

**The carbon budget  
of terrestrial  
ecosystems in East  
Asia**

S. Piao et al.

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Please refer to the corresponding final paper in BG if available.

# The carbon budget of terrestrial ecosystems in East Asia over the last two decades

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Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Received: 27 February 2012 – Accepted: 14 March 2012 – Published: 29 March 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Abstract

This REgional Carbon Cycle Assessment and Processes regional study provides a synthesis of the carbon balance of terrestrial ecosystems in East Asia, a region comprised of China, Japan, North- and South-Korea, and Mongolia. We estimate the current terrestrial carbon balance of East Asia and its driving mechanisms during 1990–2009 using three different approaches: inventories combined with satellite greenness measurements, terrestrial ecosystem carbon cycle models and atmospheric inversion models. The magnitudes of East Asia's natural carbon sink from these three approaches are comparable:  $-0.264 \pm 0.033 \text{ Pg C yr}^{-1}$  from inventory-remote sensing model-data fusion approach,  $-0.393 \pm 0.141 \text{ Pg C yr}^{-1}$  (not considering biofuel emissions) or  $-0.204 \pm 0.141 \text{ Pg C yr}^{-1}$  (considering biofuel emissions) for carbon cycle models, and  $-0.270 \pm 0.507 \text{ Pg C yr}^{-1}$  for atmospheric inverse models. The ensemble of ecosystem modeling based analyses further suggests that at the regional scale, climate change and rising atmospheric  $\text{CO}_2$  together resulted in a carbon sink of  $-0.289 \pm 0.135 \text{ Pg C yr}^{-1}$ , while land use change and nitrogen deposition had a contribution of  $-0.013 \pm 0.029 \text{ Pg C yr}^{-1}$  and  $-0.107 \pm 0.025 \text{ Pg C yr}^{-1}$ , respectively. Although the magnitude of climate change effects on the carbon balance varies among different models, all models agree that in response to climate change alone, southern China experienced an increase in carbon storage from 1990 to 2009, while northern East Asia including Mongolia and north China showed a decrease in carbon storage. Overall, our results suggest that about 13–26 % of East Asia's  $\text{CO}_2$  emissions from fossil fuel burning have been offset by carbon accumulation in its terrestrial ecosystems over the period from 1990 to 2009. The underlying mechanisms of carbon sink over East Asia still remain largely uncertain, given the diversity and intensity of land management processes, and the regional conjunction of many drivers such as nutrient deposition, climate, atmospheric pollution and  $\text{CO}_2$  changes, which cannot be considered as independent for their effects on carbon storage.

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 1 Introduction

Quantifying the ability of regional terrestrial ecosystems to remove anthropogenic CO<sub>2</sub> emissions brings understanding of the global carbon cycle and provides option for policy (Gurney et al., 2009). The East Asia region in RECCAP (Canadell et al., 2011) includes China, Japan, North and South Korea, and Mongolia) located in the East Eurasian continent in the Northern Hemisphere. This region covers a land area of  $12 \times 10^6$  km<sup>2</sup> and a range of 49-degree latitude and 72-degree longitude amounting to 28 % of the Asian continent land area. The population of East Asia has increased by 40.46 million (China, Japan and South Korea contributes 92.8 %, 2.5 % and 2.7 % of total increase respectively) since 1980 (UN, 2008). East Asia has also been characterized by rapid economic development and fast GDP increase. According to data from World Bank, China alone accounted for approximately 11 % of the increase in total global GDP from 1980 to 2009, and Japan contributed another 8.6 % (World Bank, 2009). Fossil-fuel emissions of CO<sub>2</sub> in East-Asia is rising significantly with GDP, with moderate gains in the carbon intensity (ratio of emissions-to-GDP) (Raupach et al., 2007). Based on the recent IEA statistics of CO<sub>2</sub> emissions from fuel combustion (International Energy Agency, 2011), East Asian fossil fuel CO<sub>2</sub> emissions observably increased by a factor of two between 1990 and 2009, to reach an average source of 1.5 Pg C yr<sup>-1</sup> to the atmosphere from 1990 to 2009 (Fig. 1). This regional emission represents a fraction of about 23 % of global fossil fuel CO<sub>2</sub> emissions during the same period, and this fraction increased from 18 % in 1990 to 30 % in 2009 (International Energy Agency, 2011). Such a rapid increase in Fossil-fuel emissions is the first important motivation for studying the carbon balance over East Asia.

The second important motivation for studying the carbon balance over East Asia is the rapid land use change going on in this region. For example, the world's faster urbanization has occurred in East Asia since the 1990s. The World Urbanization Prospects (2009) shows that the percentage of urban population (the ratio of the urban population to the total population of a given region) in East Asia increased from 32 % in

**BGD**

9, 4025–4066, 2012

### The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

1990 to 50 % in 2010 (UN, 2009; Sun et al., 2010), still growing. In 2025, Tokyo, Japan is likely to become the largest city in the world, with its population approaching 37.1 million. Shanghai, China is projected to be the 9th largest city, with a population of 15 million (UN, 2009). Besides urbanization trends, East Asia also experiences large afforestation over the last three decades. Based on the latest report of FAO on Global Forest Resources Assessment (FAO, 2010), the annual change in forest area of East Asia increased from  $1.76 \times 10^6$  ha in 1990–2000 to  $2.78 \times 10^6$  ha in 2000–2010. It is worth noting that East Asia has the highest yearly growth in forest area over 2000–2010 (1.2 % per year) among all countries (FAO, 2010). Such afforestation mainly occurs in China, whereas Japan and Korea are already highly forested countries (68 % and 65 % of forest cover in early 1990s, respectively) (FAO, 2010). The Chinese government developed several large-scale forest plantations programs (e.g. Three-North Protective Forest Program, Taihang Mountains Greening Project, South China Timber Program, the Pearl River Protective Forest Project, and the Yangtze River Protective Forest Project) since the late 1970s (Shen, 1999), leading to an increase of forest area at  $1.6 \% \text{ yr}^{-1}$  over the last two decades. The annual increasing rate of Chinese forest area increased from  $1.99 \times 10^6$  ha per year during 1990–2000 to  $2.99 \times 10^6$  ha per year during 2000–2010 (FAO, 2010). In Japan, forestation programs were developed after the World War II for providing timbers construction materials. Because of drastic shifts in life style and industrial structure, these young forests are harvested for less than their annual wood increment, resulting in carbon sequestration mainly in woody biomass (Fang et al., 2005).

The third important motivation for studying the carbon balance over East Asia concerns regional climate trends. As a sensitive region of the climate system (Fu et al., 2006; Piao et al., 2010), East Asia experienced significant climate changes in the past decades. According to CRU climate data (Mitchell and Jones, 2005), mean annual temperature over East Asia has increased by  $0.04 \text{ }^\circ\text{C yr}^{-1}$  over the last three decades, a higher rate than the observed global land surface temperature trend ( $0.03 \text{ }^\circ\text{C yr}^{-1}$ ) (Fig. 2). Associated with this warming, significant changes in precipitation pattern are

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



observed (Fig. 2). The drier northern China (except the northwest part) has been receiving less precipitation in summer and autumn, whereas the wetter southern China has seen more rainfall during summer and winter (Piao et al., 2010).

