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

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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 terrestrial carbon sink from these three approaches are comparable: -0.293 ± 0.033 PgC yr^{-1} from inventory–remote sensing model–data fusion approach, -0.413 ± 0.141 PgC yr^{-1}(not considering biofuel emissions) or -0.224 ± 0.141 PgC yr^{-1} (considering biofuel emissions) for carbon cycle models, and -0.270 ± 0.507 PgC yr^{-1} for atmospheric inverse models. Here and in the following, the numbers behind $\pm$ signs are standard deviations. The ensemble of ecosystem modeling based analyses further suggests that at the regional scale, climate change and rising atmospheric CO_2 together resulted in a carbon sink of -0.289 ± 0.135 PgC yr^{-1}, while land-use change and nitrogen deposition had a contribution of -0.013 ± 0.029 PgC yr^{-1} and -0.107 ± 0.025 PgC 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 13–27 % of East Asia's CO_2 emissions from fossil fuel burning have been offset by carbon accumulation in its terrestrial territory 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 CO_2 changes, which cannot be considered as independent for their effects on carbon storage.

1 Introduction

Quantifying the ability of regional terrestrial ecosystems to remove anthropogenic CO_2 emissions brings understanding of the global carbon cycle and provides options 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 on the East Eurasian continent in the Northern Hemisphere. This region covers a land area of 12×10^6 km^2 and a range of 49 degrees latitude and 72 degrees 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 contribute 92.8 %, 2.5 % and 2.7 % of this total increase, respectively) since 1980 (UN, 2009). 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_2 in East Asia are 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_2 emissions from fuel combustion (International Energy Agency, 2011), East Asian fossil fuel CO_2 emissions observably increased by a factor of two between 1990 and 2009, becoming an average source of 1.5 Pg C yr^{-1} to the atmosphere from 1990 to 2009 (Fig. 1). This regional emission represents a fraction of about 23 % of global fossil fuel CO_2 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, fast 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 1990 to 50 % in 2010 (UN, 2009; Sun et al., 2010a), and is 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 experienced large afforestation over the last three decades. Based on the latest report by FAO (Food and Agriculture Organization of the United Nations) on Global Forest Resources Assessment (FAO, 2010), the annual change in forest area of East Asia increased from 1.76×10^6 ha in 1990–2000 to 2.78×10^6 ha in 2000–2010. It is worth noting that East Asia has higher yearly growth in forest area over 2000–2010 (1.2 % per year) than any other country or region (FAO, 2010). Such afforestation mainly occurs in China, whereas Japan and Korea are already highly forested countries (68 % and 65 % forest cover in the early 1990s, respectively) (FAO, 2010). The Chinese government has developed several large-scale forest plantation 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 % yr^{-1} over the last two decades. The annual increasing rate of Chinese forest area increased from 1.99×10^6 ha per year during 1990–2000 to 2.99×10^6 ha per year during 2000–2010 (FAO, 2010). In Japan, forestation programs were developed after 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., 2004; Piao et al., 2010), East Asia experienced significant climate changes in the past decades. According to CRU (Climate Research Unit) climate data (Mitchell and Jones, 2005), mean annual temperature over East Asia has increased by 0.04 °C yr^{-1} over the last three decades, a higher rate than the observed global land surface temperature trend (0.03 °C yr^{-1}) (Fig. 2). Associated with this warming, significant changes in precipitation patterns are 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 the 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_2 in China rose by about 8 % from 1990 to 2003 (Lu 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, 2003). 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 in these areas had reached a high level, higher 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, 2003).

There is no doubt that the changes in regional economic and climatic drivers of ecosystem CO_2 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 territory 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. (2011a) used three different terrestrial carbon cycle models to estimate changes in the carbon balance of East Asian ecosystems over the last century, but that study only considered climate and rising atmospheric CO_2 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 and combined with satellite observations of vegetation greenness (NDVI: Normalized Difference Vegetation Index), terrestrial ecosystem carbon cycle models, and a top-down approach based on atmospheric CO_2 observation data and inversion of atmospheric transport.

