Contribution of climate change and rising CO_2 to terrestrial carbon balance in East Asia: A multi-model analysis

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ABSTRACT

In this study, we use three process-based terrestrial ecosystem models (Lund-Potsdam-Jena Dynamic Global Vegetation Model — LPJ-DGVM; ORganizing Carbon and Hydrology In Dynamic Ecosystems – ORCHIDEE; Sheffield model – SDGVM) to investigate the historical response of ecosystem Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP) over East Asia to climate change and rising atmospheric CO_2. The results suggest that between 1901 and 2002, the modeled NPP has significantly increased by 5.5–8.5 Tg C yr^{-1} (15–20% growth). Such increase in NPP has caused an increased cumulated terrestrial C storage by about 5–11 Pg C. About 50–70% fraction of this total C sink is located in vegetation biomass. Our modeling results also suggest that 40–60% of the accumulate C uptake of the 20th century is credited to the period of 1980–2002. Although all models tend to agree at the continental scale that East Asia played a role of net C sink (0.14–0.18 Pg C yr^{-1}) during 1980s and 1990s, the trends of NEP are different among the models. Both LPJ and ORCHIDEE estimate a slight but insignificant NEP decrease from 1980 to 2002 ($P>0.05$), while SDGVM estimates a statistically significant increase in NEP at a rate of 0.005 Pg C yr^{-2} ($P<0.05$). Also, there is no consensus among models on the dominant driving factors controlling interannual variation in NPP and NEP at the continental scale, implying that more efforts are needed to investigate the vulnerability of the East Asian terrestrial carbon cycle.

1. Introduction

In the past two decades, inversion models of atmospheric CO_2 concentration have provided evidence that terrestrial ecosystems of the Northern Hemisphere are a large carbon sink (Gurney et al., 2002; Peylin et al., 2005; Stephens et al., 2007). The strength of that sink shows high year-to-year variation in response to climate variation (Bousquet et al., 2000; Piao et al., 2008). Most of the focus has been given so far to the North American and European continents (Schimel et al., 2000; Pacala et al., 2001; Janssens et al., 2003; Ciais et al., 2008). For example, Schimel et al. (2000) used three ecosystem models to estimate that rising atmospheric CO_2 and climate change stimulated net carbon (C) accumulation by about 0.08 Pg C yr^{-1} in the conterminous United States. Vetter et al. (2008) investigated the variability of the European C balance using seven models, and estimated that the total carbon flux anomaly during the European heatwave in 2003 ranged between -0.02 and -0.27 Pg C relative to the net carbon flux in 1998–2002. However, substantial uncertainties remain for the spatial distribution of the carbon source/sink and its underlying causes (IPCC, 2007).

East Asia (including China, Japan, Korea, and Mongolia) covers a vast area of $12*10^6$ km². Regional climate is dominated by the Asian monsoon, with diverse climate types ranging from tropical to cold-temperate and from humid to extremely dry. Due to the large climate variance, the vegetation of East Asian includes a broad range of tropical, temperate, and boreal forests, grassland, and desert (Fang et al., 2001). On the other hand, East Asia is maybe one of the most critical and sensitive regions in the global climate system (Fu et al., 2006; Piao et al., 2010). During the past two decades, mean annual temperature over China increased by more than 0.6 °C/decade, a much faster rate than the global land mean temperature trend (~0.27 °C/decade; IPCC, 2007). Associated with this warming, a significant change in seasonal precipitation pattern has been also observed (Piao et al., 2005). Such

rapid shifts in temperature and precipitation certainly impact the regional carbon balance between productivity and decomposition rates. Better quantification and understanding of the carbon cycle of East Asian ecosystems, and of its perturbation by past and current climate change, is a high priority where research is needed (IPCC, 2007).

Ecosystem models have established as useful tools for understanding and predicting terrestrial carbon cycle at local, regional, continental and global scales (Ciais et al., 2005; Piao et al., 2008; Sitch et al., 2008; Peng et al., 2009), in synergy with observations. Modeling the effects of climate on the terrestrial carbon cycle of East Asia has been tackled for instance by Piao et al. (2005) and Mu et al. (2008). Using a biogeochemical model, Piao et al. (2005) concluded that vegetation productivity in China has increased significantly due to climate change and rising atmospheric CO_2. More recently, after analyzing interannual variations in the terrestrial C budget of China, Mu et al. (2008) found an increasing C sink for China from 1960 to 2000, with C being mainly packed away in the vegetation biomass. Although these modeling studies helped to improve our understanding of the response of ecosystem C fluxes to climate and CO_2, their conclusions depend to an unknown extent on the model parameterizations. To assess the uncertainties due to model structure and parameter choices, it is necessary to perform simulation analysis with an ensemble of independent models (Cramer et al., 2001; Friedlingstein et al., 2006; Sitch et al., 2008). Although in a current study Piao et al. (2009a,b) have presented China's C budget estimate using five different biogeochemical models, the linkage between climate change and terrestrial ecosystem C balance of these regions was not fully investigated because the study focused mainly on the magnitude of current C budget at national scale.

In this work, three independently developed process-based models, Lund-Potsdam-Jena (LPJ) model (Sitch et al., 2003), ORganizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model (Krinner et al., 2005), and Sheffield (SDGVM) model (Woodward and Lomas, 2004) are used to estimate the impact of climate change on the East Asian terrestrial carbon budget and make comparison. The simulation period covers the last century to incorporate a long-term dynamics that affects the ecosystem carbon cycle. The primary objective of this study is to investigate uncertainties of historical variation in vegetation net primary productivity (NPP) and net ecosystem productivity (NEP) driven by climate change and by rising atmospheric CO_2.

2. Methods

2.1. Ecosystem models

We applied three process-based ecosystem models to simulate the terrestrial biogeochemical processes from 1901 to 2002. The three

models are: Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) (Sitch et al., 2003); ORganizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model (Krinner et al., 2005); and Sheffield model (Woodward and Lomas, 2004). The main features of the three models are summarized in Table 1. These models have been extensively validated against measured carbon fluxes at particular sites around the world (Krinner et al., 2005; Sitch et al., 2003); they also realistically simulate observed historical change in leaf area index (LAI) and transient responses of carbon fluxes to climate variability (Lutch et al., 2002; Ciais et al., 2005; Piao et al., 2006, 2008). Tao and Zhang (2010) have also validated LPJ derived NPP and carbon storage against observation in China. Terrestrial NEP fluxes from ORCHIDEE have also been successfully validated against measured carbon fluxes at particular sites in China (Tan et al., 2009; Peng et al., in prepare).