The fourth important motivation for studying the carbon balance over East Asia is the rapid change in atmospheric composition caused by industrial and agricultural emissions from this region. The concentration of reactive nitrogen deposition has doubled worldwide and is five times higher than 1860 level in East Asia as a result of intensive fertilizer use, and fossil fuel burning (Galloway et al., 2004; Churkina et al., 2007). For instance, dry deposition of NO<sub>2</sub> in China rose by about 8 % from 1990 to 2003 (Lü and Tian, 2007). Apart from nitrogen deposition, tropospheric ozone pollution also characterizes atmospheric composition changes over East Asia. Because East Asia, particularly China, is on the road of rapid economic development, the emissions of ozone precursors that were still at low concentrations in the 1970s dramatically increased in the past decade (Richter et al., 2005) and are larger than North American and European emissions (Akimoto, 2003a). Some Chinese regions such as the North China Plain, the Yangtze River Delta and the Pearl River Delta are significantly affected by ozone pollution (Dufour et al., 2010). At the end of the last century, tropospheric ozone concentrations of these areas have reached a high level larger than any other areas of the northern mid-latitudes (Oltmans et al., 1998; Lee et al., 1998) and are projected to further increase in the future (Akimoto, 2003b).

There is no doubt that the changes in regional economic and climatic drivers of ecosystem CO<sub>2</sub> fluxes mentioned above affect the carbon balance of East Asia. In comparison to other regions such as Europe (Janssens et al., 2003; Ciais et al., 2010) and North America (Pacala et al., 2001; Crevoisier et al., 2010), our knowledge on the carbon budget of terrestrial ecosystems in East Asia remains rather limited, because most studies focused mainly on national C budget estimates (Piao et al., 2010; Ichii et al., 2010; Tian et al., 2011). Recently, Piao et al. (2011) used three different terrestrial carbon cycle models to estimate changes in the carbon balance of East Asian ecosystems over the last century, but this study only considered climate and rising

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

atmospheric CO<sub>2</sub> forcing. The primary objective of this paper is to quantify the C balance of East Asia's terrestrial ecosystems over the last two decades as well as its drivers and uncertainties. To do so, we use three different approaches: a bottom-up approach derived from biomass and soil carbon inventory data, combined with satellite observation of vegetation greenness index (NDVI: Normalized Difference Vegetation Index), terrestrial ecosystem carbon cycle models, and a top-down approach based on atmospheric CO<sub>2</sub> observation data and inversion of atmospheric transport.

## 2 Methods

### 2.1 Inventory and satellite based estimation

East Asia contains almost all major forest types of the Northern Hemisphere including tropical rain forest, subtropical evergreen broadleaf forest, deciduous broadleaf forest, broadleaf and needleleaf mixed forest and deciduous needleleaf forest from south to north. According to the latest report of FAO on Global Forest Resources Assessment (FAO, 2010), the total forest area of East Asia is about  $2.54 \times 10^8$  ha in 2010, accounting for about 6 % of global total forest area. In this study, forest biomass carbon sink is assessed based on FAO reports (FAO, 2010) and previous published estimates. We only selected literature data that used national forest inventories to calculate forest biomass change. The relatively systematic and spatially extensive forest inventory data provide one of the key sources for estimating the basic elements of forest C stock and stock change at the country scale, although there are large uncertainties associated to allometry, non-measured soil C pools, and sampling of disturbed forest (Phillips et al., 2000; Pan et al., 2004, 2011).

Grassland is a widespread vegetation type in East Asia. Temperate grasslands are distributed in arid and semi-arid regions, while cold alpine grassland spread mainly over the Tibetan Plateau, and some high elevation mountainous area. Here, we estimate grassland biomass change using satellite NDVI observations, and the empirical

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



approach developed by Piao et al. (2007). The NDVI data used are from the Global Inventory Monitoring and Modeling Studies (GIMMS) group derived from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR) Land data set, at a spatial resolution of  $8 \times 8 \text{ km}^2$  and 15-day interval, for the period January 1982 to December 2009 (Tucker et al., 2005). Information on the fractional coverage of grassland in China was derived from the Map of Grassland Resources in China at 1: 4 000 000 scale (Commission for Integrated Survey of Natural Resources, 1996), and information in other regions is from the UMD Global Land Cover Classification at  $8 \times 8 \text{ km}^2$  resolution (DeFries et al., 1998).

Shrublands in East Asia mainly distributed in China (DeFries et al., 1998), with an area approximating  $2.1 \times 10^7 \text{ ha}$  (Commission for Integrated Survey of Natural Resources, 1996) mainly dispersed over mountainous area, in particular southwestern, southern and northeastern China. Similar to the estimation of grassland biomass change, a satellite-based empirical approach (Piao et al., 2009) was applied to estimate biomass change for shrubland in East Asia.

Carbon accumulated in wood products must be considered in the estimation of regional carbon balance (Ciais et al., 2008). In Europe, wood products represent a C sink of  $-0.024 \text{ Pg C yr}^{-1}$  (Ciais et al., 2008). Based on FAO data (<http://www.fao.org/waicent/portal/statistics.en.asp>), the wood products in East Asia are about 43% of those in Europe. As distinguishing long-lived and short-lived wood products requires detailed wood product statistics in categories, which are not accessible for all East Asian countries, we apply the ratio of wood production to carbon storage change in wood products estimated in Europe (Kohlmaier et al., 2007; Ciais et al., 2008) to estimate the C sink of wood products in East Asia.

Soils are the largest source of uncertainty in the terrestrial ecosystem carbon balance at regional and country scales, as one lacks data from repeated inventories (Huang et al., 2010). Here, change in soil carbon storage of natural ecosystems (forest, shrubland, and grassland) over East Asia is estimated using biomass change estimated for each biome as specified above, and the ratio of soil-to-biomass carbon storage



change in China reported in previous studies (Piao et al., 2009; Tian et al., 2011). For cropland, soil organic carbon (SOC) changes and uncertainties are provided through a synthesis of literature data (Huang et al., 2010).

It has been suggested that riverine export of dissolved organic carbon (DOC) and particulate organic carbon (POC) makes a considerable contribution to the budget of carbon stock (Meybeck et al., 2006; Ciais et al., 2006). For major catchments, the amounts of riverine DOC and POC export are derived from a global synthesis by Meybeck et al. (2006).

