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REVIEW

The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau

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Abstract

With a pace of about twice the observed rate of global warming, the temperature on the Qinghai-Tibetan Plateau (Earth's 'third pole') has increased by 0.2 °C per decade over the past 50 years, which results in significant permafrost thawing and glacier retreat. Our review suggested that warming enhanced net primary production and soil respiration, decreased methane (CH_4) emissions from wetlands and increased CH_4 consumption of meadows, but might increase CH_4 emissions from lakes. Warming-induced permafrost thawing and glaciers melting would also result in substantial emission of old carbon dioxide (CO_2) and CH_4. Nitrous oxide (N_2O) emission was not stimulated by warming itself, but might be slightly enhanced by wetting. However, there are many uncertainties in such biogeochemical cycles under climate change. Human activities (e.g. grazing, land cover changes) further modified the biogeochemical cycles and amplified such uncertainties on the plateau. If the projected warming and wetting continues, the future biogeochemical cycles will be more complicated. So facing research in this field is an ongoing challenge of integrating field observations with process-based ecosystem models to predict the impacts of future climate change and human activities at various temporal and spatial scales. To reduce the uncertainties and to improve the precision of the predictions of the impacts of climate change and human activities on biogeochemical cycles, efforts should focus on conducting more field observation studies, integrating data within improved models, and developing new knowledge about coupling among carbon, nitrogen, and phosphorus biogeochemical cycles as well as about the role of microbes in these cycles.

Keywords: carbon budget, ice retreat, intact ecosystems, land use change, permafrost

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Introduction

In the last 50 years, human activities have caused unprecedented changes in many of the processes, and especially climate that control the structure and function of ecosystems and the services they provide. Such changes have been detrimental or even catastrophic in many parts of the world (Rockstrom *et al.*, 2009), especially for the most sensitive and fragile ecosystems, including those in Arctic regions, Antarctic regions, and the Qinghai-Tibetan Plateau. However, despite being the 'third pole' of the Earth (average elevation 4000 m a.s.l.) and the world's largest plateau, with a size of about 2.5 million km^2 (almost a quarter of the area of China or the United States of America), the plateau receives much less attention than the Arctic and Antarctic regions (Qiu, 2008). Even so, the importance of this region has increasingly been acknowledged by scientists concerning themselves with climate-induced environmental changes. Furthermore, as is the case for the Arctic Region, the Qinghai-Tibetan Plateau with many of the natural ecological processes and feedbacks still intact, may provide one of the last remaining chances to study climate-induced environmental changes over a large region (Li & Zhou, 1998). Understanding these changes is important, because the plateau's high spatial heterogeneity has created a complex and diverse mosaic of vegetation communities that are likely to respond differently to climate change (Fig. 1).

Synthesis of relevant knowledge of this region is a crucial step for identifying the key environmental issues and exploring innovative approaches for sustaining ecosystem services and enhancing the ability of local communities to adapt to global change. Several recent articles have reviewed various aspects of the impacts of climate change on the Qinghai-Tibetan Plateau and have provided valuable information on these impacts (Cui & Graf, 2009; Harris, 2010; Yang *et al.*, 2010a). Although biogeochemical cycles are important ecological processes which are greatly influenced by climate change and human activities, especially for the fragile ecosystems, no one has yet comprehensively reviewed the impacts of climate

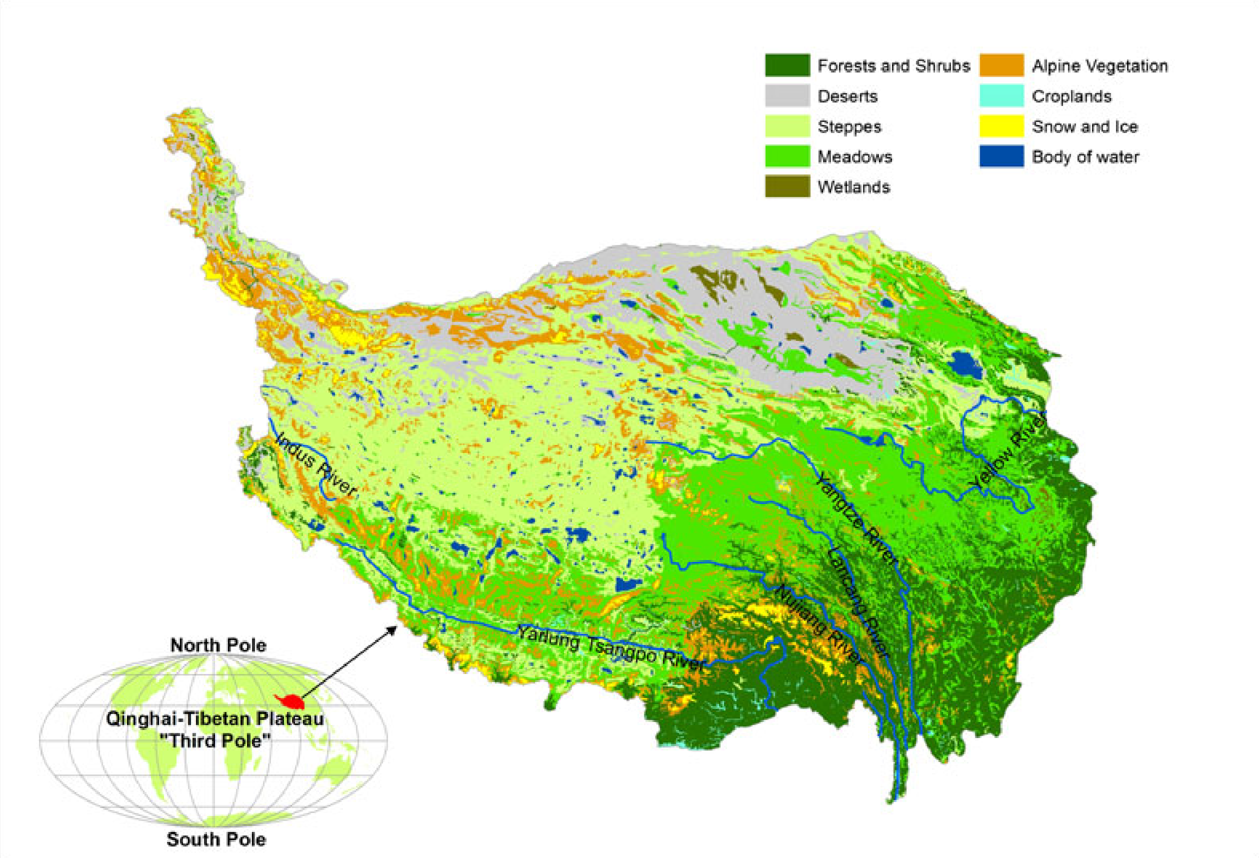

Fig. 1 Distribution of vegetation types throughout the Qinghai-Tibetan Plateau, which is known as Earth's 'third pole'. The plateau's diverse climate conditions create an equally diverse vegetation pattern. Strong temperature and precipitation gradients along the steep mountains bordering the plateau to the south and east create a heterogeneous environment for vegetation, meanwhile make local vegetation communities highly sensitive to climate change. The wet and warm southeastern and eastern margins of the plateau are dominated by forests and shrubs. Above the treeline (more than ca. 4000 m a.s.l.), alpine meadow covers most of the area. The dry north-eastern and central parts of the plateau are characterized by temperate and alpine steppes. Alpine deserts form the main landscape of the dry north-central and north-western parts of the plateau.

change and human activities on biogeochemical cycling on the plateau. In this article, we review studies of climate change, human activities and related environmental challenges, and synthesize the reported impacts on biogeochemical cycling on the plateau, including variations in plant biomass, the soil carbon stock, and fluxes of greenhouse gases, based on both field observations and modeling. We also discuss the effects of grazing and land cover change on the plateau's biogeochemistry. Finally, we highlight the limitations of the existing knowledge as well as future challenges and research directions.