The LPJ-DGVM is a coupled dynamic biogeography-biogeochemistry model which explicitly considers key ecosystem processes such as photosynthesis, carbon allocation, mortality, resource competition, fire disturbance and soil heterotrophic respiration. To account for the variety of structure and functioning among plants, 10 plant functional types (PFTs) are distinguished. Gross primary production is calculated following Farquhar et al. (1980) using an inner-leaf CO_2 concentration that is dependent on the canopy conductance. Canopy conductance is constrained by photosynthesis and soil water supply. The effect of soil water availability on LAI is taken into account. LPJ's sub-model of light use efficiency assumes no limitation of nitrogen uptake (Haxeltine and Prentice, 1996). The dynamic vegetation carbon pools for leaves, sapwood, heartwood, and fine roots determine plant functioning, e.g. NPP and soil water uptake. Three soil carbon pools with different turnover rates are used to calculate temperature and moisture dependent heterotrophic respiration. The depth of soil in LPJ is 1 m.

The ORCHIDEE model (Krinner et al., 2005) is a dynamic global vegetation model to simulate the global carbon and water cycles. ORCHIDEE consists of five vegetation carbon reservoirs, four litter reservoirs, and three soil reservoirs. The vegetation assimilation in ORCHIDEE is based on Farquhar et al. (1980) for C3 photosynthesis and Collatz et al. (1991) for C4 photosynthesis, and the carbon allocation among leaves, stem and roots is according to the allocation scheme of Friedlingstein et al. (1998). Maintenance respiration is a function of each living biomass pool and temperature (Ruimy et al., 1996). Heterotrophic respiration parameterization is taken from the CENTURY model (Parton et al., 1993). The depth of soil in ORCHIDEE is 2 m.

The SDGVM model was developed to simulate both functional variables (e.g., primary productivity) and structural variables (e.g., leaf area index). Plant CO_2 assimilation is based on work by Farquhar et al. (1980). Stomatal conductance is taken from Jarvis (1976) and

Table 1
Characteristics of the biogeochemical models.

Process	LPJ	ORCHIDEE (ORC)	SDGVM (SHE)
Photosynthesis	Farquhar et al. (1980)/Collatz et al. (1991)	Farquhar et al. (1980)/Collatz et al. (1991)	Farquhar et al. (1980)/Collatz et al. (1991)
Stomatal conductance	Haxeltine and Prentice(1996)	Ball et al. (1987)	Leuning (1995)
Sapwood respiration	Dependent on sapwood mass and C:N ratio (Lloyd and Taylor, 1994)	Dependent on temperature, sapwood mass and C:N ratio	Annual sapwood increment, C:N f(T)
Fine root respiration	f(T,C_{root})	f(T,C_{root})	f(T,C_{root})
Evapotranspiration	Total evapotranspiration (Monteith, 1995)	Transpiration, interception loss, bare ground evaporation and snow sublimation are computed using Monteith-type formulations (Ducoudré et al., 1993)	Penman-Monteith transpiration (Monteith, 1981) + interception + evaporation from soil surface
Soil water balance	2 soil layers Modified bucket model from Neilson (Neilson, 1993)	2 soil layers (deep bucket layer and upper layer of variable depth)	3 soil + 1 litter layer Modif. Bucket model
Litter fall	Annual litter carbon balance	Daily litter carbon balance	Monthly litter carbon balance
Hetetrophic respiration	f(T,θ_{top},tissue type)	Based on Parton et al. (1988)	Similar to CENTURY (Parton et al., 1993)
C allocation	Annual allometric relationship for individuals	Based on resource optimization (Friedlingstein et al., 1998)	Daily allocation by demand in order of priority LAI>roots>wood
N uptake			f (soil C, N, T, and moisture)
N allocation	Implicit, dependent on demand	Fixed C:N	Variable N with light

Stewart (1998). Maintain respiration depends on the mass of living tissue and on temperature. The temperature response function for maintenance respiration was derived from Hay and Delecolle (1989) and Paembonan et al. (1991). The soil C dynamics model is based on CENTURY (Parton et al., 1993). The depth of soil in SDGVM is 1 m.

2.2. Model runs

Each model was run from its pre-industrial equilibrium at 1901, and then over the historical period 1901–2002 using observed data of monthly climatology and annual global atmospheric CO_2 concentration (Keeling and Whorf, 2005). The meteorological data (air temperature, precipitation, wet day frequency, diurnal temperature range, cloud cover, relative humidity of the air, and wind speed) with spatial resolution of 0.5° for 1901–2002 were supplied by the Climatic Research Unit (CRU), School of Environmental Sciences, University of East Anglia, U.K. (Mitchell and Jones, 2005), while annual global atmospheric CO_2 concentrations for the period 1901–2002 were based on data from ice-core records and atmospheric observations (Keeling and Whorf, 2005). Both ORCHIDEE and SDGVM used

prescribed actual vegetation (Loveland et al., 2000), while LPJ calculated its own vegetation distribution (Sitch et al., 2003; Tao and Zhang, 2010). Soil texture distribution information was derived from the Zobler (1986) soil texture map.

3. Results

3.1. Carbon cycle from 1901 to 2002

3.1.1. Interannual variations

During the period 1901–2002, the East Asian climate shows variability and a significant positive trend in temperature (0.01 °C yr^{-1}, $R^2 = 0.38$, $P < 0.001$), but no trend in precipitation ($R^2 = 0.01$, $P > 0.05$) (Fig. 1). In response to change in climate and to rising atmospheric CO_2 concentration, regional total NPP estimated by the three models increased 8.5 Tg C yr^{-1} (a 20% growth) in ORCHIDEE, 6.3 Tg C yr^{-1} (a 16% growth) in SDGVM, and 5.5 Tg C yr^{-1} (a 15% growth) for LPJ, respectively.