## 2.2 Ecosystem models

Process-based terrestrial ecosystem models have been applied to assess the dynamics of the terrestrial carbon cycle (Morales et al., 2005). Ecosystem model results, however, generally depend to an unknown extent on model parameter values (Mitchell et al., 2009), climate and soil forcing data (Zhao et al., 2011), initial conditions (Carvalho et al., 2008), and on model structure (Lin et al., 2011), although data assimilation techniques are developing and may enable us to determine optimal parameter values in an objective manner (Santaren et al., 2007). Accordingly, analyses with an ensemble of independent models are preferable to assess the uncertainties due to model structure and parameter choices (Friedlingstein et al., 2006; Sitch et al., 2008). In this study, we estimated the carbon balance of terrestrial ecosystems in East Asia using 10 ecosystem models, HyLand (Levy et al., 2004), Lund-Potsdam-Jena DGVM (Sitch et al., 2003), ORCHIDEE (Krinner et al., 2005), Sheffield-DGVM (Woodward et al., 1995; Woodward and Lomas, 2004), TRIFFID (Cox, 2001), LPJ\_GUESS (Smith et al., 2001), NCAR\_CLM4CN (Oleson et al., 2010; Lawrence et al., 2010), OCN (Zaehle and Friend, 2010), VEGAS (Zeng, 2003; Zeng et al., 2005), and VISIT (Ito, 2008). Detailed description of the surface fluxes of CO<sub>2</sub>, water and the dynamics of water and carbon pools in response to environmental change in each model could be found in corresponding literatures. Previous studies (e.g. Tao and Zhang, 2010; Tan et al., 2010) have applied

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

some of these models in estimating vegetation and carbon dynamics over different parts of the East Asia.

Following the historical climate carbon cycle model intercomparison project (Trendy) protocol ([http://dgv.m.ceb.ac.uk/system/files/Trendy\\_protocol%20Nov2011\\_0.pdf](http://dgv.m.ceb.ac.uk/system/files/Trendy_protocol%20Nov2011_0.pdf)), each model was run from its equilibrium (assumed at the beginning of the 1900s) to 2009. All the models consider change in climate and rising atmospheric CO<sub>2</sub> concentration (simulation S2), while 9 of 10 models run a factorial simulation considering only rising atmospheric CO<sub>2</sub> (simulation S1). Only three models account for N-limitation on vegetation productivity (Sheffield-DGVM, NCAR\_CLM4CN and OCN). The spatial resolution of each simulation differs among models (Table 1).

The historical changes in atmospheric CO<sub>2</sub> for the period 1901–2009 are derived from ice core records and atmospheric observations (Keeling and Whorf, 2005). For the climate forcing datasets, monthly climate data for the period 1901–2009 from CRU-NCEP datasets with a spatial resolution 0.5° × 0.5° (<http://dods.extra.cea.fr/data/p529viov/cruncep/>) were used in all models. Information on atmospheric nitrogen deposition for NCAR\_CLM4CN and OCN was taken from Dentener et al. (2006).

### 2.3 Atmospheric inversion models

The spatio-temporal characterization of atmospheric CO<sub>2</sub> concentration between different stations provides integrated constraints to the net land-atmosphere CO<sub>2</sub> exchange. Inverse models, referred to as the “top-down” approach, infer spatial patterns of land-atmosphere CO<sub>2</sub> flux and its variability using atmospheric CO<sub>2</sub> concentration measurements made at a surface network of about 100 stations, atmospheric transport modelling, and prior information on the land and ocean fluxes, and on fossil fuel CO<sub>2</sub> emissions in the case of Bayesian synthesis inversions (Enting et al., 1995; Gurney et al., 2002; Peylin et al., 2005). There are large uncertainties in inversions estimates of regional CO<sub>2</sub> fluxes, particularly for a region like East Asia where the surface network is sparse (9 stations over North Asia). Inversion results are also sensitive to biases in transport-models and to biases in the assumed magnitude and

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



distribution of fossil-fuel emissions (Peylin et al., 2005; Gurney et al., 2005). One advantage, however, of inversions is that they provide an estimation encompassing all surface sources and sinks of CO<sub>2</sub>, in principle with an uncertainty which propagates random error on prior fluxes, and on atmospheric measurements and models (Enting et al., 1995). By contrast with the top-down approach of inversions, there is a risk of bias in omitting important processes or ecosystems (e.g. wetlands and urban ecosystems) in inventories and ecosystem carbon cycle modeling (bottom-up approaches) described above. Here, we provide carbon balance estimates from seven inversions, carried out by the TRANSCOM (Baker et al., 2006) modelers, and made available for the RECCAP project. The inversions giving CO<sub>2</sub> flux estimates for at least 10 yr during 1990–2009 are adopted in our study (Peylin et al., 2011). They are: C13\_CCAM, C13\_MATCH, JENA\_S96, JMA\_2010, NICAM, NIES, and PYVAR. In addition, the net CO<sub>2</sub> land-atmosphere flux estimated by the CarbonTracker (CTRACKER\_US, Peters et al., 2007) in 2000–2009 are also considered. The study period of each inverse model simulation is provided in Table 2.

In atmospheric inversions, uncertainties treated as Gaussian purely random errors formally account for uncertain prior fluxes, uncertain atmospheric measurements and uncertain capabilities of transport models to represent these measurements (see Ciais et al., 2010 for instance for an overview). In the RECCAP inversions used in this study over East Asia, however, the optimized flux does not account, for prior flux uncertainties in fossil fuel combustion CO<sub>2</sub> emissions. In other words, each inversion prescribes to the atmospheric transport model fossil fuel emissions assumed of perfectly known global magnitude and spatio-temporal distribution. To minimize the influence of inter-model differences in assumed fossil fuel emission in estimating land-atmospheric CO<sub>2</sub> flux, adjustments have been made by adding posterior land-atmospheric flux of each model with the difference between assumed fossil fuel emissions by the model and the common fossil fuel emissions (EDGAR3.2 Fast Track 2000 emission database, Olivier et al., 2001). In order to account for regional fossil fuel CO<sub>2</sub> emissions uncertainty, which are particularly large in the case of a fast developing economy such as China

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

(Gregg et al., 2008), we added to the inversions uncertainties from the RECCAP-East Asia study the estimated standard error (one  $\sigma$ ) of fossil fuel emissions of each East Asian countries (8.9 % for China and North Korea, 2.0 % for Japan, 7.6 % for Mongolia and 6.2 % for South Korea, R. J. Andres et al., personal communication, 2011). The inter-model errors and fossil fuel emissions errors are propagated assuming that they are independent.

### 3 Results and discussion

#### 3.1 Inventory and satellite based estimation

##### 3.1.1 Forest biomass accumulation

In East Asia, forest area is significantly increased from  $2.09 \times 10^6$  km<sup>2</sup> in 1990 to  $2.55 \times 10^6$  km<sup>2</sup> in 2010, most of this increase being in China. According to the latest report of FAO on Global Forest Resources Assessment (FAO, 2010), Chinese forest increased by  $2.49 \times 10^4$  km<sup>2</sup> per year during the period of 1990–2010. Partly in response to expanding forest area, forest biomass in China is estimated to have increased from 4.4 PgC in 1990 to 6.2 PgC in 2010, resulting in a net sink of  $-0.09$  PgC yr<sup>-1</sup> over the last two decades (FAO, 2010). This estimation based on FAO data is very close to the recent synthesis of Pan et al. (2011) who inferred a biomass carbon sink of  $-0.06$  PgC yr<sup>-1</sup> during the 1990s, and that of  $-0.115$  PgC yr<sup>-1</sup> during the period of 2000–2007 (average of  $-0.084$  PgC yr<sup>-1</sup> over the past two decades). Owing primarily to the growth of relatively young stands (age of 40–60 yr) Japanese forests are estimated to be a net C sink in the range  $-0.024$ – $-0.019$  PgC yr<sup>-1</sup> over the last two decades (FAO, 2010; Pan et al., 2011). In contrast, due to the decrease in forest area in Mongolia (loss of  $8.19 \times 10^2$  km<sup>2</sup> per year) and North Korea (loss of  $1.27 \times 10^3$  km<sup>2</sup> per year) during 1990s and 2000s, forest biomass in these two countries has decreased (most likely transformed as CO<sub>2</sub> emitted to the atmosphere) at a rate of  $0.004$  PgC yr<sup>-1</sup>