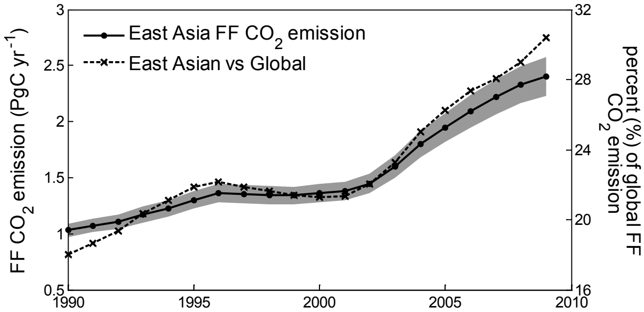

Fig. 1. Change in fossil fuel CO_2 emissions (FF CO_2 emission) over East Asia and its relative contribution to global fossil fuel CO_2 emissions, from 1990 to 2007. Data acquired from IEA statistics. Grey area shows 1-sigma standard error of the fossil fuel CO_2 emission estimates.

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 by FAO on Global Forest Resources Assessment (FAO, 2010), the total forest area of East Asia is about 2.54×10^8 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 with allometry, non-measured soil C pools, and sampling of disturbed forests (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

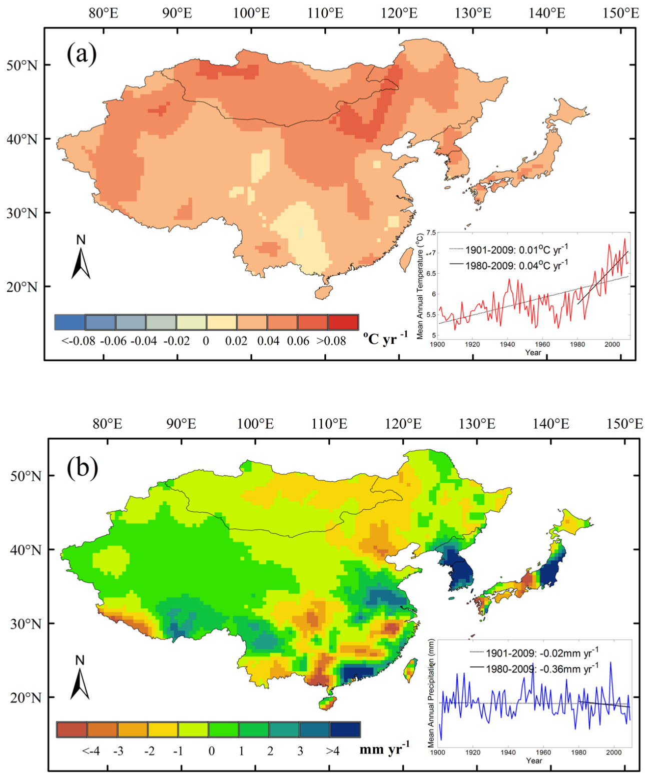

Fig. 2. Climate change in East Asia. **(a)** Spatial pattern of trend in mean annual temperature (MAT) from 1970 to 2009. **(b)** Spatial pattern of trend in mean annual precipitation (MAP) from 1970 to 2009. Inset figures show interannual variability of MAT and MAP averaged over the whole region.

regions, while cold alpine grasslands are 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 approach developed by Piao et al. (2007) (see Supplement Text S1). 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 dataset at a spatial resolution of 8×8 km and a 15-day interval for the period January 1982 to December 2009 (Tucker et al., 2005; Wang et al., 2011). 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 8×8 km resolution (DeFries et al., 1998).

Shrublands in East Asia are mainly distributed in China (DeFries et al., 1998), with an area approximating 2.1×10^7 ha (Commission for Integrated Survey of Natural Resources, 1996) mainly dispersed over mountainous areas, in particular in southwestern, southern and northeastern China. Similar to the estimation of grassland biomass change, a satellite-based empirical approach (Piao et al., 2009a) was applied to estimate biomass change for shrubland in East Asia (Supplement Text S1).

Carbon accumulated in wood products must be considered in the estimation of the regional carbon balance (Ciais et al., 2008). In Europe, wood products represent a C sink of -0.024 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 % than 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 data are lacking from repeated inventories (Huang et al., 2010). Here, change in soil carbon storage of natural ecosystems (forest, shrubland, and grassland) in 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., 2009a; 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 inorganic and organic carbon (DIC and DOC) and particulate organic carbon (POC) makes a considerable contribution to the budget of carbon stock (Ciais et al., 2008; Cai et al., 2008). The lateral transport of carbon to the coast was estimated at the river basin scale using the Global Nutrient Export from WaterSheds (NEWS) model framework (Mayorga et al., 2010), including NEWS basin areas. The carbon species models are hybrid empirically and conceptually based models that include single and multiple linear regressions developed by the NEWS effort and Hartmann et al. (2009), and single regression relationships assembled from the literature. Modeled dissolved and particulate organic carbon (DOC and POC) loads used here (from Mayorga et al., 2010) were generated largely using drivers corresponding to the year 2000, including observed hydroclimatological forcings, though some parameters and the observed loads are based on data spanning the previous two decades. The amounts of riverine DIC export are provided by Hartmann et al. (2009). Carbon, sediment and water exports were aggregated from the river basin scale to coastal segmentation regions (COSCAT, 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., 2012), initial conditions (Carvalhais 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., 2011), OCN (Zaehle and Friend, 2010), VEGAS (Zeng, 2003; Zeng et al., 2005), and VISIT (Ito, 2008). Detailed descriptions of the surface fluxes of CO_2, water and the dynamics of water and carbon pools in response to environmental change in each model can be found in the corresponding literature. Previous studies (e.g. Tao and Zhang, 2010; Tan et al., 2010) have applied some of these models in estimating vegetation and carbon dynamics over different parts of East Asia.