The largest cumulated NEP, or net C storage, is estimated by LPJ (10.6 Pg C), followed by ORCHIDEE (6.4 Pg C) and SDGVM (5.2 Pg C)
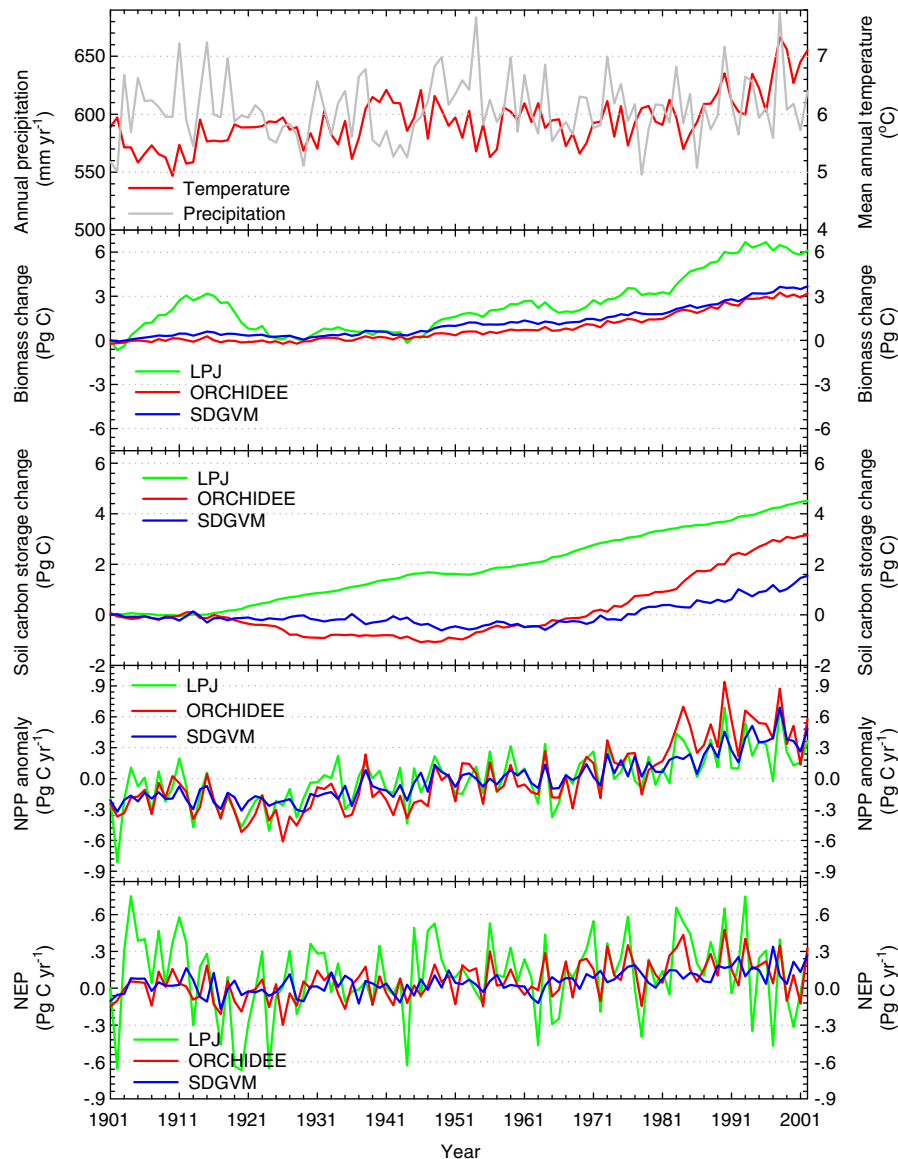
Fig. 1. Changes in anomalies of terrestrial net primary productivity (NPP, Pg C yr^{-1}), biomass carbon storage (Pg C) in relative to 1901, soil carbon storage (Pg C) in relative to 1901, terrestrial net ecosystem productivity (NEP, Pg C yr^{-1}), anomalies of annual precipitation (mm), and anomalies of annual mean temperature (°C) in East Asia from 1901 to 2002. Positive values of NEP indicate carbon sink and negative values of NEP indicate carbon source.

(Table 2). Furthermore, ORCHIDEE estimates that about 3.2 Pg of C has been accumulated in vegetation, which is very close to the estimation of SDGVM (3.7 Pg C), but is only 50% of the estimation by LPJ (6.1 Pg C) (Fig. 1 and Table 2). All models predicted a net carbon gain in soil C storage as the net effect of soil warming (that increased soil respiration) and increased NPP (that increased litterfall). Yet, there are large differences in soil C storage estimated by the 3 models. The soil C estimated by SDGVM (1.5 Pg C) is only 30% of that estimated by LPJ (4.5 Pg C). The ORCHIDEE result is intermediate with 3.2 Pg of net soil C gain. For the partition of the C sink between biomass and soil, SDGVM estimated 70% of the net carbon gain to be stored in biomass, while LPJ and ORCHIDEE estimated about 50% and 60% respectively (Table 2).

At the continental scale, all three models show that interannual variations in NEP corresponded more closely with those in NPP ($R^2 = 0.65$, 0.52, and 0.35 for ORCHIDEE, LPJ, and SDGVM, respectively) than with those in HR (heterotrophic respiration) ($R^2 = 0.24$, 0.34, and 0.04 for ORCHIDEE, LPJ, and SDGVM, respectively). This result implies that the interannual variations in terrestrial net C uptake in East Asia are primarily attributed to the variations in productivity.

Regarding the effects of climate on NPP (Fig. 2A), ORCHIDEE and SDGVM simulate that interannual variations in NPP corresponded more closely with those in temperature ($R^2 = 0.22$ and 0.47 for ORCHIDEE and SDGVM, respectively) than with those in precipitation ($R^2 = 0.17$ and 0.15 for ORCHIDEE and SDGVM, respectively). In contrast, LPJ suggests that NPP variations are rather driven by precipitation ($R^2 = 0.26$) than by temperature ($R^2 = 0.14$). Accordingly, interannual variation of NPP is more significantly correlated between in ORCHIDEE and SDGVM ($R = 0.91$) than both between in ORCHIDEE and LPJ ($R = 0.83$) and between in LPJ and SDGVM ($R = 0.78$) (Fig. 3).