Climate change and climate-induced environmental issues on the Qinghai-Tibetan Plateau

Ubiquitous and rapid warming

During the past five decades, the Qinghai-Tibetan Plateau has experienced a universal and significant warming (Yao *et al.*, 1997; Liu & Chen, 2000; Duan *et al.*, 2006; Li *et al.*, 2010), except for some sporadic episodes of slight cooling (Fig. 2a and e). The temperature has increased by 0.2 °C per decade since 1960 (Fig. 2a), with the warming trend even intensified since 2000 (Yao *et al.*, 2007). The rates of winter and autumn warming (more than 0.2 °C per decade) have been significantly faster than those of spring and summer warming (less than 0.2 °C per decade) (Xu *et al.*, 2008; Li *et al.*, 2010). Moreover, the northern part of the plateau has shown the most obvious warming (Li *et al.*, 2010), with the rate as high as 0.08 °C yr^{-1} (Fig. 2e). Furthermore, there has been a strong elevation effect (i.e. the warming is more prominent at higher elevations) on climatic warming throughout the plateau (Liu & Chen, 2000; Yao *et al.*, 2000; Liu *et al.*, 2009b), especially in winter. Temperatures reconstructed from δ^{18}O records in ice cores and tree rings have, without exception, shown that the last century was the warmest period during at least the last millennium (Thompson *et al.*, 1997; Yao *et al.*, 1997; Shao *et al.*, 2010), with temperatures reaching levels experienced during the mid-Holocene between 6000 and 8000 years ago (Thompson *et al.*, 1989). Moreover, the Qinghai-Tibetan Plateau began warming earlier than other regions of China and even earlier than many other regions of the world at temporal scales ranging from thousands of years to decades (Thompson *et al.*, 1997; Liu & Chen, 2000). Findings from ice cores have also suggested that large-amplitude climatic changes happened not only in the polar regions but also on the Qinghai-Tibetan Plateau, which has experienced much larger changes than those experienced by Greenland (Thompson *et al.*, 1997; Yao *et al.*, 1997, 2000). The recent warming rate of the Qinghai-Tibetan Plateau has been greater than those for the northern hemisphere, the southern hemisphere, and the world as a whole (Trenberth *et al.*, 2007). Hence, with its earlier and more intense warming, the Qinghai-Tibetan Plateau serves as a sensitive indicator of regional and global climate change (Li & Fang, 1999).

The future projections based on the IPCC global climate models clearly indicate that the warming trend on the plateau will continue, but uncertainties about its extent and pattern remain high (Trenberth *et al.*, 2007). Compared with the reference period from 1960 to 2010, under the two scenarios used in this article (A2 and B1, representing high and low greenhouse gas emission levels, respectively, See Appendix S1), the plateau's mean annual temperature is expected to increase by 2.6–5.2 °C by 2100 (Fig. 2c). Compared with the reference period from 1980 to 1999, the plateau's mean annual temperature is expected to increase by 1.5 to 2.9 °C between 2030 and 2049 and between 2080 and 2099, respectively, for the IPCC mid range emission (A1B) scenario (Liu *et al.*, 2009b).

Slightly wetter climate

On the Qinghai-Tibetan Plateau, the precipitation falls mainly during the summer and autumn (from June to September), with winters and springs relatively drier. In contrast with the temperature trends, the precipitation trend since 1960 has shown less seasonal and spatial fluctuation but an overall slight increase and high interannual variation at the whole-plateau scale (Fig. 2b) (Xu *et al.*, 2008; Kang *et al.*, 2010; Li *et al.*, 2010). The precipitation trends show a significant increase during the winter and spring, but nonsignificant decreases during the summer and autumn (Li *et al.*, 2010). The central-eastern and southeastern regions generally showed increasing annual precipitation, with sporadic extremely wet periods, whereas other parts of the plateau generally showed decreasing precipitation (Fig. 2f) (Xu *et al.*, 2008). Future projections of precipitation using the IPCC models indicate that the wetting trend will continue on the plateau (Fig. 2d). Compared with the reference period from 1960 to 2010, the two scenarios we examined in this study show increases of 38 or 272 mm in mean annual precipitation by 2100. However, such projections are highly uncertain (Piao *et al.*, 2010).

Glacier retreat

The Qinghai-Tibetan Plateau is the largest existing region of glaciers outside the northern and southern polar regions, with 36 973 glaciers covering a total area

