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Possible decline of the carbon sink in the Mongolian Plateau during the 21st century

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Abstract
The Mongolian Plateau is dominated by grassland ecosystems. It frequently experiences drought and is underlain by permafrost in the north. Its complex responses of plant carbon uptake and soil carbon release to climate change are considered to have affected the global carbon cycle during the 21st century. Here we combine spatially explicit information on vegetation, soils, topography and climate with a process-based biogeochemistry model to assess the carbon responses for the 20th and 21st centuries. We estimate the region acted as a C sink of 31 Tg C yr^{-1} in the 1990s, but that this sink will likely decline in both magnitude and extent under future climate conditions. This change is due to the relatively larger enhancement of soil organic matter decomposition, which releases carbon to the atmosphere, than the corresponding enhancement of plant C uptake, by rising temperatures and atmospheric CO_2 concentrations. Future plant C uptake rates are expected to become more limited due to drier soils caused by increasing evapotranspiration rates. Complex soil thermal and moisture dynamics result in large interannual and spatial variability as a consequence of the different rates of change of air temperature and precipitation in this region.

Keywords: Mongolian Plateau, Terrestrial Ecosystem Model, carbon cycle, net ecosystem productivity, climate change

1. Introduction

The Mongolian Plateau (41.6–52.2°N and 87.6–119.9°E) lies in a prominent transition belt, which borders the Gobi Desert of Central Asia in the south and the Siberian taiga forest in the north (Batima and Dagvadorj 1998). The plateau is dominated by an arid or semiarid climate with a strong influence from the East Asia summer monsoon (Yatagai and Yasunari 1995). Due to its dry and cold climate, most of the plateau is covered by steppe. Grazing is the major anthropogenic disturbance. The northwestern part of the Mongolian Plateau belongs to the Republic of Mongolia and the south and eastern parts are the Inner Mongolia Autonomous Region of the People's Republic of China.

Similar to other regions in northern high latitudes, the intensity of climate change (e.g. surface air temperature) in the Mongolian Plateau tends to be above the average global level (Dagvadorj and Mijiddorj 1996, Serreze *et al* 2000, IPCC 2001, Gavrilova 2003). Furthermore, the feedbacks of the Mongolian Plateau to the East Asia summer monsoon systems (Yasunari 2003) may accelerate climate change in this region. Under arid and semiarid conditions, primary productivity is dramatically affected by interannual and decadal variability of climate (Maria and Barbara 1999, Bai *et al* 2004).

The atmospheric CO_2 sink/source activity of the terrestrial ecosystems in the Mongolian Plateau, especially grasslands, on annual or decadal scale, will depend heavily on how climate changes in this region, and on the responses of ecosystems to this change (Galloway and Melillo 1998, Ojima *et al* 1998, Li *et al* 2008). Because of its sensitive ecosystems and the vast area they cover, the Mongolian Plateau is considered to play an important role in the global carbon cycle in an altering climate system (Galloway and Melillo 1998, Li *et al* 2008). To date, some progress has been made in investigating terrestrial ecosystem productivity and C exchange in the Mongolian Plateau (e.g. Dong *et al* 2000, Li *et al* 2005a, 2005b, 2008, Holst *et al* 2008). However, relatively little attention has been paid to the carbon budget of the Mongolian terrestrial ecosystems on a regional scale. Further, no information has been available so far concerning how the regional carbon cycle will respond to the transient changes in climate and atmospheric CO_2 concentration in the future.

Here we apply a process-based biogeochemistry model, the terrestrial ecosystem model (TEM; Zhuang *et al* 2003), to estimate the carbon budget for the entire Mongolian Plateau. Using historical and modeled future climate data, we examine how climate change has affected C dynamics in the Mongolian Plateau over the 20th century and how these dynamics may respond to the variations in atmospheric CO_2 concentration and climate under different scenarios during the 21st century. The study also strives to identify the key controls of terrestrial ecosystem C dynamics in this region.