For NEP, LPJ shows higher interannual variation in NEP (0.32 Pg C yr^{-1} of SD) than ORCHIDEE (0.16 Pg C yr^{-1} of SD) and SDGVM (0.09 Pg C yr^{-1} of SD) (Fig. 2B). Different models also suggest different dominant driving factors of interannual variation in NEP. In SDGVM temperature ($R^2 = 0.10$) is more significantly related with NEP interannual variability than precipitation ($R^2 = 0.00$) at the continental scale, while in both ORCHIDEE and LPJ, it is estimated that the interannual variation in NEP is mainly caused by precipitation change ($R^2 = 0.22$ and 0.19, respectively) (Fig. 2B). Thus, interannual variation of NEP is more significantly correlated between in ORCHIDEE and LPJ ($R = 0.63$) than between ORCHIDEE and SDGVM ($R = 0.59$) (Fig. 3). Furthermore, interannual variation of NEP simulated by LPJ is not significantly correlated with that of SDGVM ($R = 0.16$) (Fig. 3). Both ORCHIDEE and LPJ derived NEP is not significantly correlated with temperature ($R^2 = 0.01$ and 0.02, respectively), suggesting similar temperature sensitivities of NPP and HR in these two models.
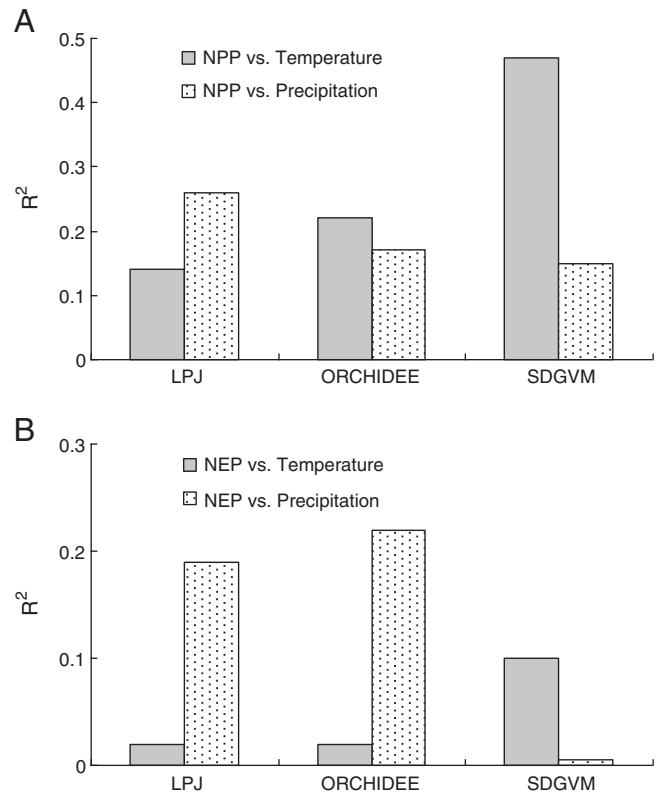
3.1.2. Spatial patterns of accumulated net C uptake

Fig. 4 shows the spatial distribution of cumulated NEP in East Asia from 1901 to 2002. All models suggest that northwest China and south Mongolia have lost C or have been C neutral, while the
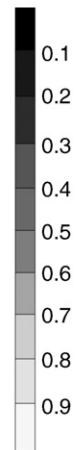

Fig. 2. Different model derived explanation (R^2) of change in temperature and precipitation on the interannual variation in total NPP (A) and total NEP (B) in East Asia.

Fig. 3. Matrix of correlation of NPP (A) and NEP (B) derived by different models.

Table 2
Different model derived terrestrial net ecosystem productivity (NEP, Pg C), biomass carbon storage change (Pg C), and soil carbon storage change (Pg C) during the period of 1901–2002 and 1980–2002.

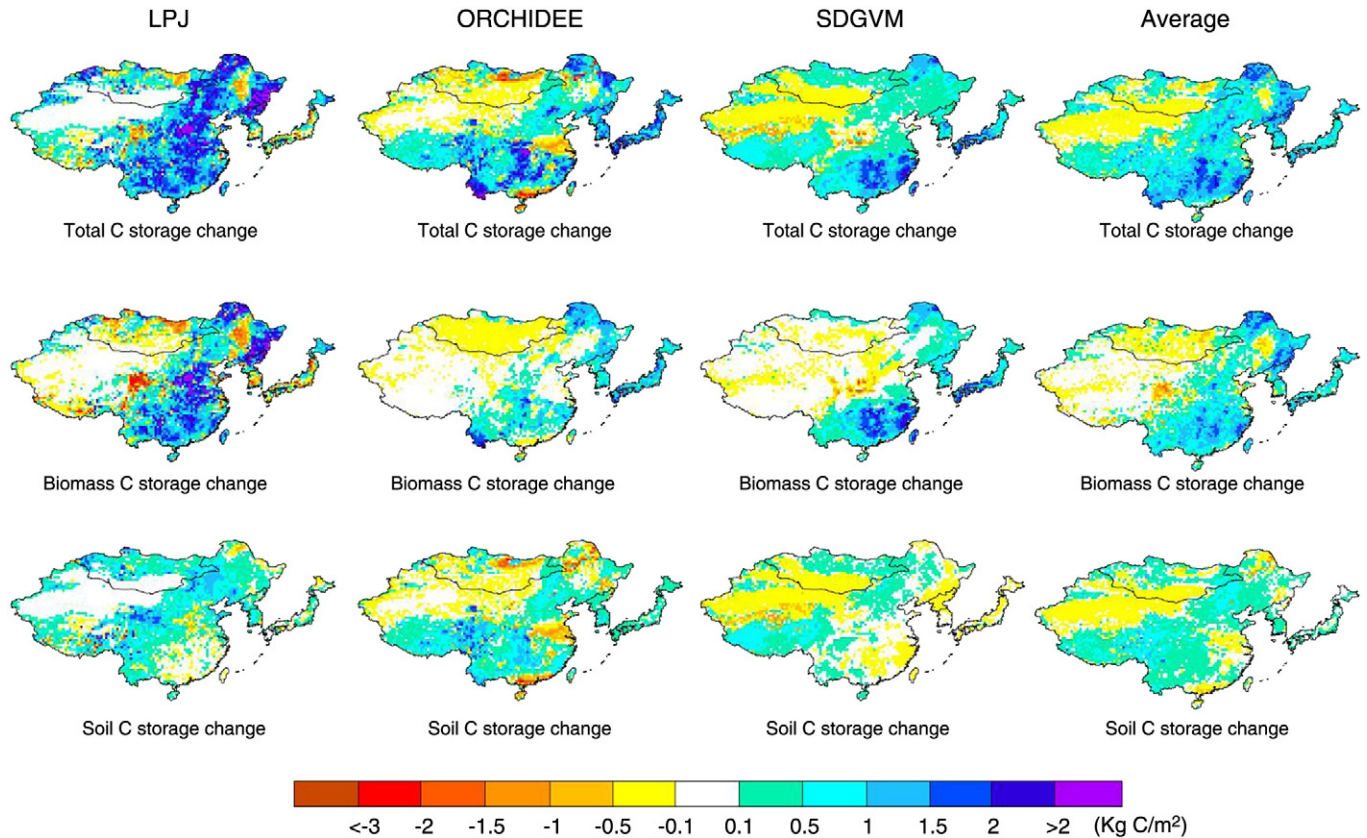| Period	Models	NEP (Pg C)	Biomass change (Pg C)	Soil C storage change (Pg C)
1901–2002	LPJ	10.6	6.1	4.5
	ORCHIDEE	6.4	3.2	3.2
	SDGVM	5.2	3.7	1.5
1980–2002	LPJ	4.2	2.9	1.3
	ORCHIDEE	4.1	1.8	2.4
	SDGVM	3.1	1.9	1.2