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





### 3.1.3 Grasslands biomass change

Grassland ecosystems in the world may contribute as much as 20 % of total terrestrial production and could be a potential C sink (Scurlock and Hall 1998), but the direct evidence is very limited. In China, several studies have suggested that grassland biomass significantly increased from early 1980s to late 1990s (Piao et al., 2007), followed by a decreasing trend over the last decade due to an increase in drought driven by reduced summer precipitation and rising temperature and to over grazing by livestock (Jeong et al., 2011; Piao et al., 2011; Peng et al., 2012). Consequently, our NDVI-biomass regression approach (see Methods section) in this study indicates that grassland biomass in East Asia is relatively stable with a slight decline  $0.001 \pm 0.001 \text{ Pg C yr}^{-1}$  (Fig. 3). It should be noted that the uncertainties of this estimation may be underestimated, since we did not consider the uncertainties of grassland inventory data, satellite time series dataset, and belowground carbon stocks estimation approach (Fan et al., 2008).

### 3.1.4 Soil carbon changes

Soils in East Asia contain large carbon stocks, and may play an important role in the regional carbon balance. The increased biomass in forest and shrubland over the last two decades implies that soils may accumulate carbon through increased litter-fall during the same period, but there are no observational data from repeated inventories to support this speculation at the regional and country scales. Using the ratio of soil-to-biomass carbon sink calculated for forest (0.05–0.2), shrubland (0.35–1.8), and grassland (0.85–4.4) in China by Piao et al., 2009 and Tian et al., 2011, in combination with biomass stock changes derived in this study, we estimated soil carbon storage change over East Asia of  $0.014 \pm 0.009 \text{ Pg C yr}^{-1}$  for forests (range from 0.005 to  $0.022 \text{ Pg C yr}^{-1}$ ), of  $0.022 \pm 0.028 \text{ Pg C yr}^{-1}$  for shrublands (range from 0.005 to  $0.063 \text{ Pg C yr}^{-1}$ ), and of  $-0.003 \pm 0.004 \text{ Pg C yr}^{-1}$  for grasslands (range from  $-0.009$  to  $-0.002 \text{ Pg C yr}^{-1}$ ), respectively (Fig. 3). Compared with natural ecosystems, changes in agricultural practices play a dominant role in controlling cropland soil carbon

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

storage. Several meta-analyses of cropland soil carbon inventory data suggest that the average rate of SOC sequestration in Chinese cropland (area of 130 M ha) was  $21.7 \pm 4.3 \text{ Tg C yr}^{-1}$  between 1980 and 2000 (Huang et al., 2006; Lu et al., 2009; Yu et al., 2009; Pan et al., 2010; Huang et al., 2010; Sun et al., 2010). Due to lack of information on change in cropland SOC in China after 2000, we used this value to extrapolate the soil carbon increase for the period of 1990–2010 (Fig. 3). Change in cropland soil carbon storage for the other four countries is not taken into account in this study because of lack of available information, but this may not significantly influence our final results of the magnitude of carbon budget in East Asia due to the relatively small cropland area in these four countries ( $9.69 \times 10^4 \text{ km}^2$  compared to  $1.43 \times 10^6 \text{ km}^2$  in China, Ramankutty et al., 2010).

### 3.1.5 Wood products change and carbon exported from the land to the ocean

In addition to change in biomass and soil carbon storage, one must account for the carbon accumulated in wood products, a component not included in forest inventories, but that should be considered in regional estimates of C storage (Pacala et al., 2001). Based on FAO data, we estimated that wood products in China are a sink of  $-0.010 \text{ Pg C yr}^{-1}$ , which is comparable with the current estimate of  $-0.008 \text{ Pg C yr}^{-1}$  (Kohlmaier et al., 2007) and  $-0.007 \text{ Pg C yr}^{-1}$  (Pan et al., 2011). The sum of the carbon sink of wood products for the other four counties in East Asia is about  $-0.005 \text{ Pg C yr}^{-1}$ , suggesting that the carbon accumulated into wood products over East Asia is  $-0.013 \pm 0.002 \text{ Pg C yr}^{-1}$ .

As a result of leaching and water erosion, a substantial amount of soil organic carbon is exported from the land to the ocean (Meybeck et al., 2006). Since refined regional estimate is not available, we estimated riverine export of  $9.8 \text{ Tg C yr}^{-1}$  by DOC and  $9.4 \text{ Tg C yr}^{-1}$  by POC over East Asia from the global synthesis (Meybeck et al., 2006), the uncertainties of which is not yet quantified. Due to the lack of information on the age of exported carbon (i.e. does it contribute to the current land-atmosphere C flux) amount of organic carbon that is trapped and decomposed along the way of river

channels and dams, carbon accumulated in sediments of reservoirs and rivers are not included in our study.

Since 1990, carbon accumulated in dead wood over China, Japan and South Korea is increased by about 0.023, 0.007, and 0.002 Pg C yr<sup>-1</sup>, respectively (Pan et al., 2011).

In addition, C storage in the China's forest litter is increased with the magnitude of 0.012 Pg C yr<sup>-1</sup>. Overall, our inventory and satellite based estimation suggests that the East Asian territory annually net accumulates 0.264 ± 0.033 Pg of carbon (range from c sink of -0.208 to -0.338 Pg C yr<sup>-1</sup>) from the atmosphere over the last two decades (Fig. 3).

## 3.2 Model attribution of net biome productivity over East Asia

### 3.2.1 Climate change and rising atmospheric CO<sub>2</sub> concentration

To evaluate the effects of climate change on C balance, we use the difference between net ecosystem exchange (NEE) between terrestrial ecosystems and atmosphere in S1 and NEE in S2 as the contribution of climate change alone to C balance over East Asia. Among the nine models (CLM4CN, HYL, LPJ, LPJ\_GUESS, OCN, ORCHIDEE, SDGVM, TRI, VEGAS) providing both S1 and S2 simulation, four models (CLM4CN, HYL, SDGVM and HYL) suggest that climate change alone causes a carbon sink in terrestrial ecosystems over East Asia. The average of the nine models attribute the fraction of NEE driven by climate change to be 0.033 ± 0.062 Pg C yr<sup>-1</sup>, with a range going from a net carbon source of 0.174 Pg C yr<sup>-1</sup> (LPJ-GUESS) to a net sink of -0.027 Pg C yr<sup>-1</sup> (HYL). The relatively small magnitude of NEE attributed to climate change results from opposite changes in carbon storage in the southern and northern regions of East Asia (Fig. 4), according to models. Although the magnitude of climate change-attributed NEE varies among different models, all models agree that in response to climate change alone, southern China experienced an increase in carbon storage from 1990 to 2009, while northern East Asia including Mongolia and north China showed a decrease in carbon storage (Fig. 4), likely due to drought. In

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



particular since the late 1990s, northern East Asia, except northwest China, suffered from drought driven by both decreasing precipitation and rising temperature (Park et al., 2010; Piao et al., 2010). Such an increase in drought further caused a decrease in satellite-observed vegetation growth in northern East Asia (Jeong et al., 2011; Piao et al., 2011). In southern East Asia where precipitation is abundant, enhanced vegetation productivity driven by current global warming may partly explain climate change-induced net carbon accumulation (Piao et al., 2004).