2. Methods

The TEM is a process-based, global-scale biogeochemistry model that uses spatially referenced information on climate, elevation, soils and vegetation to make monthly estimates of C and N fluxes and pool sizes of the terrestrial biosphere. In this study, we use the version of TEM that simulates freeze and thaw dynamics for permafrost-and non-permafrost-dominated ecosystems (Zhuang *et al* 2001, 2002, 2003). This version of the TEM has been extensively used to evaluate C dynamics at northern high latitudes (e.g. Euskirchen *et al* 2006, Zhuang *et al* 2006, Balshi *et al* 2007). The structure, algorithm, parameterization, calibration and performance of TEM have been well documented (McGuire *et al* 1992, Melillo *et al* 1993, Zhuang *et al* 2002, 2003, 2004).

In the TEM, for each monthly time step, net ecosystem productivity (NEP) is calculated as the difference between net primary productivity (NPP) and heterotrophic respiration (R_H). NPP is calculated as the difference between gross primary production (GPP) and plant autotrophic respiration (R_A). The algorithm for calculating R_A has been described elsewhere (Raich *et al* 1991, McGuire *et al* 1992, 1997). Monthly GPP considers the effects of several factors and is calculated as follows:

$$\mathrm{GPP} = \mathrm{C}_{\mathrm{MAX}} f(\mathrm{PAR}) f(\mathrm{PHENOLOGY}) f(\mathrm{FOLIAGE}) f(T) \times f(C_a, G_v) f(\mathrm{NA}) f(\mathrm{FT})$$

where C_{MAX} is the maximum rate of C assimilation, PAR is photosynthetically active radiation and f(PHENOLOGY) is monthly leaf area relative to leaf area during the month of maximum leaf area and depends on monthly estimated evapotranspiration (Raich *et al* 1991). The function f(FOLIAGE) is a scalar function that ranges from 0.0 to 1.0 and represents the ratio of canopy leaf biomass relative to maximum leaf biomass (Zhuang *et al* 2002), T is monthly air temperature, C_a is atmospheric CO_2 concentration, G_v is relative canopy conductance and NA is N availability. The effects of elevated atmospheric CO_2 directly affect $f(C_a, G_v)$ by altering the intercellular CO_2 of the canopy (McGuire *et al* 1997, Pan *et al* 1998). The function f(NA) models the limiting effects of plant N status on GPP (McGuire *et al* 1992). The function of f(FT) describes the effects of freeze–thaw dynamics on GPP. R_H is calculated based on modeled soil temperatures by considering permafrost dynamics. Further details of how GPP and R_H are calculated using permafrost dynamics can be found in Zhuang *et al* (2003).

Although many of the parameters in the model are defined from published information (e.g. McGuire *et al* 1992, Zhuang *et al* 2003), some are determined by calibrating the model to C and N fluxes and pool sizes at intensively studied field sites. For this application of the TEM, we have developed a set of parameters specifically for grasslands, the major vegetation type in the plateau, based on field observation data collected from within the region (Sui *et al* 2009). After calibration, the TEM was evaluated with the observed data of ecosystem C fluxes and pools at other sites in this region (Sui *et al* 2009). To run the TEM for the Mongolian Plateau for the 20th and 21st centuries, we organized data for climate, vegetation, soil texture and elevation at a 0.5° latitude × 0.5° longitude resolution from 1901 to 2100. Specifically, the vegetation data over the Mongolia Plateau are derived from the International Geosphere–Biosphere Program (IGBP) Data and Information System (DIS) DISCover Database (Belward *et al* 1999, Loveland *et al* 2000). The 1 km × 1 km DISCover dataset is reclassified into the TEM vegetation classification scheme (Melillo *et al* 1993) and then aggregated to the 0.5° × 0.5° spatial resolution. The soil texture data are based on the Food and Agriculture Organization/Civil Service Reform Committee (FAO/CSRC) digitization of the FAO–UNESCO (1971) soil map. For elevation, we use the 1 km × 1 km elevation data derived from the Shuttle Radar Topography Mission (SRTM) (Farr *et al* 2007). The SRTM data are resampled to match the resolution of other input data.