Following the historical climate–carbon cycle model intercomparison project (Trendy) protocol (http://dgvm.ceh.ac.uk/system/files/Trendy_protocol%20_Nov2011_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_2 concentration (simulation S2), while 9 of 10 models run a factorial simulation considering only rising atmospheric CO_2 (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_2 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 $0.5° \times 0.5°$ (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 Jean-François Lamarque (personal communication) and Dentener et al. (2006), respectively.

2.3 Atmospheric inversion models

The spatio-temporal characterization of atmospheric CO_2 concentration between different stations provides integrated constraints to the net land–atmosphere CO_2 exchange. Inverse models, referred to as the "top-down" approach, infer spatial patterns of land–atmosphere CO_2 fluxes and their variability using atmospheric CO_2 concentration measurements made at a surface network of about 100 stations, atmospheric transport modeling, and prior information on land and ocean fluxes as well as on fossil fuel CO_2 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 inversion estimates of regional CO_2 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 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_2, 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_2 flux estimates for at least 10 years 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_2 land–atmosphere fluxes 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_2 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 emissions in estimating land–atmospheric CO_2 fluxes, adjustments were made by adding posterior land–atmospheric fluxes 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_2 emissions uncertainty, which is particularly large when a fast developing economy such as China is included in a region (Gregg et

Table 1. Carbon balance derived by different carbon cycle models.

Model name (abbreviation)	Spatial resolution	Net ecosystem carbon balance ($Pg\,C\,yr^{-1}$) S1[1]	S2[1]	References
Community Land Model 4CN (CLM4CN)	$0.5° \times 0.5°$	−0.284	−0.300	Oleson et al. (2010); Lawrence et al. (2011)
Hyland (HYL)	$3.75° \times 2.5°$	−0.317	−0.344	Friend et al. (1997); Levy et al. (2004)
Lund-Postdam-Jena (LPJ)	$3.75° \times 2.5°$	−0.296	−0.216	Stich et al. (2003)
LPJ-GUESS	$0.5° \times 0.5°$	−0.648	−0.474	Smith et al. (2001)
ORCHIDEE-CN (OCN)	$3.75° \times 2.5°$	−0.303	−0.274	Zaehle and Friend (2010); Zaehle et al. (2010)
ORCHIDEE (ORC)	$0.5° \times 0.5°$	−0.240	−0.203	Krinner et al. (2005)
Sheffield-DGVM (SDGVM)	$3.75° \times 2.5°$	−0.338	−0.344	Woodward et al. (1995)
TRIFFID (TRI)	$3.75° \times 2.5°$	−0.206	−0.183	Cox (2001)
VEGAS	$2.5° \times 2.5°$	−0.051	−0.051	Zeng et al. (2005)
VISIT	$0.5° \times 0.5°$	N.A.[2]	−0.497	Ito (2008)

[1] Two model simulation experiments, noted by S1 and S2, are set in Trendy protocol. In the S1 experiment, models were forced with rising atmospheric CO_2, recycled climate of the early 20th century, and constant land use; in the S2 experiment, models were forced with rising atmospheric CO_2, observed climate, and constant land use. Negative values indicate carbon sink.
[2] S1 simulation by VISIT model is not available.

Table 2. Carbon balance derived by different atmospheric inverse models. Negative values indicate carbon sink.