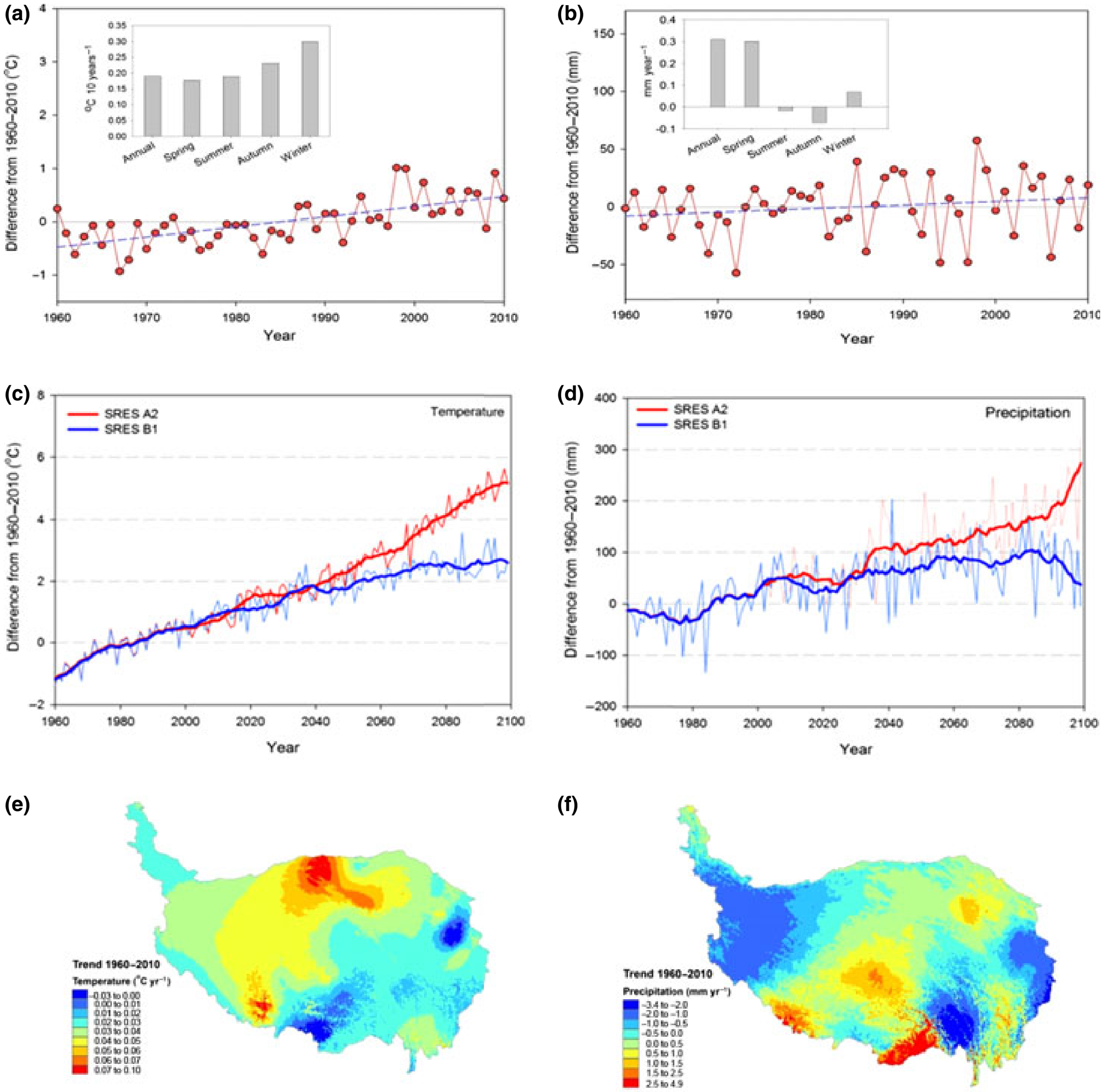

Fig. 2 Observed trends and future projections of climate on the Qinghai-Tibetan Plateau. (a) Observed mean annual temperature (derived from observed temperature data of meteorological stations of Meteorological Bureau of China) variations between 1960 and 2010 across the Qinghai-Tibetan Plateau, expressed as deviation from the mean during that period (red scatter line). The blue dashed line is a fit to the data: $y = -37.838 + 0.019x$ ($P < 0.001$). The inset shows trends in seasonal temperature (°C per 10 years) during the period 1960–2010 with P values as: spring ($P < 0.01$), summer ($P < 0.0001$), autumn ($P < 0.0001$), and winter ($P < 0.0001$) (b) Observed mean annual precipitation (derived from observed temperature data of meteorological stations of Meteorological Bureau of China) variations between 1960 and 2010 across the Qinghai-Tibetan Plateau, expressed as deviation from the mean during that period (red scatter line). The blue dashed line is a fit to the data: $y = -618.256 + 0.311x$ ($P = 0.1936$). The inset shows trends in seasonal precipitation (mm yr^{-1}) during the period 1960–2100 with P values as: spring ($P < 0.0001$), summer ($P = 0.9375$), autumn ($P = 0.4941$), winter ($P = 0.0044$). (c) Annual temperature variations (thin lines) from 1960 to 2010 across the QTP under scenarios SRES A2 (red line) and SRES B1(blue line). The data were based on the Third Generation Coupled Global Climate Model (CGCM3.1) from Canadian Centre for Climate Modelling and Analysis (CCCma). The thick lines are 10 years running average. (d) Annual precipitation variations (thin lines) from 1960 to 2010 across the QTP under scenarios SRES A2 (red line) and SRES B1(blue line). (e) Spatial pattern of the temperature trends across the Qinghai-Tibetan Plateau from 1960 to 2010 (°C per year). Annual interpolated temperature layers were constructed using thin plate smoothing splines from 1960 to 2010. Linear fit is conducted for each grid cell and the slope is shown on the map. (f) Spatial pattern of the precipitation trends across the Qinghai-Tibetan Plateau from 1960 to 2010 (mm yr^{-1}). Annual interpolated precipitation layers were constructed using thin plate smoothing splines from 1960 to 2010. Linear fit is conducted for each grid cell and the slope is shown on the map.

of 4.99 million ha, about 84% of the total area of glaciers in China (Liu *et al.*, 2000). During the past 100 years, glaciers on the plateau have been continuously retreating (Pu *et al.*, 2004), with the rate of retreat accelerating in the past decade (Yao *et al.*, 2007; Takeuchi *et al.*, 2009). There is some spatial variation in the glacial retreat: rates are relatively low in the interior of the plateau, intermediate at low-elevation margins, and greatest at higher elevations near these margins (Yao *et al.*, 2007). A recent study showed that more than 80% of glaciers in western China have retreated, losing 4.5% of their combined areal coverage (Ding *et al.*, 2006). In the short term, melting glaciers have increased runoff in some river systems, providing more water, but at the same time caused flooding and increased the risk of dangerous glacial outburst floods. Glacier retreat is attributed primarily to climatic warming, but the rapidity of the retreat is probably exacerbated by factors such as deposition of black soot (Xu *et al.*, 2009). The glacial retreat has caused hydrological changes on the plateau, including increased river discharge and rising lake water levels (Kang *et al.*, 2010). Recent glacier melting has increased river runoff by more than 5.5% (Yao *et al.*, 2007), and water levels in most of the plateau's lakes have risen by up to 0.2 m yr^{-1} (Zhang *et al.*, 2011a), accompanied by expansion of many lakes (Liu *et al.*, 2009a, 2010) on the plateau. Reduced emissions of black soot, in addition to reduced emission of greenhouse gases, may be required to avoid the demise of the Qinghai-Tibetan Plateau's glaciers and retain the benefits of these glaciers, and particularly their contribution to the water supplied to six of Asia's largest and most important rivers (the Indus, Yarlung Tsangpo, Nujiang, Lancang, Yangtze, and Yellow rivers; Fig. 1). Further efforts must be focused on continuous *in situ* monitoring of glacier fluctuations and their impacts on water availability for the ecosystems and populations on the plateau and in downstream regions.

Permafrost thawing

The extensive permafrost (about 1.4 million km^2) covers a significant portion of the Qinghai-Tibetan Plateau (Yang, 2004). However, the Tibetan permafrost is relatively warm and thin, mostly higher than −2.0 °C in temperature and <100 m in thickness (Cheng & Wu, 2007). As a result, it is highly sensitive to temperature changes, and significant warming, thawing, thinning, and retreat of permafrost have been reported throughout the plateau in recent decades (Yang *et al.*, 2010a). From the 1970s to the 1990s, the ground temperature of seasonally frozen soil and areas of some permafrost increased by 0.3–0.5 °C, whereas the mean annual ground temperature of areas of continuous permafrost increased by 0.1–0.3 °C, with the top of the permafrost becoming 4 m deeper (Wang *et al.*, 2000; Cheng & Wu, 2007). During the past decade, mean annual permafrost temperatures at a depth of 6.0 m have increased by 0.12–0.67 °C, with an average increase of about 0.43 °C (Wu & Zhang, 2008). The thickness of the active layer showed little or no change from 1956 to 1983, but increased sharply (by 39 cm) from 1983 to 2005 (Wu *et al.*, 2010). Long-term temperature measurements have indicated that the lower altitudinal limit of the permafrost has moved upward by 25 m in the north of the study area during the last 30 years and upward by 50–80 m in the south of the study area during the last 20 years (Cheng & Wu, 2007). In addition, permafrost temperature gradients have changed dramatically along the Qinghai-Tibet Highway/Railway (Wu *et al.*, 2010). Simulations predict that the Tibetan permafrost will continue to retreat and thaw, and that the area of permafrost may decrease by 8.8–19% by 2049 and by 13.4–58% by 2099 (Li & Cheng, 1999; Nan *et al.*, 2005).

Human activities on the Qinghai-Tibetan Plateau

Although the plateau's environment is harsh and inhospitable, nomads might have entered the plateau from northern Asia between 25 000 and 30 000 years BP. (Aldenderfer & Yinong, 2004). Tens of thousands of years after this initial colonization, the plateau is now still regarded as a remote region with only 12 million people distributed throughout the plateau (Zhang *et al.*, 2005). However, since 1960, China's rapid economic growth has greatly increased the population of the plateau, now about threefold that of 1950 (Zhang *et al.*, 2005). As a result, the increased intensity of human activities has dramatically reshaped many parts of the plateau.

Changes in land cover and land use represent two of the most substantial human alterations of Earth's systems (Vitousek *et al.*, 1997). Due to the extensive area of rangeland, which covers almost 60% of the plateau, livestock husbandry has become the major land use on the plateau. Since 1978, the livestock number has increased by almost 300% (Du, 2004). Moreover, significant changes have occurred as a result of the simultaneous increase in human and livestock populations: overgrazing, fertilization to improve forage production (Niu *et al.*, 2009), rangeland privatization (Yan & Wu, 2005), and sedentarization of the formerly nomadic peoples (Lu *et al.*, 2009). Such changes have increased human impacts on the plateau's environment. For example, heavy grazing is believed to lead to severe rangeland degradation or even desertification (Song *et al.*, 2009). Since 1960, pervasive logging for commercial use has profoundly decreased the forest cover on the Qinghai-Tibetan Plateau, especially in its eastern parts (Wu & Liu, 1998). The tripled population has accelerated the rate of urbanization, although the rate remains slower than in other regions of China (Fu, 2000). Since 1995, the combined influence of government and market mechanisms has led to rapid urbanization and economic growth. For example, the urban population of Tibet grew from 0.4 million in 1995 to 1.0 million in 2006 (Fan *et al.*, 2010). To mitigate the impacts of environmental degradation on the plateau, China has been implementing large-scale conservation programs, including the Natural Forest Conservation Program (initiated in 1998) and the Grain for Green Program (initiated in 1999) (Liu *et al.*, 2008).