The driving climate datasets include the monthly air temperature, precipitation and cloudiness. The historical climate datasets from 1901 to 2000 are based on data from the CRU (Mitchell and Jones 2005). Owing to a lack of meteorological data before the 1950s for the Mongolian Plateau, the data for the first half-century in this dataset might not accurately represent the actual climatic conditions in the region. To simulate future C dynamics, we use four scenarios from the IPCC SRES (IPCC 2000, 2001), which are A1FI, A2, B1 and B2. Under those scenarios, the global climate has been simulated with HadCM3 at a 0.5° × 0.5° spatial resolution (Mitchell *et al* 2004). We extract the Mongolian climate data from the output of these GCM simulations based on the boundary of the plateau. The annual atmospheric CO_2

concentration data from 1901 to 2000 are based on atmospheric CO_2 observation data (Etheridge et al 1996, Keeling et al 1995) and data from our previous studies (Zhuang et al 2003). For the period from 2001 to 2100, we retrieve the information on annual CO_2 concentrations projected by a fast carbon cycle model, ISAM (Jain et al 1995), for the four SRES scenarios (IPCC 2001).

For each grid cell, we first run the TEM to equilibrium for an undisturbed ecosystem using the long-term averaged monthly climate and annual CO_2 concentrations from 1901 to 2000. The equilibrium pools of C and N are then used as the initial conditions for the simulation. We then spin up the model for 150 years to account for the influence of interannual climate variability on the initial conditions of the undisturbed ecosystem. We use the climate data from 1901 to 1950, repeated three times, for the 150 years used in the spin up. We then run the model with the forcing of the transient monthly climate data and the changes of annual atmospheric CO_2 concentrations from 1901 to 2100. To separate the CO_2 effects on carbon dynamics from the climate impacts, we conduct additional simulations with transient climate data from 2000 to 2100 and with a constant CO_2 concentration at the level of the year 2000.

Since autocorrelation in time and/or space usually undermines standard assumptions about the independence of residuals and thus the theoretical basis for estimating significance, we use nonparametric statistical methods, which are corrected for autocorrelation, to analyze our results. The Mann–Kendall trend test is used to check the trend of time-serial data (Hamed and Rao 1998). Spearman correlation analysis is used to calculate the correlation coefficients between environmental factors and C fluxes.

3. Results and discussion

3.1. Soil thermal and moisture dynamics

Over the 20th century, climate change has directly affected soil thermal and moisture conditions on the Mongolian Plateau. For soil thermal dynamics, the TEM simulation indicates that the average annual soil temperature at a depth of 20 cm remained generally between 0 and 2 °C for the whole region throughout the 20th century (figure 1). Between 1970 and 2000, however, simulated soil temperature increased at a rate of 0.03 °C yr^{-1} ($r = 0.40$; $p < 0.01$; $n = 31$) as a result of increasing air temperatures (figure 1). Simulated soil moisture fluctuated between 38 and 42% mainly in response to the high interannual variability of precipitation (figure 1).

According to the GCM simulations, the climate in the Mongolian Plateau will be warmer and wetter, but with different intensities in the different scenarios. During the 21st century, annual air temperatures are projected to increase more than 0.6–0.8 °C over the global average in the different scenarios (figure 1). This increase causes soil temperatures in the region to increase until they reach 5.7–9.1 °C by the end of this century. Although precipitation also increases throughout the 21st century, regional soil moisture decreases to 37.4–37.7% for all scenarios, which is significantly lower than the average soil moisture in the 20th century (figure 1). This decrease in soil moisture implies that increases in evapotranspiration induced by rising temperatures more than compensates for the increase in future precipitation on the Mongolian Plateau.