Since plant photosynthesis is not saturated at current atmospheric CO<sub>2</sub> concentration, previous modeling studies suggested that global vegetation productivity increased significantly in response to current rising atmospheric CO<sub>2</sub> concentration which further caused an increase in net carbon uptake of terrestrial ecosystems (Sitch et al., 2007). By considering this CO<sub>2</sub> fertilization effect in addition to climate change (simulation S2), all ecosystem carbon cycle models suggest that at the regional scale, terrestrial ecosystems in East Asia act as a carbon sink with the average NEE of  $-0.289 \pm 0.135 \text{ Pg C yr}^{-1}$  (ranging from  $-0.051 \text{ Pg C yr}^{-1}$  for VEGAS to  $-0.497 \text{ Pg C yr}^{-1}$  for VISIT) during 1990–2009. As shown in Fig. 5, it is very likely that most of this carbon sink attributed to climate change and rising CO<sub>2</sub> is mainly distributed in southern and eastern China (except LPJ\_GUESS).

### 3.2.2 Nitrogen deposition

It is generally accepted that nitrogen deposition enhances carbon sink strength through two mechanisms: (1) stimulated vegetation productivity resulting in increased vegetation biomass (Churkina et al., 2007) and maybe (2) reduced soil organic matter decomposition rates leading to increased soil organic C storage (Pregitzer et al., 2008; Janssens et al., 2010). However, there is an intense debate about the magnitude and possible saturation of the nitrogen induced carbon sink (Janssens et al., 2010). In Europe, Churkina et al. (2010) estimated that nitrogen deposition-induced carbon sink is  $-0.037$ – $-0.030 \text{ Pg C yr}^{-1}$ , while in China, Tian et al. (2011) showed that net carbon accumulation due to nitrogen deposition is larger than that caused by elevated

atmospheric CO<sub>2</sub>. This is inconsistent with the result of the OCN model (Zaehle et al., 2010). Based on the simulation by Tian et al. (2011) using DLEM and TEM model, we estimate annually a sink of about -0.125 Pg of carbon realized in China's terrestrial ecosystems in response to nitrogen deposition during the period of 1990–2005.

This N-deposition induced carbon sink is larger than estimated by the CLM4CN model which predicts that nitrogen deposition enhanced carbon sink over East Asia is about -0.089 Pg C yr<sup>-1</sup> from 1990 to 2009 (Mao et al., 2012). These two simulations derived by different models further suggest that there is a large uncertainty in the estimation of nitrogen deposition caused carbon sink over East Asia. Here, we took the average of these two studies (-0.107 ± 0.025 Pg C yr<sup>-1</sup>) (Fig. 6).

### 3.2.3 Land use and land use change

Land use change is one of the important disturbances that alter terrestrial carbon pools and net fluxes at regional and global scales (Houghton, 2003). However, it is extremely challenging to accurately estimate the carbon balance change associated with land use change because of current lack of information on the amount and spatial pattern of deforestation and biomass and soil C stocks (Houghton, 2007; Piao et al., 2009). For instance, Houghton et al. (2003) estimated that land use change in China led to net carbon emission of 0.03 Pg C yr<sup>-1</sup> during the 1990s, while Jian and Yang (2005) found oppositely that land use change in China resulted in net carbon accumulation of -0.03 Pg C yr<sup>-1</sup> (Jian and Yang, 2005), which is very close to the estimation based on forest area changes from inventory data (-0.02 Pg C yr<sup>-1</sup>, Fang et al., 2001) and from the DLEM and TEM model (-0.03 Pg C yr<sup>-1</sup>, Tian et al., 2011). Based on these results, we estimated that land use change, dominated by afforestation, caused a net carbon accumulation in East Asia of 0.013 ± 0.029 Pg C yr<sup>-1</sup> (ranging from a source of 0.03 Pg C yr<sup>-1</sup> to a sink of -0.03 Pg C yr<sup>-1</sup>) (Fig. 6).

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3.2.4 Atmospheric ozone pollution and other disturbances

In addition to these factors (i.e. climate change, rising CO<sub>2</sub>, nitrogen deposition and land use change), previous studies have suggested that atmospheric O<sub>3</sub> pollution has also caused a decrease in carbon storage in China by 0.02 Pg C yr<sup>-1</sup> (Tian et al., 2011), while intensive agricultural practices and their changes, such as nitrogen fertilization and decreasing removal of crop residues, have been thought to lead to an increase in carbon sequestration by 0.022 ± 0.004 Pg C yr<sup>-1</sup> (Huang et al., 2010; Tian et al., 2011).

Wildfires may also play an important role in the regional carbon balance. Satellite data of burned area incorporated in the CASA terrestrial biosphere model estimated mean annual carbon emission from ecosystem fire in East Asia from 1997 to 2009 of 0.018 ± 0.010 Pg C yr<sup>-1</sup> (Van der Werf et al., 2010). Most of carbon emission from wildfires occurred in China (56.9%) and Mongolia (37.5%) which contain a vast area of dry forests, shrub lands, and grasslands (Van der Werf et al., 2010).

Finally, carbon emissions from the biofuels, such as woodfuel and agricultural residues, are not taken into account for the most of carbon cycle models. Currently, Wang et al. (2012) estimated the biofuel emissions in China is about 0.189 ± 0.010 Pg C yr<sup>-1</sup>, a very large flux compared to natural C sinks. If this biofuel harvest is exactly compensated by a vegetation regrowth sink that can not be detected by the inventory, the biofuel emissions should not be included in the carbon balance estimation based on the carbon cycle model approach. Otherwise, if the harvest of biofuel carbon stock is not compensated by vegetation regrowth, the biofuel carbon emissions should be included. Since we don't have information on the biofuel harvests compensated by the vegetation regrowth sink, we consider both situations resulting in two estimates of carbon balance either fully considering biofuel emission or not.

Overall, based on process-based ecosystem models and considering the carbon sinks/sources caused by all these different factors estimated in this and previous studies, we estimate that the carbon balance over East Asia is -0.204 ± 0.141 Pg C yr<sup>-1</sup> considering the biofuel emissions, or -0.393 ± 0.141 Pg C yr<sup>-1</sup> not considering

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

biofuel emissions (ranging from carbon source of  $0.119 \text{ Pg C yr}^{-1}$  to carbon sink of  $-0.660 \text{ Pg C yr}^{-1}$ ) (Fig. 6).

