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The transient shift of driving environmental factors of carbon dioxide and methane fluxes in Tibetan peatlands before and after hydrological restoration

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ABSTRACT

Peatlands on the Tibetan Plateau play crucial roles in regional carbon cycling but faced serious degradation in recent decades, and hydrological restoration is being conducted to regain their ecosystem function. However, how restoration affects the environmental controls on carbon processes of these unique ecosystems remains unclear, and the role of vegetation community in regulating carbon processes in response to the restoration is unknown. A long dam was built at the outlet of a large shallow lake on the plateau in order to evaluate the effects of hydrological restoration on the carbon sequestration of the world's largest alpine peatlands. The carbon dioxide (CO_2) and methane (CH_4) fluxes from three widely distributed peatland communities, i.e., *Kobresia pusilla*, *Carex enervis*, and *Carex muliensis* commuities, were investigated immediately before and after restoration. The water table rising as a consequence of restoration, at least temporarily, decreased the carbon consumption rate (plant respiration plus soil decomposition) for each unit of carbon fixation by plants, which is community dependent. However, a positive relationship between temperature sensitivity of ecosystem respiration (R_{eco}) and optimal water table for respiration implies a positive feedback between water table rising and warming on R_{eco}. Meanwhile, the dominant factor explaining the variance of R_{eco} shifted from soil temperature (explained 56%) to water table (explained 68%) after restoration. Water table rising enhanced the CH_4 emissions by 3–12 times, with significantly different changes in CH_4 flux over a standard variation in water table level among the communities. Temperature was excluded while only water table and vegetation type were included in the model to predict CH_4 fluxes after restoration in contrast to before. We argue that the shift of driving environmental factors and the role of vegetation community are essential in evaluating the effects of hydrological restoration on carbon cycling of Plateau peatlands, particularly during the transitional period.

1. Introduction

Peatlands globally store 612 Gt carbon (C) as peat (Yu, 2011), and just boreal peatlands can sequester approximately 76 Tg C y^{-1} (Vasander and Kettunen, 2006). Peatlands also act as a net source of atmospheric methane (CH_4) (Mitsch et al., 2013; Smith et al., 2004). The C sink function and CH_4 emission of peatlands, however, are being altered under peatland degradation (Fenner and Freeman, 2011; Lupascu et al., 2014; Natali et al., 2014) as a consequence of the loss of physical protection (Davidson and Janssens, 2006) or change in plant community (Ward et al., 2013). The stability of the historical C accumulated by hundreds or thousands of years is under threat (Dise, 2009). Whether peatlands will continue their function as net C sinks depends on the impact of environmental and anthropogenic forces on the C balance of these ecosystems (Moore et al., 2002; Page et al., 2002).

The hydrological restoration on the degraded peatlands has been forecasted to regain the ecosystem C sink function (Page et al., 2009; Zedler, 2000), since peatlands function as a net sink for atmospheric C dioxide (CO_2), mainly due to slow decomposition in cold, largely waterlogged soils (Gorham, 1991; Ise et al., 2008). A lot is known about

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the mechanisms behind C cycling in peatlands in response to water table changes, but the issue is the overall change in magnitude of the mechanism changes in response to variations on water table, and there might be different responses between ecosystems. Further, a lot of uncertainties exist over the magnitude of changes in CO_2 and CH_4 exchanges caused by variations in the water table. For instance, restoration of peat hydrology may not instantly affect the reduction of peat CO_2 flux rates in a tropical forest (Jauhiainen et al., 2008); Water table drawdown in peatlands can have either negative (Minkkinen and Laine, 1998; Weltzin et al., 2000) or positive (Freeman et al., 1996; Waddington et al., 2001) feedbacks to CO_2 fluxes, depending on site and vegetation characteristics. Furthermore, hydrological restoration could also promote the emission of CH_4 (Chen et al., 2009; Turetsky et al., 2008), which has 34 times greater global warming potential (GWP) than CO_2 on a 100-year timescale (IPCC, 2013). Therefore, it would be critical to understand the mechanisms underlying the CO_2 and CH_4 fluxes immediately before and after restoration to get a full picture of the restoration benefit of C sequestration or a climate cooling effect.

Meanwhile, vegetation plays an important role in regulating ecosystem C processes under environmental change (Bardgett et al., 2013; De Deyn et al., 2008; Petrie et al., 2015). The vegetation composition or plant functional type in peatlands is believed to regulate the response of the greenhouse gas (GHG) fluxes to warming (Ward et al., 2013) or drought (Kuiper et al., 2014). Therefore, understanding the role of the vegetation type in regulating the response of ecosystem C processes to the water table change, and the difference in environmental factors driving CO_2 and CH_4 fluxes among vegetation types would be crucial for evaluating the effectiveness of restoration in a catchment-scale.