Name	Study Period	Carbon balance ($Pg\,C\,yr^{-1}$)	Reference
C13_CCAM	1992–2008	−0.997	Law et al. (2006)
C13_MATCH	1992–2008	0.416	Rasch et al. (1997)
JENA_S96	1996–2009	−0.930	Rödenbeck et al. (2003)
JMA_2010	1985–2008	0.201	Taguchi (1996)
NICAM	1988–2007	−0.404	Satoh et al. (2008)
NIES	1993–2007	−0.641	Maksyutov et al. (2008)
PYVAR	1988–2008	−0.376	Chevallier et al. (2005)
CTRACKER_US	2000–2009	−0.312	Peters et al. (2007)

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

2.4 Uncertainty estimates

The uncertainties of the carbon flux components were estimated using two methods. First, when the data product includes a formal uncertainty analysis, the provided uncertainty estimates are used in our reports. Second, when there are several independent estimates of the same flux component with the same method (e.g. the net land–atmospheric CO_2 exchange estimated by inverse models), the standard deviation of the independent estimates is reported as their uncertainty. The standard deviation usually underestimates the uncertainty when there are only a few samples; in this case, we also give the range of the independent estimates. When only one sample is available for some flux component within one method and when this sample does not have a documented uncertainty, we do not estimate its uncertainty.

When summing several flux contributions that are estimated independently, we quadratically sum the corresponding uncertainty standard deviations to document the resulting uncertainty.

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 $2.09 \times 10^6\,km^2$ in 1990 to $2.55 \times 10^6\,km^2$ 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 $2.49 \times 10^4\,km^2$ 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 Pg C in 1990 to 6.2 Pg C in 2010, resulting in a net sink of $-0.09\,Pg\,C\,yr^{-1}$ over the last two decades (Supplement Table S1). 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 $-0.06\,Pg\,C\,yr^{-1}$ during the 1990s, and that of $-0.115\,Pg\,C\,yr^{-1}$ during the period of 2000–2007 (average of $-0.084\,Pg\,C\,yr^{-1}$ 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 – $-0.019\,Pg\,C\,yr^{-1}$ over the last two decades (FAO, 2010; Pan et al., 2011). In contrast, due to the decrease in forest area in Mongolia (loss of $8.19 \times 10^2\,km^2$ per year) and North Korea (loss of $1.27 \times 10^3\,km^2$ per year) during 1990s and 2000s, forest biomass in these two countries has decreased (most likely transformed as CO_2 emitted to the atmosphere) at a rate of $0.004\,Pg\,C\,yr^{-1}$ and $0.003\,Pg\,C\,yr^{-1}$, respectively. In South Korea, despite the fact that the area of forest shrunk from $6.37 \times 10^4\,km^2$ in 1990 to $6.22 \times 10^4\,km^2$ to 2010, biomass increased by 0.008–$0.009\,Pg\,C\,yr^{-1}$ (FAO, 2010; Pan et al., 2011), which is related to re-growth of young forests established in the early 1970s (Choi et al., 2004). Overall, based on national forest inventory data compiled by FAO, we obtain an average

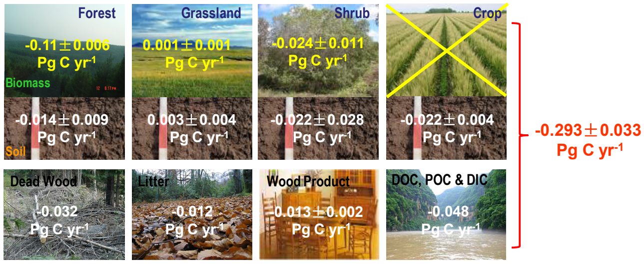

Fig. 3. The inventory- and satellite-based approach estimated a carbon sink in terrestrial ecosystems in East Asia and its components over the last two decades. A negative value indicates net carbon sink.

net forest biomass C sink of -0.11 ± 0.006 Pg C yr^{-1} over East Asia during the period 1990–2009 (Fig. 3, Supplement Table S1). This represents about 9 % of the total northern forest C sink (Pan et al., 2011). Comparatively, East Asia's forest biomass C sink was close to those of Europe (-0.14 – -0.08 Pg C yr^{-1}) and the United States (-0.13 – -0.12 Pg C yr^{-1}) (FAO, 2010; Pan et al., 2011; Luyssaert et al., 2010).