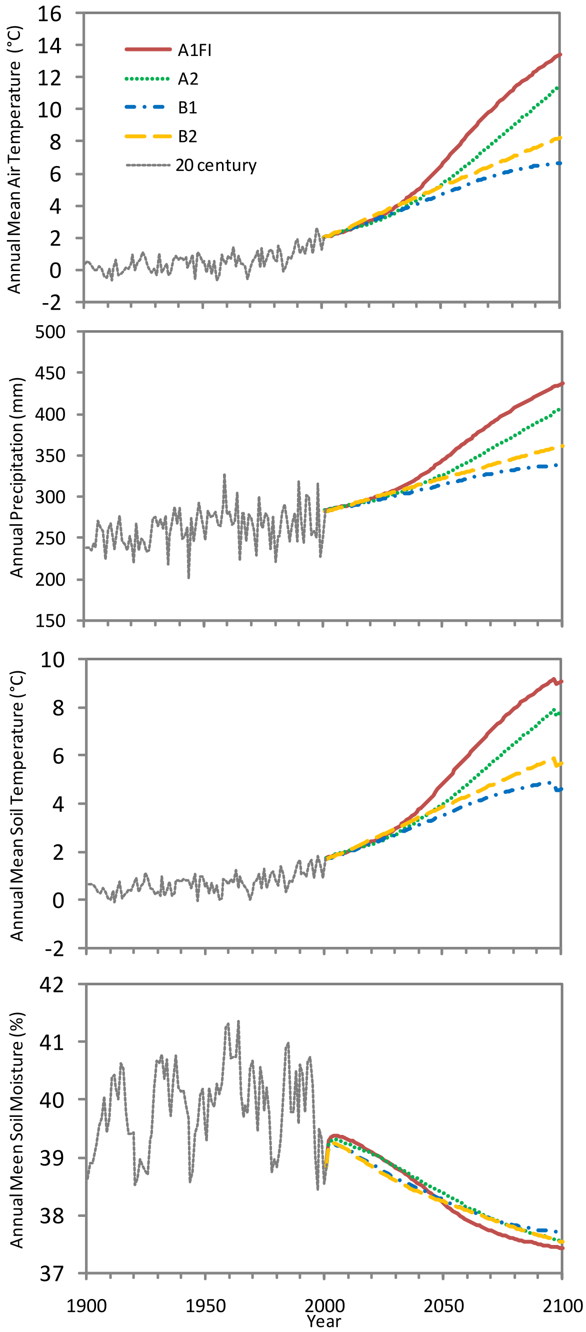

Figure 1. Annual air temperature, precipitation, soil temperature at 20 cm depth and soil moisture from 1901 to 2100 in the Mongolian Plateau. For a detailed description and information on the SRES A1FI, A2, B1 and B2 scenarios, refer to IPCC (2000) or http://sedac.ciesin.columbia.edu/ddc/sres/.

Permafrost dynamics also plays a critical role in the global C cycle (Zhuang et al 2003) and the TEM estimates that 1.12 million km^2 of the Mongolian Plateau (42%) is underlain by permafrost (figure 2). The TEM simulations of permafrost

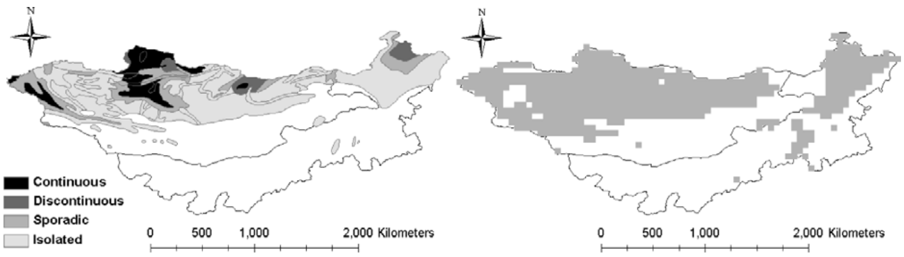

Figure 2. Permafrost distribution following Brown *et al* (1998) (left panel) and TEM simulation by using soil temperature at 200 cm depth during the 1990s (right panel) in the Mongolia Plateau.

Table 1. C fluxes and pool sizes for different ecosystems in the Mongolian Plateau during the 1990s. C_V represents the vegetation C pool and C_S represents the soil C pool for the region.