Peatlands on the Tibetan Plateau, covering an area of about 5091 km^2 (Chen et al., 2014), are the world's largest high altitude peatlands (Chai et al., 1965). Drainage due to land-use change is one of the main driving factors accelerating C loss from these ecosystems (Luan et al., 2014). Around 1050 km of channel was dug between 1965 to the 1990s to meet the increasing demand for grazing land (Sun, 1998), which resulted in more than 905 km^2 of wetland loss (Bai et al., 2009). Peatlands on the Tibetan Plateau have no moss coverage, and are mainly composed of different sedge communities depending on the water regimes. To restore the shrinking alpine peatland ecosystems, which is the habitat of some unique alpine wetland animals (e.g., *Grus nigricollis*), a long dam was built at the outlet of the second largest shallow lake (mean standing water depth: 0.36 m) on the Zoige region in order to raise the water table level of the lakeside area, providing us an opportunity to assess the effects of hydrological restoration on C cycling of peatlands in the Tibetan Plateau. The CO_2 and CH_4 fluxes of the three most widely distributed peatland vegetation communities (i.e., *Kobresia pusilla*, *Carex enervis*, and *Carex muliensis* dominant sites) were investigated immediately before and after hydrological restoration. We aimed to (1) evaluate the immediate effect of hydrologic restoration on peatlands' CO_2 and CH_4 fluxes and their relationships with environmental factors; and to (2) address the role of vegetation community in regulating CO_2 and CH_4 fluxes in response to the water table manipulation. The findings of this study would be considered in the context of more general literature discussing the effects of catchment-scale restoration strategies on peatland ecosystems.

2. Material and methods

2.1. Site description and experimental design

The study sites were located at the Zoige National Wetland Reserve (33°56′N, 102°52′E, 3430 m a.s.l.), east of the Tibetan Plateau (Fig. 1a). The area is characterized by a cold temperate continental monsoon climate. The annual mean temperature is about 0.7–1.1 °C, with the highest monthly mean being 10.8 °C in July and the lowest being −10.6 °C in January. The annual mean precipitation is 656.8 mm, with 86% of this occurring between April and October.

The surface area of Hua lake declined from 386 ha in the 1970s to 215 ha in 2009, consequently resulting in the shrinkage and degradation of the peatlands in its catchment area and the creation of the new wetlands in the previous lake areas. In 2010, a hydrological restoration project was conducted in the Hua lake area in order to restore the shrinking peatland. The project was implemented by constructing a long dam across the outlet of the lake (Fig. 1 b), starting November 10, 2010 and finishing May 20, 2011. The dam size is 4 m in width, 1 m in height, and 1740 m in length. The water table level of Hua lake was raised approximately 50 cm due to the dam construction, and the surface area of the lake increased from 215 ha (2009) to 650 ha (2012).

Three types of vegetation, which represent dominant vegetation types in the region, were chosen. They were *Kobresia pusilla* dominated sites, the most widely distributed peatland vegetation type in this area, and it accounted for more than 50% of the peatland area; *Carex enervis* dominated sites, the most typical lakerine vegetation type, and less frequently flooded lakerine area; and *Carex muliensis* dominated sites, the most typical lakerine vegetation type, and frequently flooded lakerine area; the water table levels were averaged 1.01 m, 0.36 m, and 0.07 m, respectively, beneath ground before restoration. The sites were mainly located more than 1 km up and away from the dam to avoid the fast rising of the water table after the dam construction (see Fig. 1b). The dam started to work at the end of 2011. For each vegetation type, six subplots (10 m × 10 m), over 10 m apart from each other, were established in early May 2011. Three subplots of the sites dominated by *Carex muliensis* were inaccessible during 2012 due to the deep standing water and failure of the board walk; thus, there were three replicates for this vegetation type. For plot attributes refer to Table S1.

2.2. Measurements of CO_2, CH_4 fluxes and environmental variables

The stainless steel bases (50 cm × 50 cm) were permanently inserted into the soil to a depth of 10 cm in each subplot, three weeks before the start of our measurements. The upper part of the bases had a groove for the water seal, needed for the chamber measurements. The transparent closed chamber was used in the CO_2 and CH_4 flux measurements, and two fans were installed in the chamber to mix the air during the measurements. CH_4 and CO_2 concentration inside the chamber were recorded simultaneously by a Fast Greenhouse Gas Analyzer (Los Gatos Research, CA, USA) connected to the transparent chamber, refer to Luan et al. (2016) for more details. Immediately after the transparent chamber measurement, the chamber was removed from the collar for 1 min, reinserted, and darkened with an opaque cloth (with a silver color surface) for the opaque chamber measurement. The ecosystem respiration (R_{eco}) and CH_4 flux were then measured with the same analyzer. The gas concentration data were collected at 1 Hz rate and the data acquisition lasted for five minutes for both chambers. All fluxes were calculated by linear regression; points of the first 30 s were discarded in order to get to the steady state, and the best part of the data was used to do regression analysis. The net ecosystem CO_2 exchange (NEE) was obtained by the transparent chamber measurements, and the R_{eco} and CH_4 emission rate were obtained by the opaque chamber measurements. During each measurement, peat temperature at 5 cm depth (T_5) was measured at three points near the bases with a GS3 probe connected to a ProCheck reader (Decagon Devices). Adjacent to each base, a perforated ABS pipe with sealed bottom was inserted into the peat permanently to measure the water table position (WT, positive values indicate standing water depth). Our measurements were conducted every three weeks from May to October in 2011 (before hydrological restoration) and in 2012 (after hydrological restoration). All the measurements were made between 10:00 and 16:00 of the day.

2.3. Data analysis

Hourly CH_4 or CO_2 fluxes (mg m^{-2} h^{-1}) were calculated based on the slope of the linear increase or decrease in CH_4 or CO_2 concentration