Fig. 4. Spatial patterns of modeled change in total carbon storage, biomass carbon storage, and soil carbon storage change from 1901 to 2002.

Daxing'anling Mountain of northeast China, northern China, southeast and southwest China, and North Korea have accumulated C. In north Mongolia, ORCHIDEE simulation indicates a substantial C loss, while SDGVM estimate an increase in C storage in these regions.

With respect to partition of net C accumulation between biomass and soil, large differences exist among three model simulation results (Fig. 4). For example, although LPJ estimates that biomass in most parts of South Korea and Japan decreased, both ORCHIDEE and SDGVM show an increase in biomass C storage which is the main cause of the increase in ecosystem C storage over these regions. In the Tibetan Plateau, all models suggest that the accumulated C during the last century is mainly in soil. In the Daxing'anling Mountain of northeastern China, all models estimate decrease in soil C storage, which may be related to strong increase in temperature over the last century (IPCC, 2007).

3.2. Carbon cycle from 1980 to 2002

3.2.1. Spatial patterns of NPP and NEP

Fig. 5A–D illustrates the distribution of average NPP derived by three different models during the period of 1980–2002, indicating strong spatial gradients which reflect gradients in temperature and precipitation conditions. All models show similar spatial patterns: NPP clearly decreased from southeastern to northwestern areas, although the magnitude of NPP estimated by different models is different. Because of the tropical wet climate, the highest NPP estimated by three models all appear in the southern part of China where ORCHIDEE tends to estimate higher NPP than the other two models. Due to occurrence of the subtropical wet climate, relatively high values of NPP are found in south Japan and southeast China, although LPJ derived NPP is much lower in these regions than that of ORCHIDEE and SDGVM. In the western part of East Asia, the limited precipitation causes sparse vegetation cover. As a result, NPP

in the western part of East Asia is very low, mostly lower than 300 g C m^{-2} yr^{-1}.

Regarding the spatial patterns of NEP (Fig. 5E–H), all models simulate that climate change and rising CO_2 lead to a C sink over most of the East Asian region (more than 75% of the domain).The largest difference of NEP estimation among models appears in central parts of Northeast China and Mongolia where LPJ estimates a very strong net C source (over 50 gC m^{-2} yr^{-1}), while both ORCHIDEE and SDGVM show a slight C storage change (Fig. 5). The highest net C uptake (over 50 gC m^{-2} yr^{-1}) estimated by ORCHIDEE appears in northeast of China, Central China including Hubei and Hunan province, and southwestern China, while that of SDGVM occurs in southeastern China. LPJ simulates that the highest C sinks (over 50 g C m^{-1} yr^{-1}) are mainly distributed in east parts of China and southwest China (Fig. 5).

3.2.2. Spatial patterns of the trend in NPP and NEP

In order to explore spatial patterns of NPP and NEP change from 1980 to 2002, we calculate linear trend of NPP and NEP for each pixel using ordinary least squares (Fig. 6). Large differences exist among the models in terms of NPP trend between 1980 and 2002 (Fig. 6A–D). In northern Mongolia, a large negative trend of NPP is found (over 5.0 g C m^{-2} yr^{-1}) in ORCHIDEE and LPJ, but a positive trend in SDGVM. The forcing climate data show that warming and drying occurred in this region during the period considered. All models show a substantial increase in NPP in south China of magnitude larger than 3 g C m^{-2} yr^{-1}. Overall, at the continental scale, total NPP significantly increased in SDGVM by 0.02 Pg C yr^{-2} (0.4% yr^{-1}, $R^2 = 0.51$, $P<0.001$), while ORCHIDEE (0.01 Pg C yr^{-2} or 0.2% yr^{-1}, $R^2 = 0.06$, $P>0.05$) and LPJ (0.01 Pg C yr^{-2} or 0.2% yr^{-1}, $R^2 = 0.07$, $P>0.05$) shows an insignificant increase in the continental scale NPP.

