoshan region acted as a carbon source.

1. Introduction

Global warming has been causing worldwide ecosystem changes. Within the last century, the mean global surface temperature has increased by 0.67 ± 0.2 °C. For the 21st century, an increase in mean global temperature between 1.8 and 4.0 °C over the next 100 years is predicted (IPCC, 2007). Arctic and alpine regions are likely to be particularly affected by the climate warming because observed temperature increases in these areas are higher than anywhere else (IPCC, 2007). Moreover, high latitude/altitude ecosystems might be more sensitive because plant growth is often accustomed to low temperature environment (Körner, 1998), and soil respiration is more sensitive to warming at lower temperature (Kirschbaum, 1995). The Qinghai-Tibet Plateau located in the central part of the troposphere in the mid-latitude westerlies, is regarded as the Earth's third pole and the highest unique territorial unit in the world. Thus, its ecosystems and natural environment are inherently fragile and instable, making them especially vulnerable to global warming. In fact, the air temperature in the Source Region of the Yangtze River has increased 0.06 °C every 10 years for the past 40 years (Ecology and Environment of Three Rivers' Source Region Compilation Committee, 2002).

Moreover, the high latitude/altitude ecosystems store the greatest fraction of carbon stocks in soils (IPCC, 2007). Compared to soils from temperate ecosystems, cold soils are found to comprise more labile soil organic matter (SOM) because cold soil contains slower decomposition and humification processes (Jenny, 1926; Sjögersten et al., 2003). The carbon content in Qinghai-Tibet Plateau soil was significantly higher than that in soils in other areas (Fan et al., 2003). Changes in climate are predicted to stimulate the release of a substantial portion of this reservoir by increasing soil respiration, thereby turning alpine ecosystems from a net sink to a net source of atmospheric CO_2 (Biasi et al., 2008; Knorr et al., 2005; Oechel et al., 1993; Tarnocai, 1999). The stimulation of soil respiration by increased temperatures, however, could be counterbalanced by declining soil moisture (Saleska et al., 1999), changing carbon inputs from plants (Oberbauer et al., 2007), declining resource availability, or an 'acclimatization' through physiologically adapting microbial communities (Luo et al., 2001; Melillo et al., 2002). Moreover, the response of soil CO_2 effluxes to rising temperature also depends on how plants and their C allocation to belowground sinks respond to warming (Schindlbacher et al., 2009). Winter biological processes are contributing to return the arctic ecosystems to a carbon sink

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(Turunen et al., 2004; Welker et al., 2004). For example, due to the snow-holding capacity of shrubs, the insulating properties of snow, a soil layer that has a high water content because it overlies nearly impermeable permafrost, and hardy microbes that can maintain metabolic activity at temperatures of −6 °C or even lower, deciduous shrubs have been shown to profit from warmer conditions, as demonstrated in several studies from moist tussock tundra (Sturm et al., 2005; Weintraub and Schimel, 2005).

Low temperature and short growing seasons are considered to be among the most important limiting factors for the performance of alpine plants (Gugerli and Bauert, 2001; Wang et al., 2001). Longer growing season and temperature enhancement may reinforce photosynthetic capacity and growth rates of the alpine plants (direct temperature effect). Although the effects of rising temperature on single process have been studied extensively, a comprehensive understanding of the response of entire ecosystem to climate warming still remains unexplored (Rustad et al., 2001). Many studies on the effect of experimental warming on C dynamics between ecosystems and the atmosphere were carried out in boreal forests (Niinistö et al., 2004; Bronson et al., 2008), at high latitudes (Oechel et al., 1993; Oberbauer et al., 2007), and in lichen-rich dwarf shrub tundra (Biasi et al., 2008). The results of these studies were ecosystem-dependent responses in C fluxes with initial C losses in dry tundra and boreal forests, but dampened effects under anoxic conditions. The only study conducted at high altitude was in a dry alpine meadow in Colorado, with results showing that soil heating had stronger indirect (rather than direct) effects on soil C cycling by changing plant species composition and inducing moisture limitations for soil respiration (Saleska et al., 1999). To our knowledge, there is a lack of studies on experimental warming at high altitude, including in alpine meadow and swamp meadow, commonly found on the *Kobresia humilis* meadow of the Qinghai-Tibet Plateau (Zhou et al., 2000; Zhao et al., 2006). There are even less accessible studies on the warming effects on plant–soil nutrient dynamics.