Type	Area (10^3 km^2)	NEP (Tg C yr^{-1})	NPP (Tg C yr^{-1})	R_H (Tg C yr^{-1})	GPP (Tg C yr^{-1})	C_V (Pg C)	C_S (Pg C)
Alpine tundra	9.8	0.03	0.73	0.70	1.47	0.01	0.06
Wet tundra	4.0	0.07	0.99	0.92	1.72	0.01	0.09
Boreal forests	158.1	1.51	46.01	44.50	101.00	1.81	1.88
Temperate forests	204.5	3.34	79.23	75.89	169.62	1.80	1.69
Temperate grasslands	1661.4	21.84	711.22	689.39	1566.48	2.87	6.94
Xeric shrublands	515.4	3.45	50.68	47.24	98.49	0.24	1.53
Xeric woodlands	100.3	1.14	17.92	16.78	29.35	0.14	0.53
Deserts	24.8	0.02	1.74	1.71	3.50	0.01	0.05
Total	2678.3	31.40	908.54	877.14	1847.96	6.88	12.78

distribution for the Mongolian Plateau are comparable with the data presented in Brown *et al* (1998), who estimated a total of 1.17 million km^2 underlain by permafrost mostly located north of 45°N in this region. The TEM simulations indicate that the permafrost dynamics are not sensitive to climate change in this region and its permafrost is relatively stable (data not shown). This may be mainly due to the fact that the permafrost is deep in this region. Specifically, our simulations indicate that the upper boundary of permafrost in this region is mostly deeper than 2 m, which is similar to the findings of Paetzold *et al* (2003) and Sharkhuu *et al* (2007).

3.2. Carbon dynamics

Our simulations indicate that the Mongolian Plateau acted as a C sink of 31.40 ± 172.76 Tg C yr^{-1} during the 1990s. This sink is represented by net ecosystem production (NEP), which is the difference between net primary production (NPP) of 908.54 ±176.69 Tg C yr^{-1} and heterotrophic respiration (R_H) of 877.14 ± 20.57 Tg C yr^{-1} over the total vegetated area of 2.68 million km^2 (table 1). Temperate grasslands dominate the regional sink because of its vast area and are responsible for about 70% of the total sink. Xeric shrublands and temperate forests are the next most important C sinks with similar sink strengths (10–11% of the total), but temperate forests cover less than one-half the area of xeric shrublands. Boreal forests and xeric woodlands account for 5% and 4% of the total C sink, respectively. The remainder of the C sink, less than 0.4%, is contributed by wet tundra, alpine tundra and deserts. The country of Mongolia accounts for 54% of the total sink, with Inner Mongolia accounting for 46%.

Our C flux estimates are similar to those observed or modeled in previous studies. Our NEP estimate of 38 g C m^{-2} yr^{-1} for grasslands is comparable to that of Li *et al* (2005a) estimate of 41 g C m^{-2} yr^{-1} based on eddy covariance measurements in Kherlenbayan-Ulaan (47°12′N, 108°44′E). On a per unit area basis, the TEM estimate of mean NPP is 339 ± 66 g C m^{-2} yr^{-1} for the Mongolian Plateau during the 1990s is slightly higher than the decadal average of 290 g C m^{-2} yr^{-1} estimated by the CASA model for Inner Mongolia during the period from 1982 to 2002, but is within the range of 145–502 g C m^{-2} yr^{-1} of their annual estimates for this region (Zhang *et al* 2008). Our simulation estimates GPP with a similar magnitude (1847.96± 230.79 Tg C yr^{-1} during the 1990s) and spatial pattern to those derived from satellite data in Inner Mongolia (Brogaard *et al* 2005); ecosystems in the northeast have a GPP of more than 1000 g C m^{-2} yr^{-1} while those in the southwest barely exceed 500 g C m^{-2} yr^{-1}.

Over the 20th century, the C fluxes over the Mongolian Plateau exhibited significant interannual variability (figure 3). The variation of NEP was mostly caused by the fluctuation of NPP. The C pool sizes in this region were relatively stable through the 20th century although there was a slight increasing trend in both vegetation and soil C during the latter part of the century. The TEM estimates that vegetation stored 6.88 ± 0.05 Pg C during the 1990s, while the soils stored 12.78 ± 0.02 Pg C in organic matter. While most of the soil organic matter (54%) was stored in temperate grasslands, vegetation carbon was stored more evenly across ecosystems, with 42% in temperate grasslands, 26% in boreal forests and 26% in temperate forests.