In general, the modeled spatial patterns of NEP trend are consistent with those of the NPP trend. For example, the largest CO_2

NPP   **NEP**
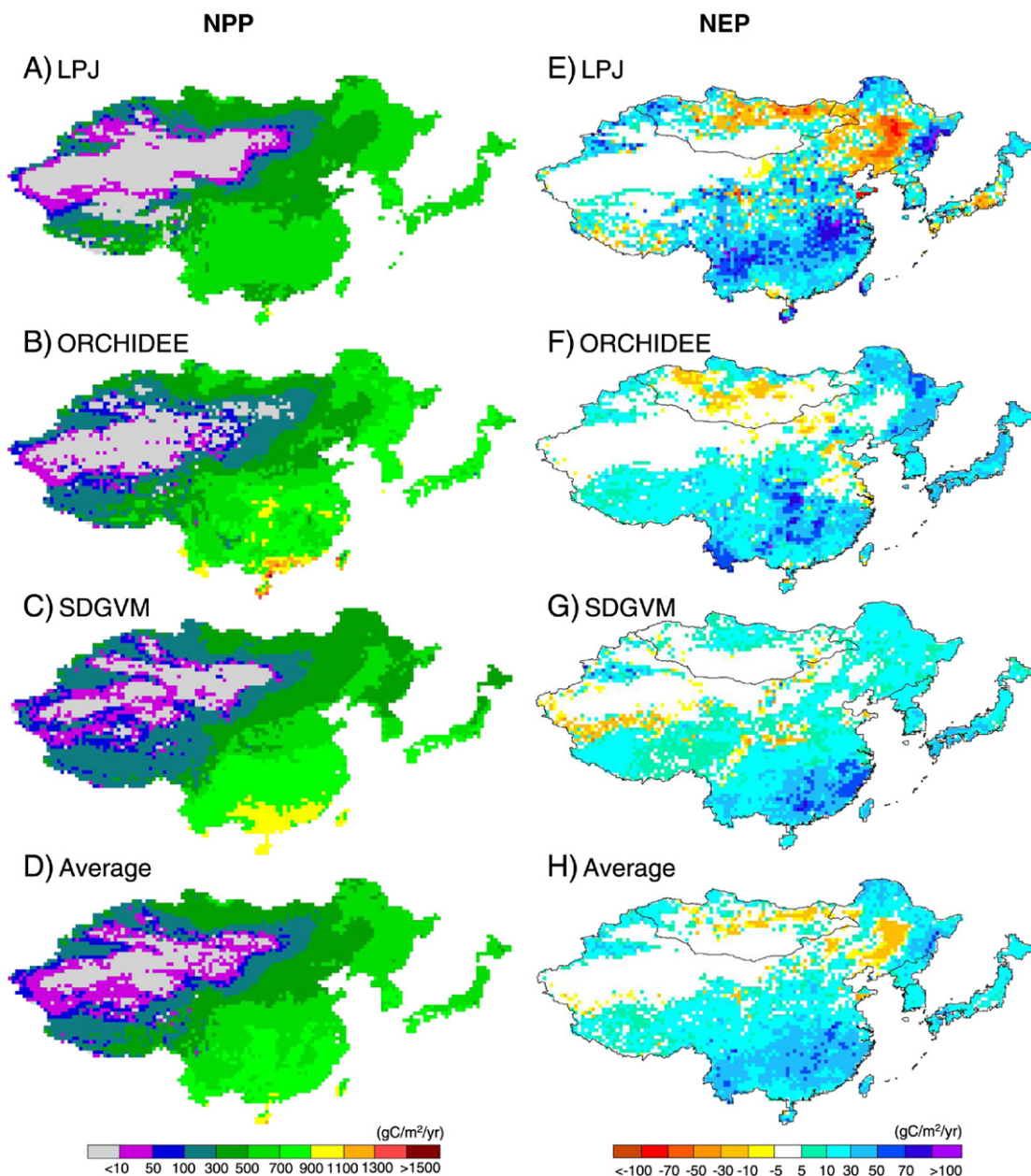
Fig. 5. Spatial patterns of different models estimated NPP and NEP during the period of 1980–2002. Positive values of NEP indicate carbon sink and negative values of NEP indicate carbon source.

sources estimated by ORCHIDEE and LPJ in northern Mongolia and northern China (Fig. 6F and G), are clearly corresponding to a substantial decrease of NPP. However, the area where NPP is currently increasing, is smaller than the one where NEP is a sink, because of a coincident acceleration in soil organic C decomposition. At the continental scale, SDGVM estimates a statistically significant increase in NEP with magnitude of 0.005 Pg C yr^{-1} ($R^2 = 0.16$, $P<0.05$). In contrast, both LPJ and ORCHIDEE estimates a slight but not significant decrease in NEP (at a rate of 0.01 Pg C yr^{-1}, $R^2 = 0.08$, $P>0.05$ for LPJ; at a rate of 0.005 Pg C yr^{-1}, $R^2 = 0.04$, $P>0.05$ for ORCHIDEE).
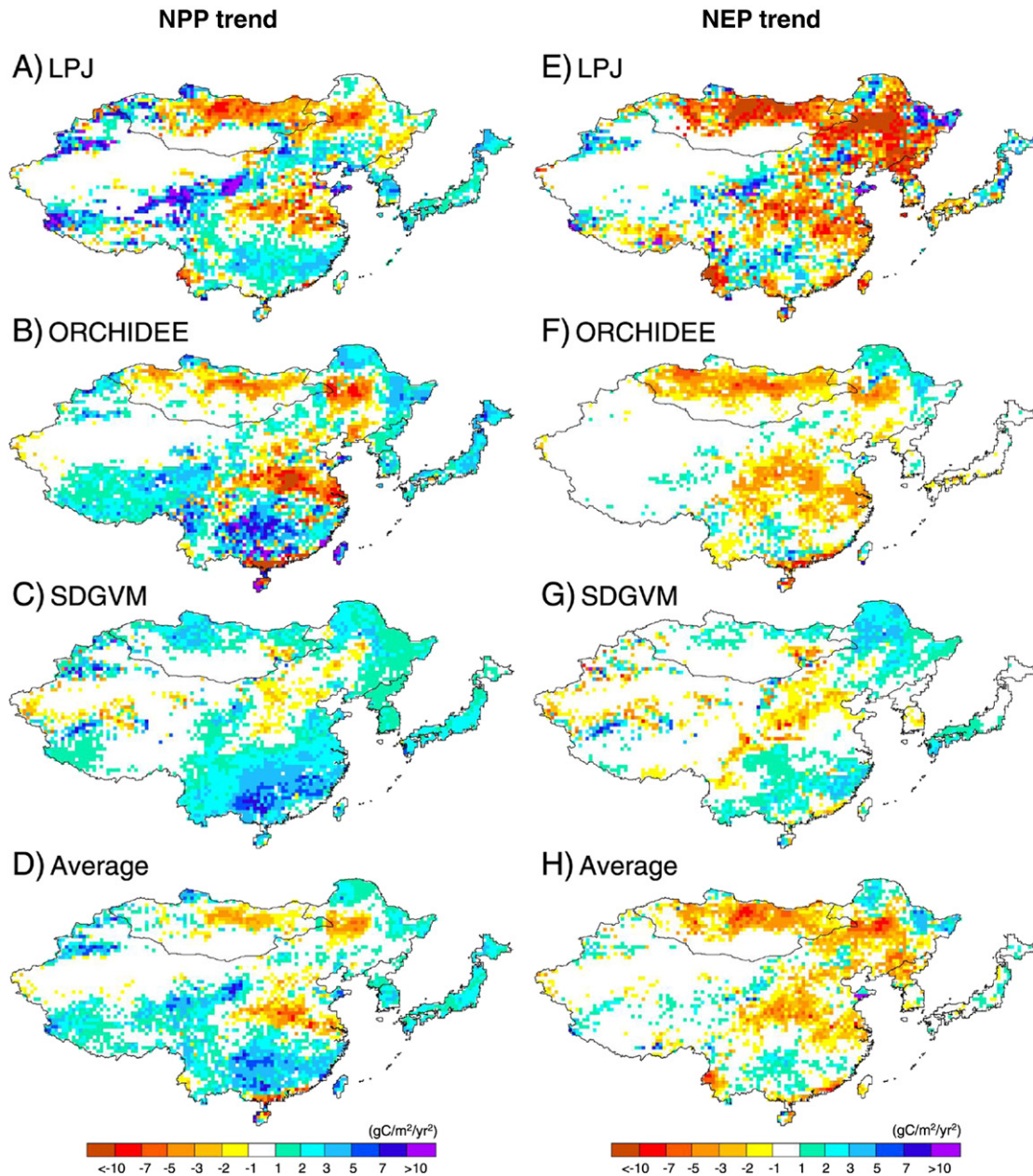
4. Discussion