3.1.2 Shrublands biomass change

Although shrubland ecosystems are widespread in China (Wu, 1980; IGCAS, 1996), there is very limited data available to ascertain C stock changes. In North America, the expansion of shrubland ecosystems in arid regions, called "woody encroachment", was estimated to be a sink of -0.12 Pg C yr^{-1}, accounting for 18–34 % of the total coterminous US carbon sink (Pacala et al., 2001). In China, changes in energy production systems in rural areas and movement of rural populations to cities have likely diminished the collection of fuel wood, and thus accelerated the recovery of shrubland and woodland vegetation. Shrublands were estimated to increase their biomass by 0.022 ± 0.01 Pg C yr^{-1} over the last two decades of the 20th century (Piao et al., 2009a), determined using an indirect estimation approach based upon site-level data and NDVI trends. Extending the approach of Piao et al. (2009a) based on NDVI–biomass regressions between sites extrapolated in time to shrublands over the entire East Asia region, we estimate that shrubland biomass C stocks over East Asia have increased by an average sink of -0.024 ± 0.011 Pg C yr^{-1} and have an uncertainty of about 50 % (estimated from the scatter around the linear regression line between NDVI and shrubland biomass at 34 available sites) (Fig. 3).

3.1.3 Grasslands biomass change

Grassland ecosystems in the world may contribute as much as 20 % of total terrestrial production and could be potential C sinks (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 due to overgrazing by livestock (Jeong et al., 2011; Piao et al., 2011b; Peng et al., 2011). 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 ± 0.001 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 datasets, and a 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 litterfall 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 ratios 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. (2009a) 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 ± 0.009 Pg C yr^{-1} for forests (range from 0.005 to 0.022 Pg C yr^{-1}), 0.022 ± 0.028 Pg C yr^{-1} for shrublands (range from 0.005 to 0.063 Pg C yr^{-1}), and -0.003 ± 0.004 Pg C yr^{-1} for grasslands (range from -0.009 to -0.002 Pg C yr^{-1}) (Fig. 3). Compared with natural ecosystems, changes in agricultural practices play a dominant role in controlling cropland soil carbon 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 ± 4.3 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., 2010b). 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 on the magnitude of the carbon budget in East Asia due to the relatively small cropland area in these four countries (9.69×10^4 km^2 compared to 1.43×10^6 km^2 in China) (Ramankutty et al., 2008).

3.1.5 Wood products change

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 $-0.010\,\mathrm{Pg\,C\,yr^{-1}}$, which is comparable with other current estimates of $-0.008\,\mathrm{Pg\,C\,yr^{-1}}$ (Kohlmaier et al., 2007) and $-0.007\,\mathrm{Pg\,C\,yr^{-1}}$ (Pan et al., 2011). The sum of the carbon sink of wood products for the other four countries in East Asia is about $-0.005\,\mathrm{Pg\,C\,yr^{-1}}$, suggesting that the carbon accumulated into wood products over East Asia is $-0.013 \pm 0.002\,\mathrm{Pg\,C\,yr^{-1}}$.

3.1.6 Carbon exported from the land to the ocean

As a result of "leaching" and physical erosion, a substantial amount of soil organic and plant litter carbon is exported as DOC and POC from the land to the ocean (Ludwig et al., 1996). We estimated riverine export of $9.8\,\mathrm{Tg\,C\,yr^{-1}}$ by DOC and $9.4\,\mathrm{Tg\,C\,yr^{-1}}$ by POC over East Asia from a global synthesis calculated by Emilio Mayorga based on the NEWS approach. The estimates considered here represent net land–ocean DOC and POC fluxes and do not take into account OC being sedimented within the river system, e.g. in dams, lakes or flood plains, or OC being decomposed during transport. These OC burials in river systems can be substantial and would represent a net loss from the here considered land–surface system (e.g. Tranvik et al., 2009). However, due to lack of quantitative data these fluxes are not included in our study.

The land–river DIC flux sources are partly atmospheric CO_2 derived via root respiration and decomposition of DOC and POC in the soil–rock system or are of lithogenic origin (carbonate dissolution). This river DIC is predominantly transported as weathering-derived bicarbonate and carbonate ions to the ocean, while excess CO_2 (CO_2 above the equilibrium level corresponding to the atmospheric CO_2 partial pressure) escapes back to the atmosphere. Over East Asia, the net DIC flux from the land to the ocean was estimated to be $0.029\,\mathrm{Pg\,C\,yr^{-1}}$ (cf. Hartmann et al., 2009). It should be noted that lithogenic DIC should be subtracted from the total DIC transported to the oceans, since it is derived from geological carbon stock rather than from the atmosphere. The proportion of lithogenic DIC in the total DIC is probably larger than 33 %. We did not consider lithogenic DIC in this study.