Impact of climate changes on biogeochemical cycles

Carbon and nitrogen cycling under climate change

Ecosystems of the Qinghai-Tibetan Plateau are very sensitive to climate change. The above-mentioned rapid and great warming have definitely shaped ecosystem structures and processes, with symptoms such as phenological changes (Yu *et al.*, 2010; Chen *et al.*, 2011b; Zhang *et al.*, 2013) and a rapid decrease in plant abundance (Klein *et al.*, 2004), which in turn have resulted in great shifts in carbon and nitrogen cycling (Zhang *et al.*, 2012). Warming usually enhances both production and respiration. However, there are many uncertainties in which progress will dominate the other and whether the whole plateau is a carbon source or sink. Short-term experiments indicated that warming significantly increased biomass of forests (Zhao & Liu, 2009) and meadows (Li *et al.*, 2011; Wang *et al.*, 2012), decreased total aboveground net primary production (NPP) in the meadows(Klein *et al.*, 2007), but showed no apparent effect on the photosynthetic rate and biomass accumulation of shrubs. The counterintuitive decrease in meadow NPP may partly be due to warming-enhanced top-down control via increased predation by predatory beetles on coprophagous beetles (decomposers), with cascading effects on nutrient cycling and primary productivity (Lin *et al.*, 2011). Soil measurements conducted with open-top chambers (OTC) showed that warming significantly increased CO_2 effluxes in forest soils of the eastern Qinghai-Tibetan Plateau (Xu *et al.*, 2010).Without changing soil moisture, Lin *et al.* (2011) introduced free-air temperature-enhancement (FATE) experiments to warm alpine meadows ecosystem, also finding that soil respiration increased by 9.2%. TEM, a process-based biogeochemistry model, indicated that the warming observed during the 20th century changed the Qinghai-Tibetan Plateau from a small carbon source or a carbon-neutral system during the early 20th century to a net carbon sink by the 1990s (36 Tg C yr^{-1}), because plant carbon uptake (increased by 0.52 Tg C yr^{-1}) was higher than soil carbon release (increased by 0.22 Tg C yr^{-1}) (Zhuang *et al.*, 2010). Compared with the reference period from 1960 to 2010, if the projected warming continues under the two scenarios, both soil respiration and NPP in the future will increase greatly. However, different from the understanding of previous studies, according to our results, the soil carbon release will exceed plant carbon uptake by 2100 (Fig. 3).

Although there are great uncertainties in changes of soil carbon stocks under climate warming, it is very likely that the soil carbon stock decreases if projected high-level warming continues on the plateau. An OTC warming experiment significantly decreased the labile fractions of the C and N soil pools (Xu *et al.*, 2010); a FATE warming experiment also decreased litter mass by 19.3% during a 2-year decomposition period (Luo *et al.*, 2010) and soil solution dissolved organic carbon (DOC) concentration by 14.1–17.2% (Luo *et al.*, 2009). However, a 3-year FATE warming experiment increased labile C and N pools in alpine meadow soils as a result of increased litter inputs (Rui *et al.*, 2011). Modeling using ORCHIDEE predicts a decrease in current soil organic carbon (SOC) stocks by ca. 10% and an increase in NPP by about 9% in grasslands of the plateau if the temperature increases by 2 °C (Tan *et al.*, 2010). However, the SOC stock in the alpine grasslands remained relatively stable from the 1980s to 2004, probably because the increased rates of decomposition as the soil warmed during the sampling period may have been offset by increased soil C inputs due to increased grass productivity (Yang *et al.*, 2009). Furthermore, a combination of warming and soil acidification on the plateau may potentially decrease the great soil inorganic carbon (SIC) stock (15.2 Pg C), which is as much as 2.1 times of SOC stocks (7.4 Pg C) (Yang *et al.*, 2008, 2010b). However, the total amount of SOC and SIC is still not determined with limited observed data.

Although only a single study has simulated the effects of drying or wetting on ecosystem processes on the plateau (Wu *et al.*, 2008), many studies have shown that the spatial pattern of precipitation determines the spatial pattern of key components of the carbon and nutrient cycles (Piao *et al.*, 2006; Yang *et al.*, 2008, 2009; Tan *et al.*, 2010; Zhuang *et al.*, 2010; Wang *et al.*, 2013). The rain use efficiency of Tibetan grasslands was lower than global grasslands in general but displayed a similar trend with precipitation, which is critical for predicting potential responses of alpine ecosystems to changing precipitation regimes on the plateau (Yang *et al.*, 2010c; Wang *et al.*, 2013). In this study, the spatial patterns of changes in NPP and soil respiration were