Significantly increased vegetation biomass C storage has been widely reported across the world in recent observational studies based on both field inventory and satellite data (Fang et al., 2001; Goodale et al., 2002; Piao et al., 2005, 2007; Ciais et al., 2008; Piao et al., 2009b). For example, according to Piao et al. (2009b), China's total vegetation biomass C storage has increased with an annual magnitude of 0.057–0.153 Pg C during the 1980s and 1990s. It was also estimated that forest biomass in Korea is a net C sink of 0.012 Pg C yr^{-1} (Choi et al., 2002), and that in Japan is a net C sink of 0.018 Pg C yr^{-1} (Fang et al., 2005). Based on the results of these previous observation based analyses, one can derive that about 0.087–0.183 Pg C yr^{-1} has been accumulated in the vegetation biomass. This sink is comparable to the modeling estimation derived in this study (0.077 Pg C yr^{-1} for ORCHIDEE, 0.083 Pg C yr^{-1} for SDGVM, and 0.126 Pg C yr^{-1} for LPJ) (Table 2).

Soils are the largest source of uncertainty in observations of the C balance because of a lack of repeated inventories (Smith, 2004). The modeling results presented in this study suggest that soil C storage in East Asia has increased by about 0.053–0.103 Pg C yr^{-1} from 1980 to 2002 (Table 2). About 90% of this soil C sink has been accumulated in China. This modeling result is in conflict with the estimation of a previous study by Xie et al. (2007) who reported that China has lost about 2.86 Pg C (or 0.143 Pg C yr^{-1}) from its soils over the last 20 yr

NPP trend

A) LPJ

B) ORCHIDEE

C) SDGVM

D) Average

NEP trend

E) LPJ

F) ORCHIDEE

G) SDGVM

H) Average

(gC/m²/yr²)

<-10 -7 -5 -3 -2 -1   1   2   3   5   7 >10

Fig. 6. Spatial patterns of different model derived trend in NPP and NEP from 1980 to 2002. The trends were calculated based on linear regression of C fluxes with year using ordinary least squares. Positive values of NEP indicate carbon sink and negative values of NEP indicate carbon source.

mainly due to the huge loss (3.56 Pg or 0.178 Pg C yr^{-1}) of soil C stored in grassland ecosystems. The results of Xie et al. (2007), however, should be viewed with caution due to the method limitation. Xie et al. (2007) calculated grassland SOC change for the whole country by simply multiplying the estimated SOC loss rate of degraded grasslands in the Tibetan Plateau (Wang et al., 2002) with an estimated total area of degraded grasslands between 1986 and 1999. However, there is no direct evidence of such a huge degradation caused soil C loss from Tibetan grasslands. Using three independent approaches (biomass and soil carbon inventories extrapolated by satellite greenness measurements, ecosystem models and atmospheric inversions), Piao et al. (2009b) estimated an increase about 0.02–0.03 Pg C yr^{-1}, which is comparable to the estimation of statistical approach based on soil inventory data (Yang, 2008). Current soil inventory data across the Tibetan grasslands in 2001–2004 also suggested that soil C storage in the Tibetan Plateau has increased by about 0.46 Pg C over the past two decades (Yang, 2008). Furthermore,

Satellite data indicate that biomass of China's grasslands significantly increased from 1982 to 1999, and only about 30% of the grasslands show a decreasing trend (Piao et al., 2007), suggesting that one cannot estimate change in SOC stock of China's grasslands based only on the area of grassland degradation regions by ignoring contribution from the regions where an increase in grassland productivity occurs.

Overall, the three models estimated that in response to climate change and rising atmospheric CO_2, the total terrestrial net C storage increased by about 5–11 Pg C in East Asia from 1901 to 2002. About 60% of this increase in C storage obtained by both ORCHIDEE and SDGVM is mainly realized by the climate change and rising atmospheric CO_2 during period of 1980–2002, while LPJ shows 40% of this C sink is attributed to the climate change and rising atmospheric CO_2 overfrom 1980 to 2002. According to the modeling simulation by Tian et al. (2003), climate change and rising atmospheric CO_2 caused net C sequestration in East Asia over the 1980s is about 0.12 Pg C yr^{-1}, which is in the range of our simulation

results by ORCHIDEE (0.18 Pg C yr^{-1}), SDGVM (0.14 Pg C yr^{-1}), and LPJ (0.18 Pg C yr^{-1}) (Table 2).