Since 1990, carbon accumulated in dead wood over China, Japan and South Korea has increased by about 0.023, 0.007, and $0.002\,\mathrm{Pg\,C\,yr^{-1}}$, respectively (Pan et al., 2011). In addition, C storage in China's forest litter has increased by the magnitude of $0.012\,\mathrm{Pg\,C\,yr^{-1}}$. Overall, our inventory- and satellite-based estimation suggests that the East Asian territory annually has accumulated net 0.293 ± 0.033 Pg of carbon (range from C sink of -0.237 to $-0.367\,\mathrm{Pg\,C\,yr^{-1}}$) from the atmosphere over the last two decades (Fig. 3, Supplement Table S2).

3.2 Model attribution of net carbon balance over East Asia

3.2.1 Climate change and rising atmospheric CO_2 concentration

To evaluate the effects of climate change on C balance, we use the difference between net ecosystem carbon balance between terrestrial ecosystems and atmosphere in S1 and net ecosystem carbon balance 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 simulations, 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 for the fraction of net ecosystem carbon balance driven by climate change is $0.033 \pm 0.062\,\mathrm{Pg\,C\,yr^{-1}}$ (positive values indicate net carbon sources), with a range going from a net carbon source of $0.174\,\mathrm{Pg\,C\,yr^{-1}}$ (LPJ-GUESS) to a net sink of $-0.027\,\mathrm{Pg\,C\,yr^{-1}}$ (HYL). This relatively small magnitude of net ecosystem carbon balance attributed to climate change results from opposite changes in carbon storage in the southern and northern regions of East Asia (Fig. 4), according to the models. Although the magnitude of the climate change-attributed carbon budget 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 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., 2011b). 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 the current atmospheric CO_2 concentration, previous modeling studies suggested that global vegetation productivity increased significantly in response to rising atmospheric CO_2 concentration, which further caused an increase in net carbon uptake of terrestrial ecosystems (Sitch et al., 2007). By considering this CO_2 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 by an average of

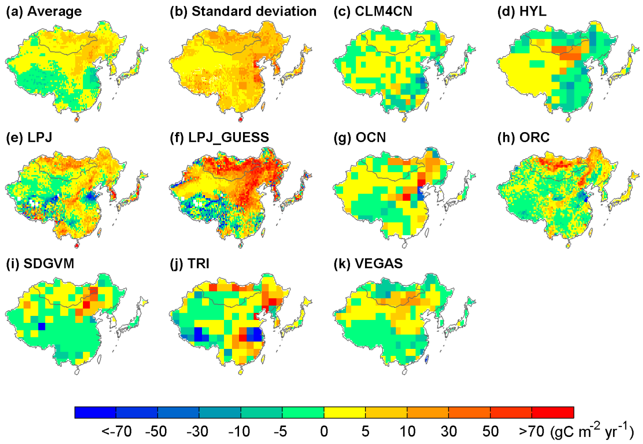

Fig. 4. Nine ecosystem models simulated spatial patterns of net ecosystem carbon balance attributed to climate change (obtained from the difference between simulation S2 and S1) during the period 1990–2009. **(a)** Average net ecosystem carbon balance from the nine models, **(b)** standard deviation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

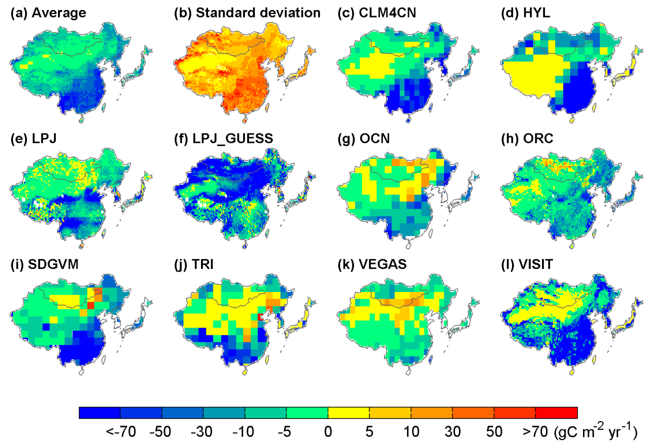

Fig. 5. Ten ecosystem models simulated spatial patterns of net ecosystem carbon balance in response to climate change and rising atmospheric CO_2 (Simulation S2) during the period 1990–2009. **(a)** Average net ecosystem carbon balance from the ten models, **(b)** standard deviation of the ten model-derived net ecosystem carbon balance, and **(c–h)** net ecosystem carbon balance estimated by each model. Negative value indicates net carbon sink.