In the 21st century, the TEM simulations indicate that the response of the C cycle to climate change varies with the different SRES scenarios (figure 3). The largest responses of

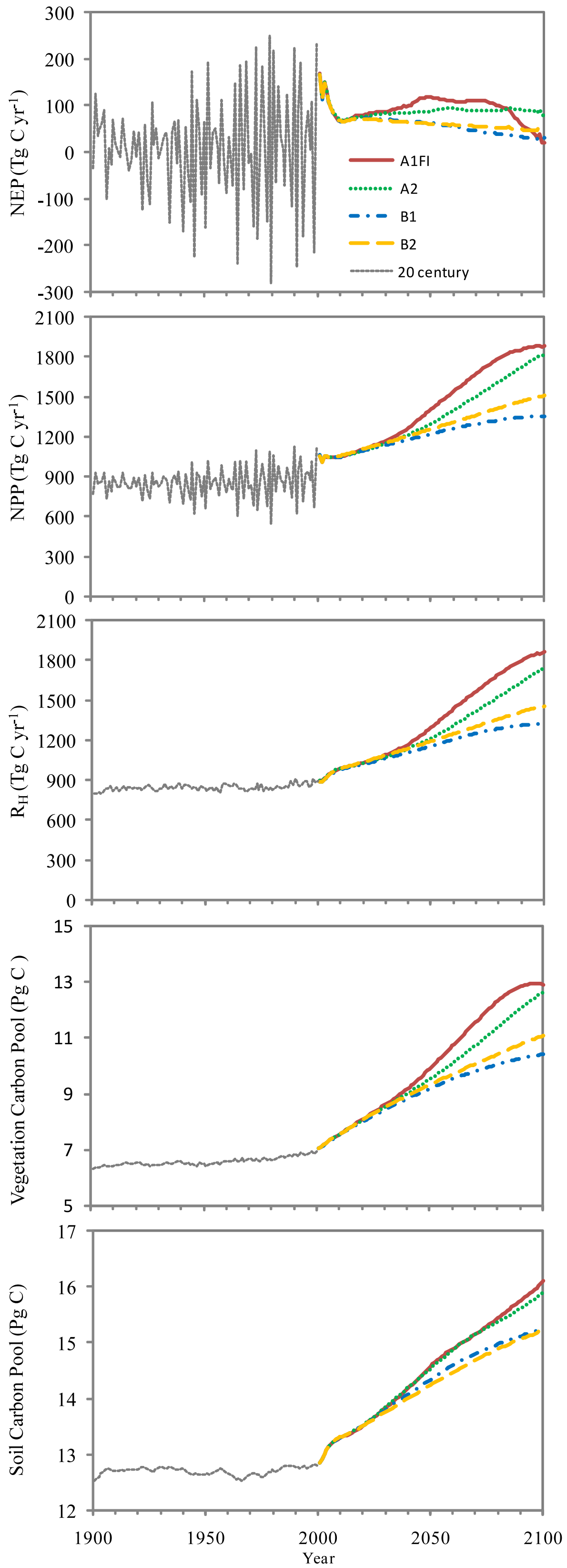

Figure 3. Annual C fluxes and pool sizes from 1901 to 2100 in the Mongolian Plateau.

NPP and R_H occur in the SRES A1FI scenario, which projects the greatest changes in air temperature and precipitation (figure 1). The smallest response occurs with the SRES B1 scenario, which projects the smallest changes in air temperatures and precipitation. The TEM estimates that NPP will increase to 1508–1883 Tg C yr^{-1} at the end of the 21st century, due to rising temperature, longer growing season and the fertilization effects of enhanced atmospheric CO_2 concentrations. As a result, C stored in the vegetation and soil will also increase (figure 3). However, the increases in NPP in the SRES A1FI scenario begin to fade during the late 21st century (figure 3) for two reasons. One is that temperatures or atmospheric CO_2 concentrations may have reached optimum values for plant C uptake during the 2080s. The other is that the lower soil moisture (figure 1), resulting from the rapid increase of evapotranspiration, hinders NPP. Our simulations indicate that R_H will increase by 4.5–10.8 Tg C yr^{-1} in response to the increase in soil C and temperature in the future.