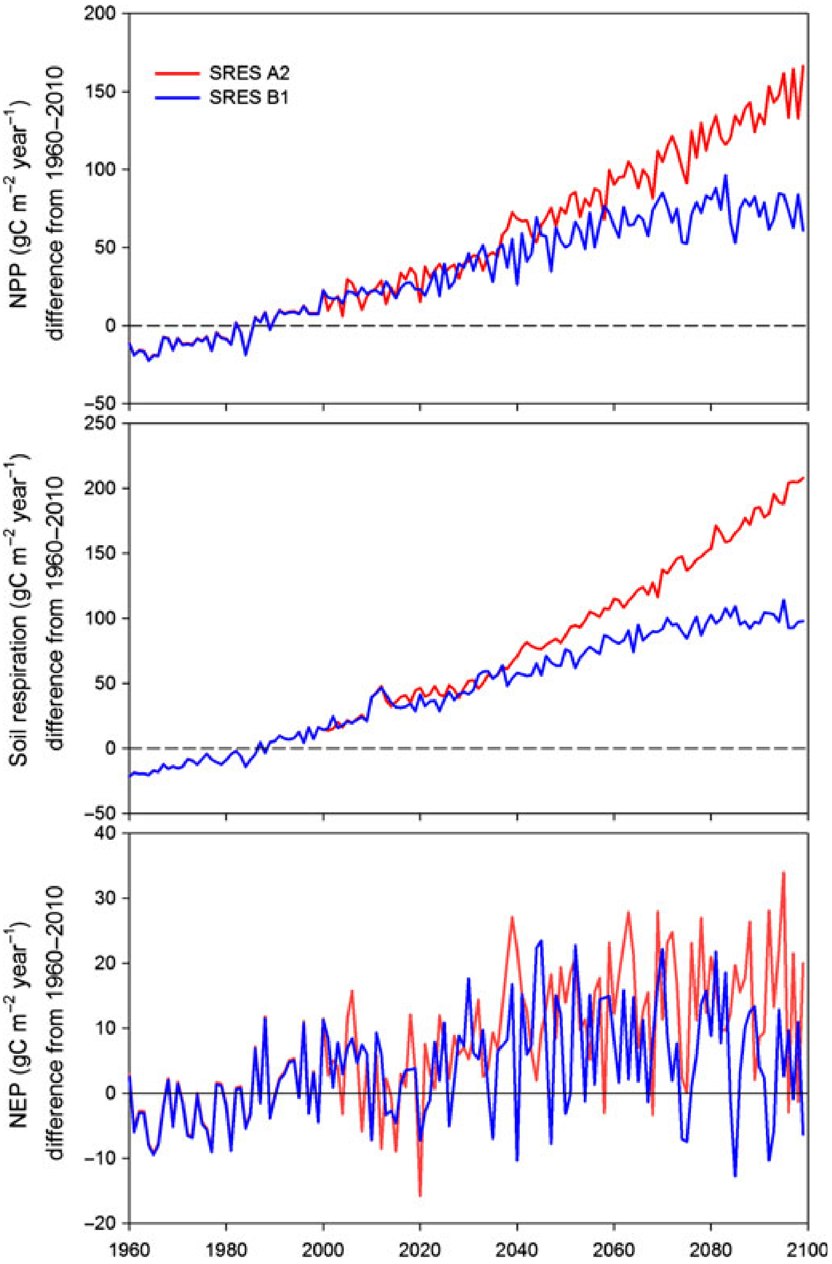

Fig. 3 (a) Simulated net primary production (NPP); (b) simulated soil respiration; and (c) simulated net ecosystem production (NEP) variations from 1960 to 2100 across the Qinghai-Tibetan Plateau, expressed as the deviation from the mean between 1960 and 2010. NPP, soil respiration, and NEP were simulated using a dynamic global vegetation model (the Integrated Biosphere Simulator, IBIS) under the SRES A2 and SRES B1 scenarios representing high and low greenhouse gas emission levels respectively (Appendix S1). The model was forced using climate data from the Third Generation Coupled Global Climate Model (CGCM3.1) developed by the Canadian Centre for Climate Modelling and Analysis. Here, soil respiration includes both root respiration and microbial respiration.

derived from simulated results using a dynamic global vegetation model (the Integrated Biosphere Simulator, IBIS) under the SRES A2 and SRES B1 scenarios (Fig. 4 and Appendix S1). The patterns of NPP and soil respiration were consistent to the predicted patterns of changes in precipitation on the plateau (Figs 2 and 4). Based on transect measurements, it was moisture, not temperature, that best explained the large-scale pattern of soil respiration (Geng *et al.*, 2012; Liu *et al.*, 2012). Furthermore, the extent of the effect of soil moisture was mainly determined by permafrost and pedogenesis (Baumann *et al.*, 2009). In both scenarios, the greatest increase in NPP and soil respiration occurred in the wetter southeastern parts of the plateau, with the

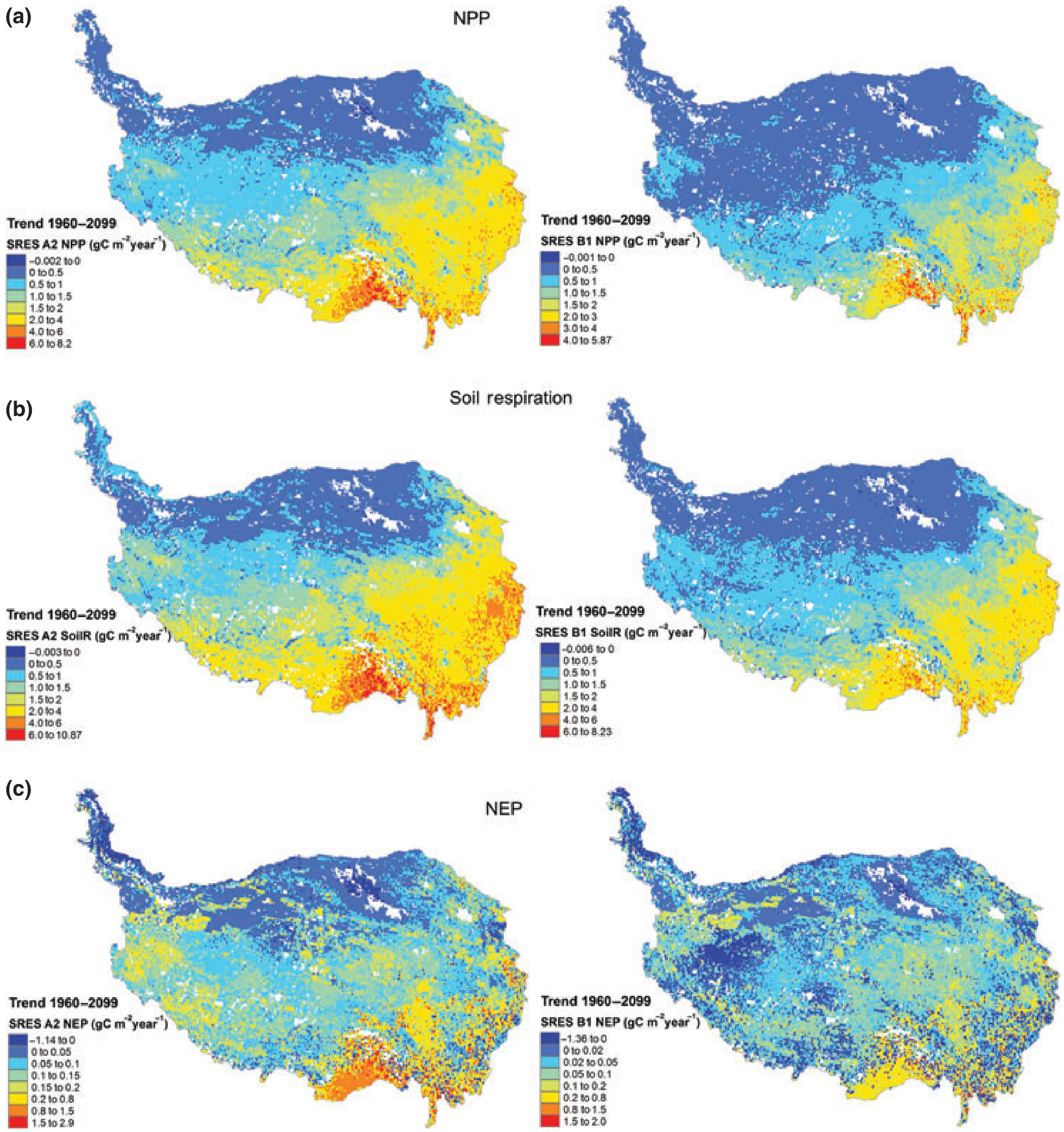

Fig. 4 Spatial patterns of linear trends in net primary production (NPP); soil respiration; and net ecosystem production (NEP) on the Qinghai-Tibetan Plateau under the SRES A2 and SRES B1 scenarios (Appendix S1). Linear regression was conducted to fit the trends for each cell in the grid based on the annual simulated NPP, soil respiration, and NEP from 1960 to 2100; the results shown in the map represent the slopes of the regressions.

lowest increase (and a slight decrease in some areas) in the drier central and northern parts. These results suggested that wetting would accelerate biogeochemical cycles due to the increasing soil moisture, resulting in increased NPP and SOC, as was projected by Tan *et al.* (2010). Similar to the Arctic regions, with high-level warming accompanied by increased rain, the magnitude of the plateau carbon budget would depend upon changes in summer rain instead of temperatures (Sharp *et al.*, 2013).

The biogeochemical cycle for carbon is fundamentally coupled with the cycles for other elements and stoichiometrically influences both primary production and decomposition (Arneth *et al.*, 2010; Finzi *et al.*, 2011). For example, nitrogen availability plays a critical role in controlling NPP because nitrogen is the limited nutrient in many ecosystems. Nitrogen deposition experiments on the plateau have indicated that stimulated nitrogen deposition could enhance carbon sequestration, because the enhancement of NPP (Xu *et al.*, 2004; Zhao & Liu, 2008) would be greater than any enhancement of soil CO_2 emission (Xu *et al.*, 2004), although the ratio of the two increases remains uncertain (Jiang *et al.*, 2010). However, the interaction between warming and nitrogen will not always have positive effects on plant growth (Zhao & Liu, 2008, 2009).

Permafrost is a large carbon reservoir, for example, the northern circumpolar permafrost region contains about 1 672 Pg organic carbon (Tarnocai *et al.*, 2009). The extensive permafrost on the Qinghai-Tibetan Plateau has, however, been subject to significant warming, leading to thawing of permafrost throughout the plateau in recent decades (Cheng & Wu, 2007; Lu *et al.*, 2008; Wu *et al.*, 2010; Yang *et al.*, 2010a). Such permafrost degradation caused rapid carbon loss through the efflux of CH_4 and CO_2, and leaching of DOC (Walter *et al.*, 2006; Wang *et al.*, 2008; Wu *et al.*, 2013). From 1986 to 2000, the loss of SOC caused by permafrost degradation was estimated at 1.8 Tg C (Wang *et al.*, 2008).