Land use change is one of the major disturbances that can greatly modify terrestrial carbon storage and flux, and may have a particularly long-term impact on terrestrial carbon cycle at regional and global scales (Eglin et al., 2010). However, current lack of information on the amount and spatial patterns of afforestation/deforestation and forest C stock makes it extremely challenging to accurately estimate the magnitude of C sink associated with land use change (Houghton, 2003; Tian et al., 2003; Jain and Yang, 2005; Piao et al., 2009a). For example, a biogeochemical modeling study suggest that land use change in China over the last two decades resulted in net C accumulation by about 0.03 Pg C yr^{-1} (Jain and Yang, 2005), which is slightly larger than estimation based on forest inventory data (0.02 Pg C yr^{-1}, Fang et al., 2001). In contrast, Houghton (2003) estimated about 0.07 Pg of annual C emission driven by land use change in the 1980s and 1990s. Such small C accumulation or emission contributed by land use change may be related to the fact that land use effects of regionally opposite sign compensate each other at the country scale (Piao et al., 2009b). For example, because of afforestation and reforestation programs including the South China Timber Program, and the Pearl River Protective Forest Project, China's terrestrial ecosystem C sink is mostly located in southern China, while about 0.021–0.027 Pg of C has been lost annually by over-harvesting and degradation of forests in Northeast China during the 1980s and 1990s (Piao et al., 2009b). A previous study has suggested that atmospheric O$_3$ pollution has caused a decrease in C storage in China by 0.021 Pg C yr^{-1} (Tian et al., 2003). In addition, intensive agriculture practices and their changes, such as decreasing removal of crop residues, and expansion of no-tillage and reduced-tillage, have been also thought to lead to an increase in the C sequestration of agricultural ecosystems by 0.015–0.037 Pg C yr^{-1} (Lal, 2004; Huang and Sun, 2006). Although nitrogen deposition generally acts to stimulate vegetation productivity (Churkina et al., 2007) and suppress soil heterotrophic respiration (Bowden et al., 2004), and thus resulting in enhancement in C sequestration (Reay et al., 2008), there is a lack information on the role of nitrogen deposition in the C balance of East Asia. Overall, applying these values reported by previous literature to our estimation of C sink induced by climate change and rising atmospheric CO$_2$ over the last two decades, one can estimate that net C balance of East Asia varies from 0.061 to 0.227 Pg C yr^{-1} (Fig. 7). This is about 4–17% of global land C sink estimated by Stephens et al. (2007) who suggested that northern land ecosystem

is a net C uptake of 1.5 Pg C yr^{-1}, while tropical is a weaker emission of −0.1 Pg C yr^{-1}, resulting 1.4 Pg C yr^{-1} of global terrestrial C sink.

Finally, we note that our current set of simulation has several limitations. First, in addition to land use change in particular urban sprawl which is especially pronounced in China, human managements including tillage and fertilization have been suggested to influence C cycle at regional scales (Gervois et al., 2008). Although analyses of the NOAA AVHRR time series satellite data indicate a substantial increase in NDVI and NPP (Piao et al., 2005) during the last two decades, all models show a decrease or slight increase in NPP over agricultural areas of east China (Fig. 7). This discrepancy may reflect the substantial influence of human agricultural activities such as irrigation and fertilization in the recent several decades (Huang et al., 2007), which have not been considered in the current models used in this study. Second, our simulations do not incorporate the effects of increasing anthropogenic nitrogen deposition and ozone exposure. Third, the relatively low spatial (0.5°) and temporal (monthly) resolution may also affect the accuracy of modeling results. Jung et al. (2007) have showed a large error (40% bias) on vegetation productivity due to uncertain climate forcing in Europe. Further studies are needed thoroughly considering all of these factors with high spatial and temporal resolution of long-term climate data.

5. Conclusions

Biogeochemical models have been widely used to clarify the C budget of terrestrial ecosystems and its response to climate change, but no integrated examination has yet been conducted in East Asia. Using the same climate forcing dataset and atmospheric CO$_2$ concentration data, we have presented how historical climate changes affect the magnitude, and spatial and temporal patterns of terrestrial C cycle derived by three different ecosystem models in East Asia. Although large differences exist between these three models in derived spatio-temporal changes in NEP, the dominant driving factors controlling interannual variation in NEP, and the partition of C sink between vegetation and soil, the results in this study have been useful in addressing uncertainties of the response of terrestrial carbon cycle in East Asia to climate change and rising atmospheric CO$_2$ concentration. In the next step, reducing these uncertainties should be given a high priority through validating current biogeochemical models with long-term observational data from East Asia.

Fig. 7. Different factors contribution on the NEP of terrestrial ecosystem in East Asia. The effects of climate change and CO$_2$ is estimated by ORCHIDEE and SDGVM. The contribution of land use change is based on the previous studies (Houghton, 2003; Tian et al., 2003; Jain and Yang, 2005), while that of O$_3$ is based on the study of Tian et al. (2003). Agriculture management is based on the study of Lal (2004) and Huang and Sun (2006).

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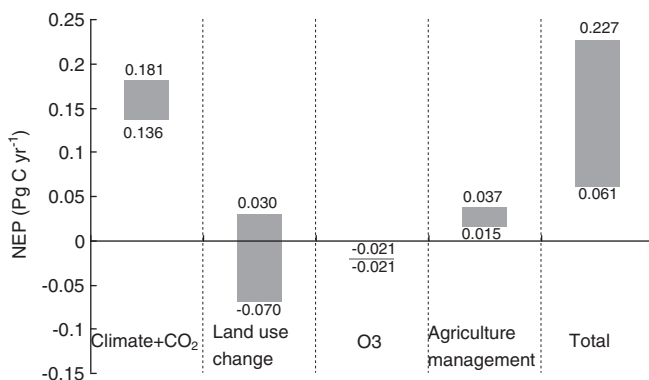
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