As the difference of NPP and R_H, NEP displays different trends under the four scenarios during the 21st century. In the SRES A2, B1 and B2 scenarios, the NEP curve does not obviously change its curvature after an initial decline during the early part of the 21st century (figure 3). The steady decline in NEP (i.e. C sink) in the SRES B1 and B2 scenarios indicate that the rate of R_H is slowly approaching the rate of NPP. The increase in NEP in the SRES A1FI and A2 scenarios indicate that NPP is increasing faster than R_H as a result of the larger and continual increases in atmospheric CO_2 concentrations that occur in these scenarios. The change in NEP in the SRES A1FI scenario during the 2080s (figure 3) is a result of the fading NPP increases (described above), allowing the rate of R_H to approach that of NPP more quickly. Thus, under intense climate change in the future, the C sink on the Mongolian Plateau will also decline and the region may even become a C source. The Mongolian Plateau remains a steady C sink only under the SRES A2 scenario where future increases in NPP are able to maintain the pace of corresponding increases in R_H.

In addition to temporal trends, different spatial patterns of C sink/source behavior are predicted for the four SRES climate scenarios (figure 4). During the 2000s, the plateau generally acted as a C sink except for regions in the northwest and northeast. With climate change, the areal extent of C source behavior generally shrinks until the middle of the 21st century in all scenarios. After that, the areal extent of C sources tends to increase. For the SRES A1FI scenario, in particular, our simulations indicate that large grasslands in the middle of the plateau shift from C sinks to C sources during the late 21st century, which directly induce the sharp decrease in regional NEP (figure 3) described earlier.

3.3. Impact of environmental factors on C dynamics

The Mongolian Plateau is characterized by low precipitation, frequent droughts and low air temperatures. Under this environment, soil thermal and moisture conditions are more likely to become limiting factors to carbon uptake by plants. To identify the key controls on C dynamics in the Mongolian Plateau, we examine correlations between environmental factors and C fluxes and pools over the 20th century (table 2). Precipitation is the most important control to C fluxes and the vegetation carbon pool. The high correlation

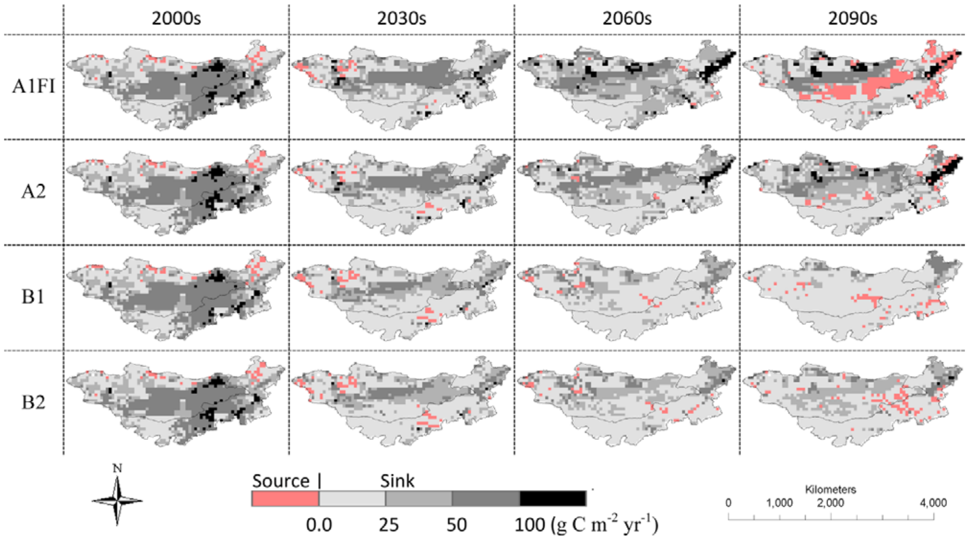

Figure 4. Spatial patterns of NEP during the 2000s, 2030s, 2060s and 2090s in different future scenarios. Red indicates carbon source and gray indicates carbon sink (g C m^{-2} yr^{-1}).

Table 2. Spearman correlations between physical variables and C fluxes as well as C pool sizes in the Mongolian Plateau. The coefficients were calculated by Spearman correlation analysis of the regional aggregated results from 1901 to 2000.