Greenhouse gases under climate change

Climate change on the Qinghai-Tibetan Plateau has greatly affected the plateau's biogeochemical cycles, as described earlier in this article, resulting in changes in the fluxes of greenhouse gases (primarily CO_2, CH_4, and N_2O; related studies are summarized in Table 1). Although CO_2 fluxes from forests on the plateau are scarcely studied (Chen *et al.*, 2010), there have been extensive researches about the diurnal, seasonal, and interannual variation in CO_2 fluxes from steppes, meadows, and shrubs throughout the plateau in recent decades (Pei *et al.*, 2003; Hirota *et al.*, 2004; Zhao *et al.*, 2005, 2006; Saito *et al.*, 2009; Wang *et al.*, 2009a). Alpine meadows and shrub meadows are considered to be CO_2 sinks (Hirota *et al.*, 2004; Zhao *et al.*, 2005), whereas steppes appear to be CO_2 emitters (Pei *et al.*, 2003), and wetlands can be either a significant source (Zhao *et al.*, 2005; Wang *et al.*, 2009a) or a significant sink (Hao *et al.*, 2011). Based on a 3-year eddy flux measurement study, temperature controlled the ecosystem CO_2 exchange of alpine meadows (Kato *et al.*, 2006; Saito *et al.*, 2009). Furthermore, warming also partly resulted in degradation of alpine meadows, thus enhancing CO_2 emission from such ecosystems (Wang *et al.*, 2009a). Increasing nitrogen deposition has probably enhanced soil CO_2 emission from alpine meadows (Xu *et al.*, 2004). With climate warming, substantial CO_2 would also be emitted from thawing permafrost and from peatlands on the Qinghai-Tibetan Plateau (Zhao *et al.*, 2005; Wang *et al.*, 2008; Hicks Pries *et al.*, 2013). Warming-enhanced respiration (Dorrepaal *et al.*, 2009) of subsurface peat may have transformed peatlands from net CO_2 consumers (sinks) into net CO_2 emitters (sources) on the plateau. Furthermore, exported old DOC from peatlands would contribute greatly to CO_2 emissions from nearby aquatic systems on the plateau (Singer *et al.*, 2012).

On the Qinghai-Tibetan Plateau, the waterlogged and anoxic condition makes freshwater marshes (including undisturbed peatlands) and lakes net emitters of CH_4, with high spatial and temporal variation in fluxes (Jin *et al.*, 1999; Hirota *et al.*, 2004; Chen *et al.*, 2008, 2009;

Table 1 Overview of greenhouse gas fluxes from different ecosystems on the Qinghai-Tibetan Plateau

Ecosystem	Location	CO_2 (mg m^{-2} h^{-1})	CH_4 (μg m^{-2} h^{-1})	N_2O (μg m^{-2} h^{-1})	Source
Forests	Miyaluo, Eastern Qinghai-Tibetan Plateau	15.8–2265.1	nd	nd	(Chen *et al.*, 2010)
Shrubs	Haibei research station	−1650.5 to 1224.4	nd	nd	(Zhao *et al.*, 2005, 2006)
Meadows	Haibei research station Zoige	−2645.3 to 1302.1	−71.9 to 600	−2.05 to 110	(Kato *et al.*, 2004; Zhao *et al.*, 2005; Chen *et al.*, 2009, 2011a; Lin *et al.*, 2009; Jiang *et al.*, 2010)
Steppes	Damxung grassland station (91°05E, 30°25N)	−1314.7 to 380.2	−74.24 to −1.6	−0.50 to 0.76	(Pei *et al.*, 2003; Shi *et al.*, 2006a)
Farmland	Lhasa River valley	16.7–625	nd	nd	(Shi *et al.*, 2006b)
Wetlands	Zoige; Huashixia Permafrost Station; Haibei research station	−550 to 595.8	−0.81 to 90	47.1 to 110	(Jin *et al.*, 1999; Hirota *et al.*, 2004; Chen *et al.*, 2008, 2009, 2011a)
Lakes	Zoige	488.6 ± 1036.2	nd	nd	(Zhu *et al.*, 2012)

nd, indicates no data.

Kato *et al.*, 2011). There have been some preliminary studies of the methanogen community on the plateau (Zhang *et al.*, 2008). Based on the distribution of wetlands, representative CH_4 fluxes, and the number of thaw days, a preliminary estimate of the emissions from Qinghai-Tibetan wetlands was 0.7–0.9 Tg CH_4 yr^{-1} (Jin *et al.*, 1999). However, researchers did not take into consideration the seasonal and interannual variations, which might arise great uncertainties in the plateau CH_4 budget (Jin *et al.*, 1999; Kato *et al.*, 2011; Chen *et al.*, 2013). As climate warming has continued, the wetlands (excluding bodies of open water) of the Qinghai-Tibetan Plateau have grown drier or even vanished from 1967 to 2004 (Zhang *et al.*, 2011b), which definitely decreased emission of CH_4. Therefore, the CH_4 source strength of the Qinghai-Tibetan wetlands has weakened during the last 50 years, and would continue to weaken if the projected warming continues. Detailed information about the methanogens of the plateau and their relationships with the regional vegetation (Tian *et al.*, 2012) would make it easier to understand the relative consequences of warming and drying.

On the other hand, the aerobic soils make steppes and meadows on the Qinghai-Tibetan Plateau a slight sink for CH_4 (Pei *et al.*, 2003; Lin *et al.*, 2009; Wang *et al.*, 2009a; Kato *et al.*, 2011; Wei *et al.*, 2012). However, apparent CH_4 emission was observed in a typical meadow on the Qinghai-Tibetan Plateau (Cao *et al.*, 2008; Wang *et al.*, 2009b). Wang *et al.* believed that the apparent CH_4 emission should be attributed to differences in CH_4 uptake between vegetated and non-vegetated plots (Wang *et al.*, 2009b), rather than differences in plant production of CH_4 under aerobic conditions (Houweling *et al.*, 2006). On the plateau, however, no evidence has yet supported the hypothesis of plant-derived CH_4 emission (Kato *et al.*, 2011). Therefore, for the whole plateau, we still regarded steppes and meadows as a CH_4 sink. Moreover, a recent study reported that warming-enhanced CH_4 oxidation during a FATE warming experiment (Zheng *et al.*, 2012), which indicated that steppes and meadows could consume more CH_4 under the future warming. Although there are no data on CH_4 emission from lakes, Yang *et al.* (2011) suggested relatively high emission from lakes on the plateau due to its convergence of organic carbon in catchment, because lakes capture most of the DOC created within a catchment. Due to warming of the lake water (Yang *et al.*, 2011) and general expansion of lakes on the plateau (Zhang *et al.*, 2011a), CH_4 emission from these lakes may have increased, and the trend may have existed for some time, with especially high emission from enlarging littoral marshes surrounding lakes (Chen *et al.*, 2009). Moreover, the expansion of thermokarst lakes would release substantial CH_4 through ebullition from labile Pleistocene-aged C if the permafrost region continues to warm (Walter *et al.*, 2006; Niu *et al.*, 2011).

Ruminants on the plateau are another important source of CH_4 emission. Due to the smaller than-average size of yaks raised on the plateau, these yaks produce low CH_4 emission (Ding *et al.*, 2010). However, with the tripling of yak and sheep populations since 1978 (Du, 2004), the CH_4 source strength of these ruminants has inevitably increased.