In order to understand the effects of global warming on biogeochemical circles of the alpine ecosystem on the Qinghai-Tibet Plateau, our study seeks to examine the effects of warming on carbon and nitrogen contents in two alpine ecosystems with undisturbed soils and thick organic layers using open-top chambers (OTCs). The swamp meadow is typical of more favorable locations with abundant soil nutrients and water regimes; whereas the alpine meadow has poor soil nutrients and low soil water content. Since the two meadows are characterized by different thermal conditions, it is expected that they will have different responses to warming. This experiment tests the following hypotheses: (1) the plant growth in high altitude and cold-climate ecosystems is mainly limited by low temperature, vegetative production of two alpine meadows will increase under a warmer condition; (2) since the two meadows are characterized by different thermal and soil conditions, nutrient dynamics in swamp meadow ecosystem is expected to contrast with alpine meadow under warming conditions.

2. Materials and methods

2.1. Study site

The experiment was undertaken in alpine meadow and swamp meadow, which represent the most common (70% in area) vegetation types in the Fenghuoshan region (34°43′43″N, 92°53′34″E) in the hinterland of Qinghai-Tibet Plateau, China. It represents an area of 112.5 km^2; with an altitude of around 4600–4800 m. The climate is cold and dry. The mean annual temperature is −5.3 °C, and the mean annual precipitation is 269.7 mm, 80% of which falls during the growing season (from May to September). The study site is underlain by permafrost. Alpine meadow and swamp meadow are the two most typical vegetations. Alpine meadow ecosystem consists mainly of cold meso-perennial herbs grow in conditions where a moderate amount of water is available. This ecosystem's primary vegetation is consisted of *Kobresia pygmaea* (C. B. Clarke), *K. humilis* (C. A. Meyer ex Trautvetter) Sergievskaja, *Kobresia capillifolia* (Decaisne) (C. B. Clarke), *Kobresia myosuroides* (Villars) Foiri, *Kobresia graminifolia* (C. B. Clarke), *Carex atrofusca Schkuhr* subsp. (minor (Boott) T. Koyama), and *Carex scabriostris* (Kukenthal). Swamp meadow populated by hardy perennial hygrophilous or hygro-mesophilic herbs under waterlogged or moist soil conditions, mainly occurs in patches or strips in the mountains, wide-valley terraces and rounded hills, which represent a small portion of the study region. These areas are dominated by *Kobresia tibetica* Maximowicz, *Stipa aliena* Keng and *Festuca* spp. (Zhou, 2001).

2.2. Experimental design

In our experiment, we followed the methods of the International Tundra Experiment and used open-top chambers (OTC) as a passive warming device to generate an artificially warmed environment (Marion et al., 1997). The experiment was conducted with a comparative trial design in two meadows, both with vegetation coverage of above 70%. In July 2008, we installed 12 OTCs in total: three pairs of two heights in each of alpine meadow and swamp meadow. The OTCs, which were hexagonal in shape with 60° inwardly inclined sides, are made of 6 mm-thick, translucent synthetic glass, this material has high solar transmittance in visible wavelengths (about 90%) and low transmittance in the infrared (heat) range (<5%) (Marion et al., 1997) (Fig. 1). All the top opening of OTCs was 60 cm, OTCs of 40 cm in height covers an area of 0.98 m^2, and OTCs of 80 cm height covers an area of 2.01 m^2. These OTCs were in use throughout the entire length of the experiment. For comparisons of the warming effect of OTCs, the air temperature 20 cm above the soil surface was measured in OTCs and in the control plots in each meadow. Measurements were taken at 30-min intervals during the growing seasons of the experimental period (2008–2009) by automatic recording thermometers and thermistor sensors (FDR) (CS616, USA). The results were auto-transmitted to recorders (Campbell AR5, Avalon, USA). A control plots (50 × 50 cm, 0.25 m^2) were also established in the vicinity of each height of OTC, and four control plots were set up in total. With the exception of light exposure, the selected plots in the same meadow were seemed to have similar microhabitat characteristics. The distance between OTCs and adjacent control plots was between 3 and 4 m, and the distance between the replicate blocks ranged from

Fig. 1. Open-top chamber (OTC1) and associated control plot (right) in an alpine site.