	CO_2 level	Air temperature	Precipitation	Soil temperature	Soil moisture
NEP	0.01	−0.09	0.40[a]	−0.15	0.02
NPP	0.11	0.03	0.46[a]	−0.02	0.09
R_H	0.46[a]	0.71[a]	0.30[a]	0.70[a]	0.29[a]
C_V	0.89[a]	0.55[a]	0.37[a]	0.53[a]	0.27[a]
C_S	0.21[b]	0.15	0.00	0.13	0.07

[a] $p < 0.01$. [b] $p < 0.05$.

between precipitation and C dynamics is consistent with field observations (Dong *et al* 2000, Bai *et al* 2004, Knapp and Smith 2001, Li *et al* 2005a), suggesting that water availability highly constrains vegetation growth and soil microbial activity in such arid or semiarid regions. Further investigation at the site level also indicates that soil moisture conditions mainly govern the seasonal variation of C dynamics in this region (Li *et al* 2008). Our analysis, however, indicates that the regional soil moisture is only weakly correlated with annual C flux or pool size, suggesting that other physical factors (e.g. soil thermal regime), together with moisture condition, collectively affect carbon dynamics. Precipitation, soil moisture and temperature all have high positive correlation with the regional R_H, suggesting that soil respiration in this region is sensitive to both thermal and moisture conditions. Further, the positive Spearman correlation coefficient between the atmospheric CO_2 concentrations and R_H indicates that the enhanced CO_2 concentrations will increase regional R_H by stimulating soil C accumulation. Taken together, the warmer and wetter future climate combined with higher atmospheric CO_2 concentrations are likely to promote more C release in the Mongolian Plateau.

From our additional simulations with constant atmospheric CO_2 concentrations, we estimate that, under the SRES future climate scenarios A1, FI, A2, and B2, the region will become a C source ranging from 23.38 to 138.84 Tg C yr^{-1} by the end of the 21st century. This suggests that future atmospheric CO_2 concentration levels will also determine the carbon dynamics in this region.

4. Conclusions and future work

This study represents an attempt to explicitly examine the regional C dynamics in response to climate change on the Mongolian Plateau. Our model simulations indicate that the permafrost in this region is relatively stable due to a thick top soil layer above the permafrost table in spite of increases in air temperature. The rising temperature increases ground evapotranspiration, drying soils even in wetter climate conditions. These dynamics determine why the Mongolian Plateau acted as a C sink of 31.40 Tg C yr^{-1} in the 1990s along with large interannual and spatial variabilities in this sink/source behavior. During the 21st century, warming will likely induce the decline of the C sink on the Mongolian Plateau.

This study focuses on analyzing the regional response of ecosystem carbon dynamics to future climate change. However, the large grid cell areas used by the Global General Circulation Models (GCMs) to simulate future climate conditions for the SRES scenarios along with the lack of interannual climate variability may bias our evaluations. These deficiencies could be better addressed with the use of Regional Climate Models that are bounded by the output of GCMs to provide more reasonable future climate predictions and thus help to improve evaluation of future carbon dynamics for this region. Further, rapid economic development is occurring in this region, but little information exists to document the timing and spatial pattern of associated land-use changes. Thus, we have not considered the impacts of land-use change in our analysis. To improve future analysis of carbon dynamics in this region, research priorities should be directed to quantifying how humans will appropriate and alter the land ecosystems in this region to allow development of spatially explicit time series datasets of land-use change.

In addition, regional peatlands contain a large amount of carbon and are recognized to be important in carbon cycling over the Mongolian Plateau (Minayeva *et al* 2004, 2005). Unfortunately, datasets were not available to us to document the distribution of these peatlands for our analysis. We would expect the climate changes examined in this study to accelerate the C release from the peatlands, similar to our results for upland ecosystems, and to potentially cause the region to become a source rather than a sink of atmospheric CO_2 in the future. Thus, the development of datasets describing peatlands distribution and their fluxes of carbon, water and energy, and further quantifying their role in regional C dynamics, should be the other research priorities for the region.

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