-0.289 ± 0.135 Pg C yr^{-1} (ranging from -0.051 Pg C yr^{-1} for VEGAS to -0.497 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_2 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 (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 the nitrogen deposition-induced carbon sink is -0.037 – -0.030 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_2. 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 models, 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 the nitrogen deposition-enhanced carbon sink over East Asia is about -0.089 Pg C yr^{-1} 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 the nitrogen deposition-caused carbon sink over East Asia. Here, we took the average of these two studies (-0.107 ± 0.025 Pg C yr^{-1}) (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., 2009b). For instance, Houghton et al. (2003) estimated that land-use change in China led to net carbon emission of 0.03 Pg C yr^{-1} 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^{-1} (Jian and Yang, 2005), which is very close to the estimation based on forest area changes from inventory data (-0.02 Pg C yr^{-1}, Fang et al., 2001) and from the DLEM and TEM models (-0.03 Pg C yr^{-1}, 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^{-1} (ranging from a source of 0.03 Pg C yr^{-1} to a sink of -0.03 Pg C yr^{-1}) (Fig. 6).

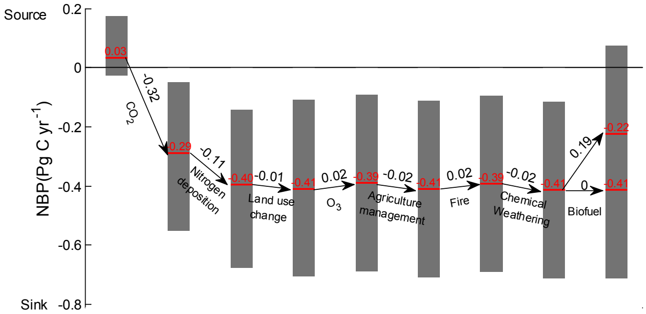

Fig. 6. Different factors' (climate, climate + CO_2, nitrogen deposition, land-use change, O_3 pollution, agricultural management, fire and biofuels) contributions to the carbon balance of terrestrial ecosystems in East Asia. Negative values indicate net carbon sink. Grey bars show ranges in the estimates by different models or sources. Biofuel emissions are fully accounted for when assuming the harvested carbon stock is not compensated by vegetation regrowth, and they are not accounted for 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_3 pollution and agriculture management on the carbon balance are estimated over China rather than over the entire East Asia region due to lack of information for other countries (see Sect. 3.2.4).

3.2.4 Atmospheric ozone pollution and other fluxes

In addition to these factors (i.e. climate change, rising CO_2, nitrogen deposition and land-use change), previous studies have suggested that atmospheric O_3 pollution has also caused a decrease in carbon storage in China by 0.02 Pg C yr^{-1} (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^{-1} (Huang et al., 2010).

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^{-1} (van der Werf et al., 2010). Most of the carbon emission from wildfires occurred in China (56.9 %) and Mongolia (37.5 %), which contain vast areas of dry forests, shrub lands, and grasslands (van der Werf et al., 2010).

In addition, CO_2 consumption by chemical weathering of silicates and carbonates is a carbon sink not counted in the modeling. Based on lithological maps, river runoff and river chemistry datasets (Hartmann et al., 2009; Hartmann, 2009), net CO_2 consumption by chemical weathering over the considered East Asian territory was estimated to be 0.020 Pg C yr^{-1}.

Finally, carbon emissions from biofuels, such as woodfuel and agricultural residues, are not taken into account for most of the carbon cycle models. Recently, Wang et al. (2012) estimated the biofuel emissions in China to be about 0.189 ± 0.010 Pg C yr^{-1}, a very large flux compared to natural C sinks. If 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 do not 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 emissions 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 -0.224 ± 0.141 Pg C yr^{-1} considering the biofuel emissions, or -0.413 ± 0.141 Pg C yr^{-1} not considering biofuel emissions (ranging from a carbon source of 0.099 Pg C yr^{-1} to a carbon sink of -0.680 Pg C yr^{-1}) (Fig. 6, Supplement Table S2).

3.3 Atmospheric inverse model estimates

Over the whole East Asia, the average of eight inverse models give a net sink of atmospheric CO_2 of -0.380 ± 0.497 Pg C yr^{-1}, but the eight models do not agree with each other. Six models estimate a net CO_2 uptake over East Asia, but two models show a net CO_2 source (Table 2). The C13 MATCH model estimated the highest net carbon uptake rate of -0.997 Pg C yr^{-1}, while the C13 CCAM model showed the largest net carbon emission of 0.416 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 Pg C yr^{-1}), the uncertainty of net CO_2 exchange estimated by inverse models increases to 0.507 Pg C yr^{-1}.