N_2O is expected to be the most potent terrestrial greenhouse gas on a time horizon of 20–500 years and is the chief precursor of tropospheric O_3, which is also an important greenhouse gas (Arneth *et al.*, 2010). On the plateau, steppes, meadows, and shrubs are currently acting as a weak source of N_2O (Pei *et al.*, 2003; Du *et al.*, 2008; Kato *et al.*, 2011; Zheng *et al.*, 2012), whereas alpine wetlands may function either as a source (Chen *et al.*, 2011a) or as a sink (Kato *et al.*, 2011). Due to their great area, alpine meadows throughout the plateau are a relatively important source of N_2O on the plateau, contributing an average annual emission of 0.3 Tg N_2O (Du *et al.*, 2008). However, large spatial and temporal variations exist in N_2O emission, probably due to the complicated processes involved in the formation of N_2O (Pei *et al.*, 2003; Du *et al.*, 2008; Jiang *et al.*, 2010; Chen *et al.*, 2011a; Kato *et al.*, 2011). FATE warming experiments did not significantly affect N_2O flux, probably due to the offsetting positive and negative effects of warming (Hu *et al.*, 2010). However, a weak but significant positive correlation between N_2O flux and the water-filled pore space suggested that precipitation is an important factor that controls N_2O flux from alpine meadows (Jiang *et al.*, 2010). Therefore, if the climate continues to grow wetter, as projected by the two scenarios in this study, the N_2O emission from alpine meadows will be stimulated. Together with increasing nitrogen deposition, alpine meadows on the plateau would therefore emit slightly more N_2O in the future (Jiang *et al.*, 2010).

Consequences of human activities

Land cover and biogeochemistry

Although our focus in this article is on the interactions between climate and biogeochemical cycles, changes in the natural vegetation cover and in anthropogenic land use cannot be neglected because of their important effects on carbon cycling as well as the surface albedo, energy, and water balances (Chapin *et al.*, 2009). During the last 50 years, pervasive logging to produce commercial wood has profoundly decreased forest cover on the Qinghai-Tibetan Plateau, especially in its eastern parts (Wu & Liu, 1998). Deforestation or the replacement of forests by farmland could release substantial amounts of carbon into the atmosphere that would not be recaptured by terrestrial ecosystems (Arneth *et al.*, 2010). Afforestation and reforestation on the plateau should therefore be considered, particularly under national restoration programs such as the Natural Forest Conservation Program and the Grain for Green Program. The land cover change that results from both programs can significantly increase carbon sequestration (Liu *et al.*, 2008), especially in the eastern Himalayas and the Hengduan mountains, where forests are mainly distributed.

Grassland degradation and the shrinking area of wet meadow have been observed and are predicted to continue on the plateau (Cui *et al.*, 2006; Xiang *et al.*, 2009). Such processes are irreversible in the short term without large-scale human intervention, and would release a large amount of carbon, particularly if they are accompanied by permafrost thawing (Rigby *et al.*, 2008). Extensive desertification on the plateau has significantly reduced soil organic carbon and nutrient contents in many areas, particularly in the north (Li *et al.*, 2006). This reinforces the importance of monitoring human land uses to reduce the degradation of these vegetation communities. As mentioned above, the expansion of lakes (Zhang *et al.*, 2011a) and their littoral wetlands on the plateau would not only increase methane emission but would also lead to biogeochemical alterations as a result of the flows of water and nutrients from terrestrial to aquatic ecosystems. This suggests the need for careful fertilizer management to avoid problems such as eutrophication of water body. Fertilization to support the expansion of forage-producing meadows after settling down of the former nomadic pastoralists has altered biomass allocation in alpine meadows (Niu *et al.*, 2008), thereby affecting carbon and nitrogen cycles in ways that have increased emissions of NO_x (Jiang *et al.*, 2010). There have been few studies of the impacts of warming climate or of human induced land cover changes on biogeochemical cycles on the plateau, so it is difficult to provide a reliable quantitative synthesis. Integrating *in situ* experiments with modeling should therefore be a future research priority (Arneth *et al.*, 2010).

Biogeochemical cycling under livestock grazing

Heterogeneous rangeland ecosystems, which cover about 60% of the plateau, encompass more territory than any other ecosystem on the plateau. In these ecosystems, nomadic Tibetan pastoralists have grazed their livestock for thousands of years. Thus, livestock grazing may have been the most important anthropogenic impact on the plateau's landscapes and biogeochemical cycles. In the past three decades, this impact has undergone significant changes such as overgrazing due to rising populations of both humans and livestock, pasture improvement (including ploughing and fertilization) (Niu *et al.*, 2009), privatization of livestock ownership and rangelands (Yan & Wu, 2005), and sedentarization of pastoral nomads (Liu *et al.*, 2009a), all of which have had profound impacts on rangeland ecosystems (Wu, 1999; Wu & Yan, 2002). Heavy grazing, for instance, is believed to cause severe rangeland degradation or even desertification on the Qinghai-Tibetan Plateau (Song *et al.*, 2009; Wang *et al.*, 2012), although this has been questioned by others (Klein *et al.*, 2007; Harris, 2010), possibly due to a different definition of grazing intensity. Higher grazing intensity has been found to greatly increase soil respiration (Cao, 2004), but was believed by other researchers to potentially increase C and N pools in the soil–plant system of an alpine meadow (Gao *et al.*, 2007, 2008; Hafner *et al.*, 2012). However, a recent study suggested that grazing would increase carbon loss into the atmosphere if it decreased litter biomass and increased dung production during a period of continued warming (Luo *et al.*, 2010).

Although experimental warming was shown to increase species loss, the soil solution DOC concentration and aboveground net primary production (ANPP), grazing mitigated these effects on the plateau (Klein *et al.*, 2004; Wang *et al.*, 2012). Another study suggested that grazing might modify the effects of warming on soil C and N pools through its strong impacts on soil microbial processes and on N cycling (Rui *et al.*, 2011). However, grazing is also believed to stimulate CO_2, CH_4, and N_2O fluxes from alpine meadows and wetlands on the plateau (Lin *et al.*, 2009). A recent study indicated that the stimulatory effect on N cycling and even on N_2O emission might be more than offset by the effects of a parallel reduction in microbial biomass and inorganic nitrogen production in a steppe in Inner Mongolia (Wolf *et al.*, 2010). This result has implications for the steppes on the Qinghai-Tibetan Plateau, as this vegetation community is expanding due to shrinkage of the plateau's meadows (Chen *et al.*, 2011b). However, warming was found to reduce the response of N_2O fluxes to grazing on the plateau (Hu *et al.*, 2010).

Comparisons with polar regions

Similar to the Qinghai-Tibetan Plateau, polar regions show significant warming and moistening trends (Raper *et al.*, 1983; Min *et al.*, 2008) and such trends may be amplified by ice-albedo feedback (Min *et al.*, 2008). Due to warming, arctic tundra ecosystems have recently changed from a net carbon sink to a source (Oechel *et al.*, 1993; McKane *et al.*, 1997); polar ice sheets are significantly losing their mass (Rignot & Thomas, 2002), causing changes not only in hydrological processes but also in elements' biogeochemical cycles in aquatic systems (Min *et al.*, 2008; Singer *et al.*, 2012). For Arctic regions, substantial old methane emits from Siberian thawing lakes as a positive feedback to climate warming (Zimov *et al.*, 1997; Walter *et al.*, 2006, 2007). Besides, thawing permafrost also increases old soil respiration in tundra ecosystems, with such increases in old soil respiration likely outpacing productivity in the future (Hicks Pries *et al.*, 2013). However, when warming is combined with increased summer rain, the future Arctic regional carbon budget may depend on changes in summer rainfall, but not on temperature (Sharp *et al.*, 2013). Compared with the Qinghai-Tibetan Plateau, biogeochemical cycles in the polar regions are probably less influenced by human activities and more impacted by ice and ocean processes, despite the already noticed effect of Antarctic tourism on carbon emissions (Farreny *et al.*, 2011).