### 3.3 Atmospheric inverse models estimates

Over the whole East Asia, the average of eight inverse models give a net sink of atmospheric  $\text{CO}_2$  of  $-0.380 \pm 0.497 \text{ Pg C yr}^{-1}$ , but the eight models do not agree with each other. Six models estimate a net  $\text{CO}_2$  uptake over East Asia, but two models show a net  $\text{CO}_2$  source. The C13 MATCH model estimated the highest net carbon uptake rate of  $-0.997 \text{ Pg C yr}^{-1}$ , while the C13 CCAM model showed the largest net carbon emission of  $0.416 \text{ Pg C yr}^{-1}$  (Fig. 7), indicating that inversion fluxes over East Asia are rather poorly constrained by a regionally scarce atmospheric observation network. If we further consider propagating uncertainty of fossil fuel emissions over East Asia ( $0.098 \text{ Pg C yr}^{-1}$ ), the uncertainty of net  $\text{CO}_2$  exchange estimated by inverse models increase to  $0.507 \text{ Pg C yr}^{-1}$ .

The inverse model derived net land-atmosphere  $\text{CO}_2$  exchange is not directly comparable with the carbon sink estimated by the bottom-up approaches. In order to reconcile the two approaches,  $\text{CO}_2$  fluxes out and in the atmosphere from food and wood products trade, non- $\text{CO}_2$  gases emissions, and from the emission of C pools not counted in fossil fuel emissions (e.g. peat use) must be considered to adjust the inverse model estimate (Ciais et al., 2008). The emission of  $\text{CO}_2$  to the atmosphere from consumption of imported (exported) food and wood should be added to (removed from) the regional inverse estimates for making a comparison with bottom-up C accounting approaches. We estimated the carbon emission of imported food and wood by analyzing FAO statistics of international trade (FAO, 2010). The imported crop biomass into East Asia was converted into carbon using crop-specific conversion factor (Goudriaan et al., 2001), and imported wood was transformed to carbon following the method of Ciais et al. (2008). Thus we estimated that the imported wood and food consumption was  $0.04 \text{ Pg C yr}^{-1}$  during 1990–2009. The non- $\text{CO}_2$  compounds such as  $\text{CO}$ ,  $\text{CH}_4$

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and BVOC emitted by ecosystems, which were also not captured by atmospheric CO<sub>2</sub> observation, should be subtracted from the inverse estimate when assessing the total carbon balance. Using atmospheric chemistry database (Folberth et al., 2005), we estimated that the biogenic non-CO<sub>2</sub> emission was 0.15 Pg C yr<sup>-1</sup>. Due to the lack of information, the removal of fossil C not counted in fossil fuel emissions (e.g. peat use) are not considered in our study. By adjusting the inversed estimates using these lateral fluxes, the top-down approach estimated that the terrestrial ecosystems of East Asia functioned as a net carbon sink of  $-0.270 \pm 0.507$  Pg C yr<sup>-1</sup> during 1990–2009, with the range from net carbon emission of 0.526 Pg C yr<sup>-1</sup> to net carbon sink of  $-0.887$  Pg C yr<sup>-1</sup> (Fig. 7).

## 4 Conclusions

In summary, based on the average carbon sink from three approaches presented in this study, we estimate that East Asia's terrestrial ecosystems during 1990s and 2000s were a net carbon sink of  $-0.204$ – $-0.393$  Pg C yr<sup>-1</sup>, accounting for 13–26 % of the carbon sink over the Northern Hemisphere (Stephens et al., 2007). During the same period, fossil fuel burning in East Asia produced a cumulated emission of 1.5 Pg C yr<sup>-1</sup> to the atmosphere (IEA, 2011; Fig. 1), suggesting that about 13–26 % of East Asia's CO<sub>2</sub> emissions from fossil fuel burning are offset by carbon accumulation in its terrestrial ecosystems. Although the average carbon sink estimated by three different approaches was found to be comparable, there are still large uncertainties in each approach. For the inventory and satellite data based approach, the largest uncertainty lies in the estimation of soil organic carbon storage change, while for the terrestrial ecosystem modeling approach, carbon balance associated with land use change and nitrogen deposition was inconsistent among different models. Promoting regional model intercomparison project for East Asia, like VEMAP project for United States, will help constrain the uncertainties associated with process representation and parameters in the models. There are also large variations in the estimated carbon balance among

**BGD**

9, 4025–4066, 2012

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



different inverse models. To enable more precise assessments of East Asia's carbon cycle, there is an urgent need to increase the sampling of forest and grassland soils, and to deploy more atmospheric CO<sub>2</sub> stations. On the analogy of meteorology, such an integration system will allow us to establish a "re-analysis" dataset of the global and regional carbon cycles.

*Acknowledgements.* This study is part of the REgional Carbon Cycle Assessment and Processes (RECCAP), Global Carbon Project. We thank Trendy modelers to provide ecosystem model results and atmospheric inversion modelers to provide atmospheric CO<sub>2</sub> inversion results. This study was supported by the National Natural Science Foundation of China (grant 41125004 and 30970511), National Basic Research Program of China (Grant No. 2010CB950601 and Grant No. 2010CB833501), Foundation for Sino-EU research cooperation of Ministry of Science and Technology of China (1003) and CARBONES EU FP7 foundation (242316).

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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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S. Piao et al.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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5

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---

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

**Table 1.** Characteristics of land carbon cycle models used in this study (Trendy models).

Model name (abbreviation)	Spatial resolution	Simulation experiments*		References
		S1	S2	
Community Land Model 4CN (CLM4CN)	0.5° × 0.5°	Yes	Yes	Oleson et al., 2010; Lawrence et al., 2010
Hyland (HYL)	3.75° × 2.5°	Yes	Yes	Friend et al., 1997; Levy et al., 2004
Lund-Postdam-Jena (LPJ)	3.75° × 2.5°	Yes	Yes	Stich et al., 2003
LPJ.GUESS	0.5° × 0.5°	Yes	Yes	Smith et al., 2001
ORCHIDEE-CN (OCN)	3.75° × 2.5°	Yes	Yes	Zaehle and Friend, 2010; Zaehle et al., 2010
ORCHIDEE (ORC)	0.5° × 0.5°	Yes	Yes	Krinner et al., 2005
Sheffield-DGVM (SDGVM)	3.75° × 2.5°	Yes	Yes	Woodward et al., 1995
TRIFFID (TRI)	3.75° × 2.5°	Yes	Yes	Cox, 2001
VEGAS	2.5° × 2.5°	Yes	Yes	Zeng et al., 2005
VISIT	0.5° × 0.5°	No	Yes	Ito, 2008

\* Two model simulation experiments, noted by S1 and S2, are set in Trendy protocol. In S1 experiment, models are forced with rising atmospheric CO<sub>2</sub>, recycling climate of the early 20th century and constant land use; In S2 experiment, models are forced with rising atmospheric CO<sub>2</sub>, observed climate, and constant land use.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