The inverse model-derived net land–atmosphere CO_2 exchange is not directly comparable with the carbon sink estimated by the bottom-up approaches. In order to reconcile the two approaches, CO_2 fluxes out of and into the atmosphere from food and wood products trade, non-CO_2 gas emissions, and the emissions 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 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 emissions of imported food and wood by analyzing FAO statistics on international trade (FAO, 2010). The imported crop biomass in East Asia was converted into

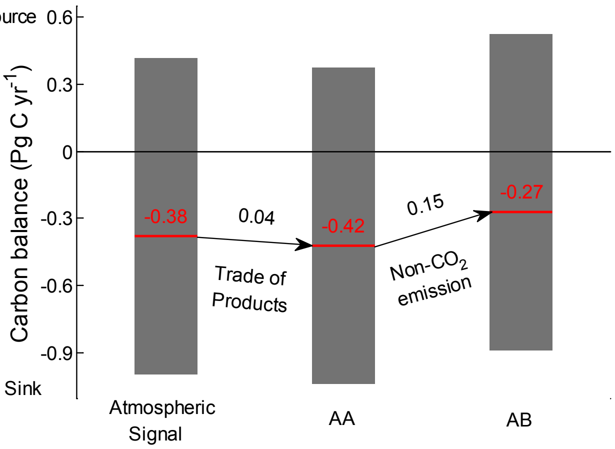

Fig. 7. Atmospheric inversion model estimated carbon balance in East Asia through considering lateral carbon fluxes. The same fossil fuel CO_2 emission estimate has been removed from each inversion to obtain the land–atmosphere CO_2 flux. The average of seven inverse model estimations (atmospheric signal) is corrected by two lateral fluxes. (1) CO_2 emissions due to imported wood and food products ($0.04\,\mathrm{PgC\,yr^{-1}}$) are added to the atmospheric inversion result, resulting in AA; (2) the carbon sink in AA is reduced by carbon fixed by photosynthesis but released to the atmosphere by non-CO_2 compounds ($0.15\,\mathrm{PgC\,yr^{-1}}$), including CO, CH_4 and volatile organic compounds (VOCs), resulting in AB, which should be comparable to estimates by the inventory- and satellite-based approach. Grey bars show ranges in the estimates by different inverse models.

carbon using a 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 $0.04\,\mathrm{Pg\,C\,yr^{-1}}$ during 1990–2009. The non-CO_2 compounds such as CO, CH_4 and BVOC (biogenic volatile organic compounds) emitted by ecosystems, which were also not captured by atmospheric CO_2 observations, should be subtracted from the inverse estimate when assessing the total carbon balance. Using an atmospheric chemistry database (Folberth et al., 2006), we estimated that the biogenic non-CO_2 emission was $0.15\,\mathrm{Pg\,C\,yr^{-1}}$. Due to the lack of information, the removal of fossil C not counted in fossil fuel emissions (e.g. peat use) is not considered in our study. By adjusting the inverse estimates using these lateral fluxes, the top-down approach estimated that the terrestrial ecosystems of East Asia functioned as a net carbon sink of $-0.270 \pm 0.507\,\mathrm{Pg\,C\,yr^{-1}}$ during 1990–2009, with a range from net carbon emission of $0.526\,\mathrm{Pg\,C\,yr^{-1}}$ to net carbon sink of $-0.887\,\mathrm{Pg\,C\,yr^{-1}}$ (Fig. 7, Supplement Table S2).

4 Summary

In summary, based on the average carbon sink from three approaches presented in this study, we estimate that East Asia's terrestrial territory during the 1990s and 2000s were a net carbon sink of -0.224 to $-0.413\,\mathrm{Pg\,C\,yr^{-1}}$ (average of $-0.294\,\mathrm{Pg\,C\,yr^{-1}}$), accounting for 13–27 % 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 $1.5\,\mathrm{Pg\,C\,yr^{-1}}$ to the atmosphere (IEA, 2011; Fig. 1), suggesting that about 13–27 % of East Asia's CO_2 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 a regional model intercomparison project for East Asia, like the VEMAP project for the 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 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_2 stations. In order to correct the differences among different approaches, there is also a need to improve data products of lateral fluxes (e.g. non-CO_2 emissions and carbon exchange between terrestrial ecosystems and inland waters), particularly in their spatial and temporal resolutions. On the analogy of meteorological re-analyses, such an integration system will allow us to establish a "re-analysis" dataset of the global and regional carbon cycles.

Supplementary material related to this article is available online at: http://www.biogeosciences.net/9/3571/2012/bg-9-3571-2012-supplement.pdf.

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