Summary and outlook

Our review suggests that recent climate change has had significant impacts on biogeochemical cycling throughout the Qinghai-Tibetan Plateau, and that human activities such as grazing and changes in land cover have modified and sometimes amplified these impacts. Figure 5 summarizes the results of these changes to the best of our current knowledge. For the carbon cycle, the warmer and wetter climate has increased NPP and soil respiration (Tan *et al.*, 2010; Zhuang *et al.*, 2010), but the plateau has become an increasingly weak carbon sink, with significant decreases in both SOC and SIC due to increased CO_2 emission (Wang *et al.*, 2008). If the plant species on the plateau can be confirmed to produce

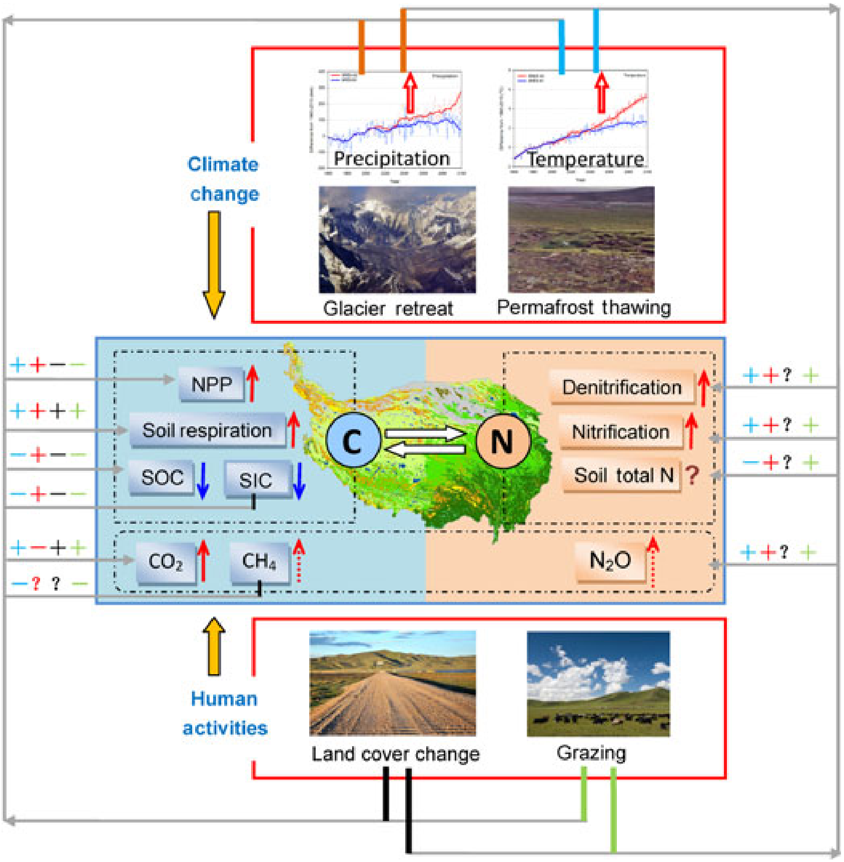

Fig. 5 Schematic diagram showing the effects of climate change, its induced cryospheric changes, and their cumulative impacts on the biogeochemical cycles of the Qinghai-Tibetan Plateau since 1960, and predictions for the near future. The warming and wetting is stimulating carbon and nitrogen cycling, and these trends are expected to continue for some time. As a result of the current and predicted future climate changes, the plateau will be a growing source of carbon and possibly a weakening emitter of methane and nitrous oxide. Human activities such as grazing and changes in land cover have modified these impacts of climate change, and will continue to do so. NPP, net primary production; SOC, soil organic carbon; SIC, soil inorganic carbon.

CH_4, increased NPP will mean that the vegetation becomes a stronger source of CH_4. Although the extent of typical peatlands has obviously decreased at most study sites (Zhang *et al.*, 2011b), the glacier retreat and permafrost thawing that have been observed on the plateau could create larger or new freshwater marshes or lakes (Zhang *et al.*, 2011a), which may lead to increased CH_4 emission from wetlands (Yang *et al.*, 2011) and probably even large-scale ebullition of labile CH_4 originating during the Pleistocene (Walter *et al.*, 2006). With the increase in human and livestock populations grazing has been ever greater, thus increased and intensified changes in land cover, further enhancing carbon loss from the plateau. One exception is moderate grazing, which may enhance carbon sequestration and increase the soil carbon stock (Hafner *et al.*, 2012). However, the increasing livestock population will definitely increase ruminant emission of CH_4.

In terms of the nitrogen cycle, the warmer and wetter climate has stimulated both nitrification and denitrification throughout the plateau, which would possibly increase N_2O emission, although it is not clear whether the net effects will be increased or decreased soil N pools (Xu *et al.*, 2010; Rui *et al.*, 2011). Grazing might also modify the effect of warming on soil N pools through its strong impacts on N cycling (Rui *et al.*, 2011). Fertilization and grazing are also believed to stimulate N_2O emission from the alpine meadows and wetlands on the plateau (Lin *et al.*, 2009; Jiang *et al.*, 2010). However, grazing might reduce N_2O emission from the steppes (Wolf *et al.*, 2010).

If the projected warming and wetting continue, NPP and soil respiration will increase continually and the whole plateau will become an increasing source of carbon (Fig. 3). Warming-induced retreat of glaciers and permafrost thawing will stimulate substantial carbon loss through increased efflux of CH_4 and CO_2 and increased loss of DOC. With increasing nitrogen deposition, the projected wetting and warming trends will accelerate the nitrogen cycle and increase N_2O emission from the plateau, although our current understanding of the carbon and nitrogen biogeochemical cycles on the plateau is largely uncertain at different temporal and spatial scales.

Since 1960, humans have modified the impacts of climate change on the Qinghai-Tibetan Plateau, but as this review shows, researchers have generally overlooked the impacts of human activities on the Qinghai-Tibetan Plateau. Because the plateau has sensitive and fragile ecosystems highly vulnerable to climate change, especially in terms of the plateau's biogeochemical cycles, it is crucial that we improve our understanding of this unique part of the Earth. Although difficult to determine, the critical climate thresholds for the plateau's ecosystem structure and functions should be an urgent research priority (Piao *et al.*, 2010). To improve our understanding of the plateau's biogeochemistry, we must also study phosphorus dynamics, because this important nutrient can greatly affect carbon and nitrogen cycles through its effects on vegetation growth (Vitousek *et al.*, 2010). Climate change and human activities have already created an imbalance between carbon, nitrogen, and phosphorus cycles in Earth's life support system, but the consequences of these interactions remain poorly understood (Zhang *et al.*, 2008; Vitousek *et al.*, 2010; Peñuelas *et al.*, 2012).

Preliminary evidence suggests that microorganisms and their responses to climate change have contributed greatly to biogeochemical cycles, more than what we expected. Therefore, studies on soil microbes and their roles in biogeochemical cycles must become a future research priority. Moreover, large uncertainties remain in our estimates of greenhouse gas emissions from the Qinghai-Tibetan Plateau in response to climate change and human activities, mainly because of the inadequate spatial and temporal resolution of climatic, ecosystem, and anthropogenic parameters and a lack of high-resolution datasets capable of adequately describing the heterogeneous landscape and vegetation communities of the plateau. As a result, global climate models and dynamic global vegetation models cannot accurately estimate future climate and land cover changes on the plateau.

Based on this summary, future research should focus on the following(i) collecting more field data at various temporal and spatial scales by establishing a coordinated national and international research network; (ii) developing an improved process-based ecosystem model that can account for the complexity of biogeochemical cycles of C, N, and P on the plateau; and (iii) developing a new framework that combines high-resolution data with improved models so as to calibrate and validate biogeochemical models and improve our ability to predict the impacts of changing climate and human activities on biogeochemical cycling on the plateau.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Integrated biosphere simulator model and its use to simulate trends for the Qinghai-Tibetan Plateau.
Fig. S1. Integrated biosphere simulator simulated net primary production plotted against MODIS NPP product on QTP.