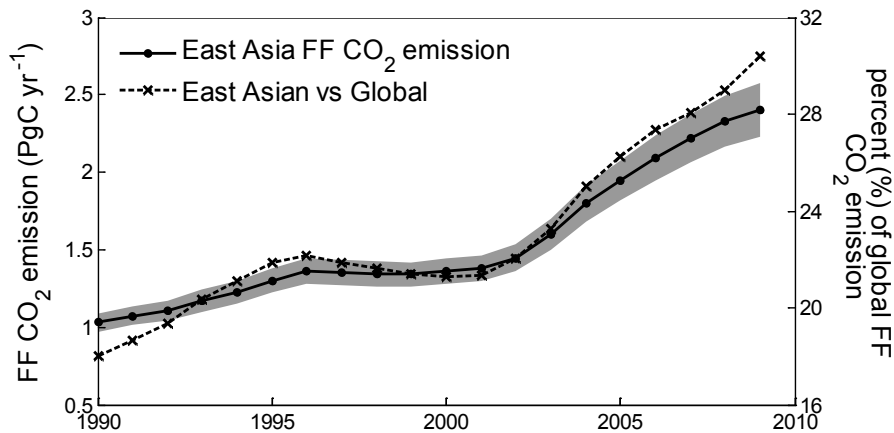
Interactive Discussion

**Table 2.** Characteristics of atmospheric inversion models used in this study.

Name	Study Period	Reference
C13_CCAM	1992–2008	Law et al. (2006)
C13_MATCH	1992–2008	Rasch et al. (1997)
JENA_S96	1996–2009	Rödenbeck et al. (2003)
JMA_2010	1985–2008	Taguchi (1996)
NICAM	1988–2007	Satoh et al. (2008)
NIES	1993–2007	Maksyutov et al. (2008)
PYVAR	1988–2008	Chevallier et al. (2005)
CTRACKER_US	2000–2009	Peters et al. (2007)

**The carbon budget of terrestrial ecosystems in East Asia**

S. Piao et al.



**Fig. 1.** Change in fossil fuel CO<sub>2</sub> emission (FF CO<sub>2</sub> emission) over East Asia and its relative contribution to global fossil fuel CO<sub>2</sub> emission, from 1950 to 2007. Data acquired from IEA statistics (IEA, 2011). Grey area shows 1-sigma standard error of the fossil fuel CO<sub>2</sub> emission estimates.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

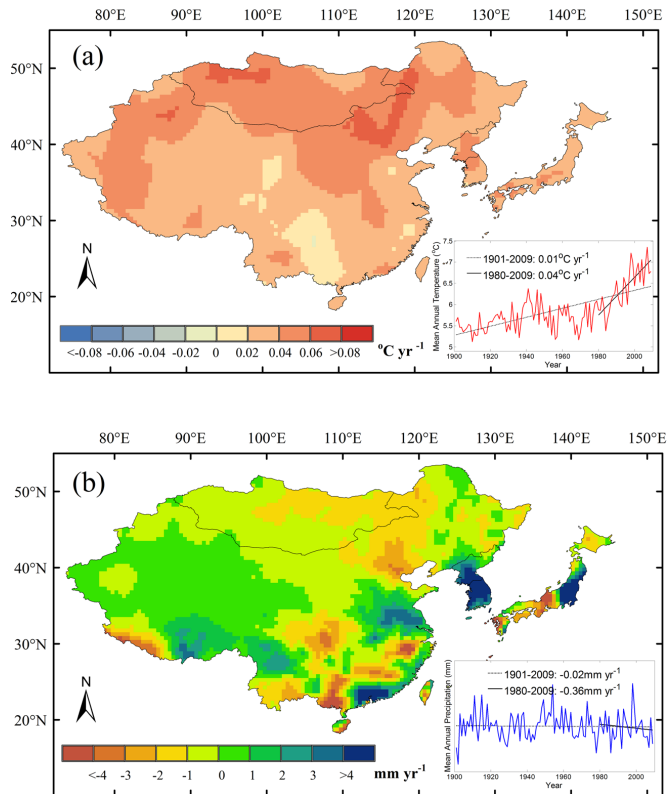
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Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Fig. 2.** Climate change in East Asia. **(a)** Spatial pattern of trend in mean annual temperature (MAT) from 1970 to 2009. **(b)** Spatial pattern of trend in mean annual precipitation (MAP) from 1970 to 2009. Inset figure shows interannual variability of MAT and MAP averaged over the whole region.

**The carbon budget of terrestrial ecosystems in East Asia**

S. Piao et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

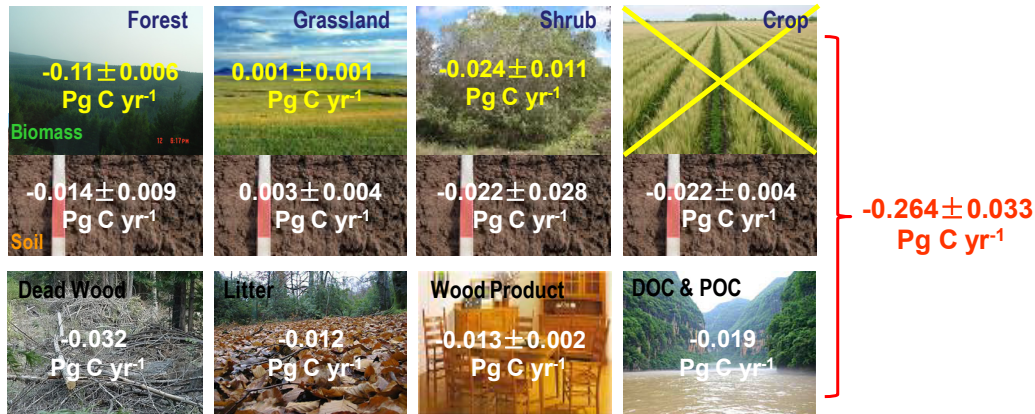
Printer-friendly Version

Interactive Discussion



## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.



**Fig. 3.** Inventory and satellite based approach estimated carbon sink of terrestrial ecosystems in East Asia and its components over the last two decades. Negative value indicates net carbon sink.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

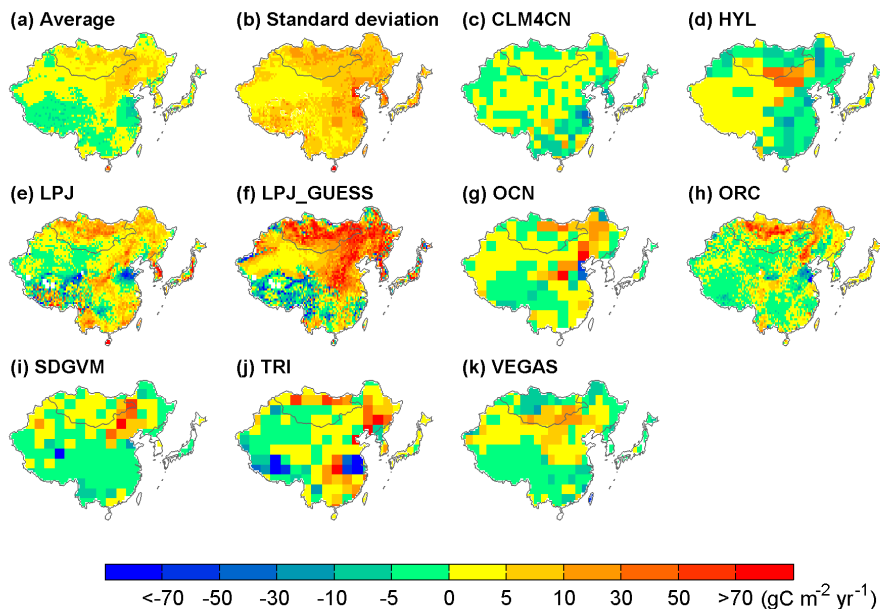
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Printer-friendly Version

Interactive Discussion

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.

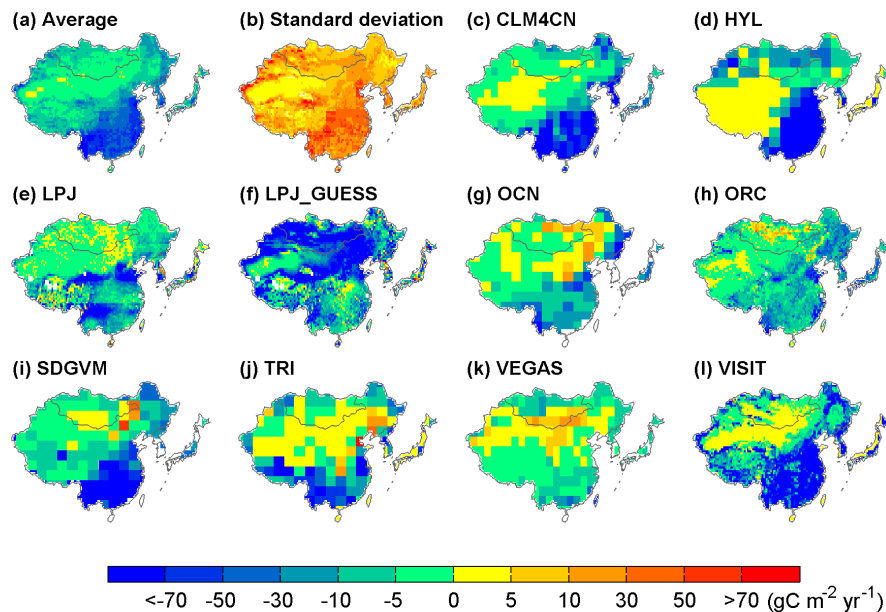


**Fig. 4.** Nine ecosystem models simulated spatial patterns of net ecosystem exchange (NEE) attributed to climate change (obtained from the difference between simulation S2 and S1) during the period 1990–2009. **(a)** average NEE from seven models, **(b)** standard deviations of seven models derived NEE, and **(c–h)** NEE estimated by each model. Negative value indicates net carbon sink.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[⏪](#)
[⏩](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.



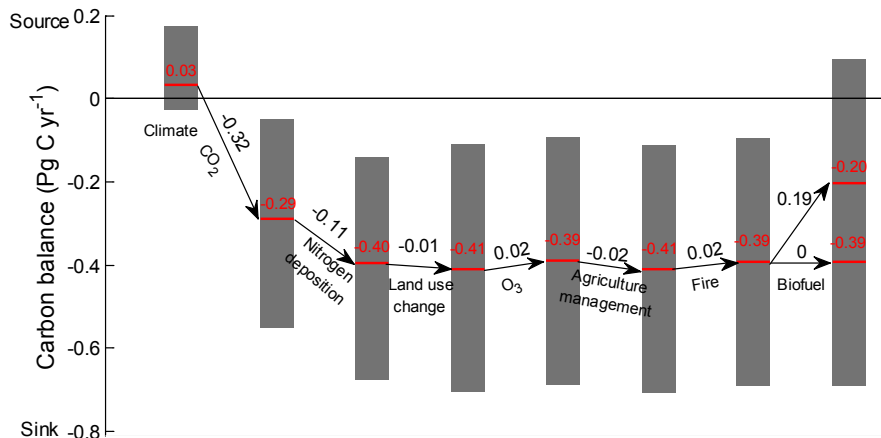
**Fig. 5.** Ten ecosystem models simulated spatial patterns of net ecosystem exchange (NEE) in response to climate change and rising atmospheric  $\text{CO}_2$  (Simulation S2) during the period 1990–2009. **(a)** average NEE from ten models, **(b)** standard deviations of ten models derived from NEE, and **(c–h)** NEE estimated by each model. Negative value indicates net carbon sink.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



The carbon budget of terrestrial ecosystems in East Asia

S. Piao et al.



**Fig. 6.** Different factors (climate, climate + CO<sub>2</sub>, nitrogen deposition, land use change, O<sub>3</sub> pollution, agricultural management, fire and biofuels) contribution on the carbon balance of terrestrial ecosystem in East Asia. Negative value indicates net carbon sink. Grey bar show ranges in the estimates by different models or sources. Biofuel emission is fully accounted when assuming the harvested carbon stock is not compensated by vegetation regrowth, and it is not accounted when assuming the harvested carbon stock is fully compensated by vegetation regrowth. Potential interactions among different factors are not considered. The contributions of atmospheric O<sub>3</sub> pollution and agriculture management on the carbon balance are estimated over China rather than over the entire East Asia due to lack of information for other countries (see Sect. 3.2.4).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

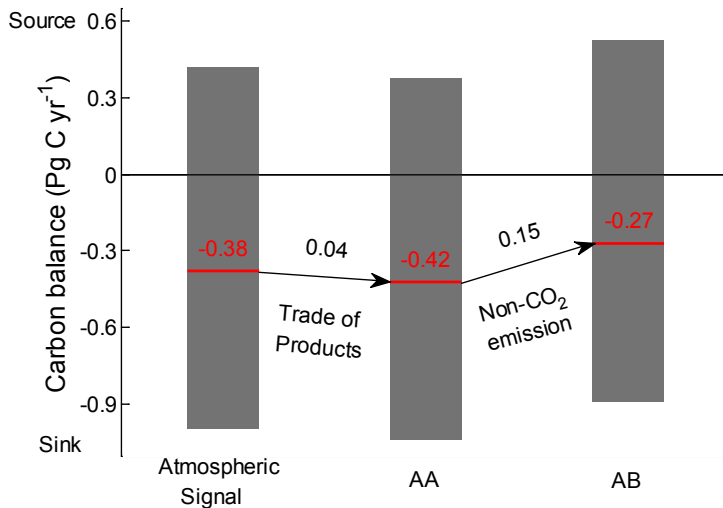
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 7.** Atmospheric inversion model estimated carbon balance in East Asia through considering lateral carbon fluxes. The same fossil fuel CO<sub>2</sub> emission estimate has been removed from each inversion to obtain the land-atmosphere CO<sub>2</sub> flux (NBP). The average of seven inverse models estimation (atmospheric signal) is corrected by two lateral fluxes. (1) atmospheric inversion result is added by CO<sub>2</sub> emission due to imported wood and food product (0.04 Pg C yr<sup>-1</sup>), resulting in AA; (2) the carbon sink in AA is reduced by carbon fixed by photosynthesis but released to the atmosphere by non-CO<sub>2</sub> compounds (0.15 Pg C yr<sup>-1</sup>), including CO, CH<sub>4</sub> and volatile organic compounds (VOCs), resulting in AB, which should be comparable to estimate by inventory and satellite approach. Grey bar show ranges in the estimates by different inverse models.

**The carbon budget of terrestrial ecosystems in East Asia**

S. Piao et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

⏪ ⏩

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

