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Special Topic:

Greenhouse Gas Observation From Space: Theory and Application

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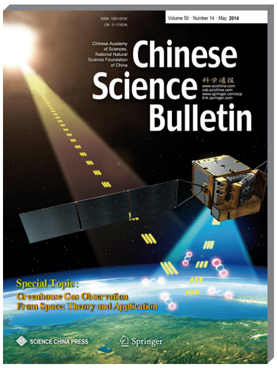

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COVER It has been demonstrated that satellite measurement of CO_2 is important for carbon budget and climate change studies. To achieve scientific goals in these areas, we not only need satellite platforms and instruments, but also remote sensing theory for CO_2 retrieval, validation and applications. This special topic provides a theoretical basis to support the TanSat Chinese Carbon Dioxide Observation Satellite, represented on the front cover. TanSat is sponsored by the National High Technology Research & Development Program of the Ministry of Science and Technology of China, and by the Strategic Priority Research Program of the Chinese Academy of Sciences-Climate Change: Carbon Budget and Relevant Issues. TanSat will carry two instruments: a hyperspectral grating spectrometer for CO_2 and a moderate-resolution polarization imaging spectrometer for cloud and aerosol observations. TanSat acquires data in three different measurement modes, nadir, glint and target, and it will acquire precise measurements of atmospheric CO_2 column amount and CO_2 flux on global and regional scales (see the special topic: Greenhouse Gas Observation From Space: Theory and Application).

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Article

Atmospheric Science

China's sizeable and uncertain carbon sink: a perspective from GOSAT

Li Zhang · Jingfeng Xiao · Li Li · Liping Lei · Jing Li

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Abstract Despite the agreement that China's terrestrial ecosystems can provide a carbon sink and offset carbon dioxide (CO_2) emissions from fossil fuels, the magnitude and spatial distribution of the sink remain uncertain. Accurate quantification of the carbon sequestration capacity of China's terrestrial ecosystems has profound scientific and policy implications. Here, we report on the magnitude and patterns of China's terrestrial carbon sink using the global monthly CO_2 flux data product from the Greenhouse gases Observing SATellite (GOSAT), the world's first satellite dedicated to global greenhouse gas observation. We use the first year's data from GOSAT (June 2009–May 2010) that are currently available to assess China's biospheric carbon fluxes. Our results show that China's terrestrial ecosystems provide a carbon sink of -0.21 Pg C a^{-1}. The consumption of fossil fuels in China leads to carbon dioxide emissions of 1.90 Pg C a^{-1} into the atmosphere, approximately 11.1 % of which is offset by China's terrestrial ecosystems. China's terrestrial ecosystems play a significant role in offsetting fossil fuel emissions and slowing down the buildup of CO_2 in the atmosphere. Our analysis based on GOSAT data offers a new perspective on the magnitude and distribution of China's carbon sink. Our results show that China's terrestrial ecosystems provide a sizeable and uncertain carbon sink, and further research is needed to reduce the uncertainty in its magnitude and distribution.

Keywords Carbon sink · Fossil fuel emissions · Carbon offsets · Biosphere flux · Forest plantations

1 Introduction

There is general agreement that China's terrestrial ecosystems provide a carbon sink and can offset carbon dioxide emissions from fossil fuels, but the magnitude and spatial distribution of the carbon sink remain uncertain. Quantifying the carbon sequestration capacity of China's terrestrial ecosystems would have significant scientific and policy implications. Previous studies have quantified the carbon budgets in China using modeling methods [1] and inventory data [2–4]. However, few studies have investigated the integrated effects of biosphere and fossil fuel fluxes over China using satellite data products.

The greenhouse gases (GHGs), including carbon dioxide (CO_2) and other chemical compounds, such as methane (CH_4), nitrous oxide, and halocarbons, are subject to emission regulations under the Kyoto Protocol. The dramatically increasing concentrations of GHGs in the atmosphere are elevating global average surface air temperatures. CO_2 is the most important anthropogenic greenhouse gas, and its concentrations in the atmosphere continue to increase due to massive consumption of fossil

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fuels by the world's growing economies [5]. Accurate quantification of ecosystem carbon sequestration and fossil fuel emissions will inform national-level carbon policy-making and international negotiation activities for carbon emissions and reductions. Currently, ground-based observation is the main method for monitoring GHGs, e.g., the continuous measurement of CO_2 concentrations at Mauna Loa, USA since 1958 [6]. Although the ground-based techniques have high accuracy, they cannot provide information on regional and global distributions of CO_2 concentrations because of their limited spatial coverage, leading to large uncertainties in the retrievals of CO_2 column abundance [7]. Satellite remote sensing is a potentially effective approach for monitoring the global distributions of greenhouse gases at high spatial and temporal resolutions and is expected to improve the accuracy of source and sink estimates of CO_2 [8–12].

Satellites such as SCIAMACHY/ENVISAT, AIRS/Aqua, and IASI/METOP can monitor the components of the atmosphere, including CO_2. However, the sensors onboard these satellites simultaneously monitor several different gases (H_2O, O_3, CO, and CH_4) and were not designed specifically for the spectrum features of greenhouse gases. Therefore, the GHG measurements by these satellites have relatively low accuracy [13, 14]. For example, the CO_2 column abundance observed by SCIAMACHY has a measurement error of 10–15 ppm [13, 15]. Accurate simulation of the global carbon cycle often requires a precision within 1–5 ppm for CO_2 column abundance [16]. To improve the accuracy of the CO_2 observations, the United States and Japan designed the Orbital Carbon Observatory (OCO) and the Greenhouse gases Observing SATellite (GOSAT), respectively, for monitoring GHGs and providing direct estimates of CO_2 concentrations at the global scale.

The launch of OCO failed on February 24, 2009, while GOSAT was successfully launched on January 23, 2009. GOSAT became the world's first and only spacecraft to measure the concentrations of CO_2 and methane (CH_4) using shortwave infrared (SWIR) bands [17, 18]. GOSAT can collect observational data consistently over clear-sky regions globally and thus is expected to reduce errors in CO_2 flux estimates. The GOSAT is designed to observe the column-averaged dry air mole fraction of CO_2 (X_{CO_2}) with a relative accuracy of 1–4 ppm. With more than two years of improvement on data processing algorithms, the errors for the current version of the GOSAT FTS SWIR Level 2 data (version 2) are less than 2.0 ppm [19–21], which are much smaller than those of the previous version of the data product (version 1). GOSAT thus provides an accurate dataset for regional and global analyses of atmospheric CO_2 variations.

GOSAT generates a suite of products, including X_{CO_2} and CO_2 fluxes, and provides unique data for assessing the regional and global carbon balance [17, 22, 23] with good approximations compared to in situ measurements of CO_2 and CH_4 [24]. GOSAT can significantly improve our knowledge of the CO_2 surface fluxes over terrestrial land areas at the time interval of 1 week and the spatial resolution of a few hundred kilometers [10]. The current estimates of carbon sources and sinks based on atmospheric inversions rely heavily on ground-based observational data. The estimation errors are particularly large in Siberia, Asia, Africa, and South America where ground stations are sparse. The recent study by Takagi et al. [25] demonstrated that GOSAT has the capability of lowering uncertainty of annual mean flux by up to 48 % (annual mean). GOSAT offers new opportunities to improve our understanding of the global carbon cycle.

Here, we report on the magnitude and patterns of Mainland China's terrestrial carbon sink using the GOSAT Level 4A data product. We analyzed the first year's biosphere flux from GOSAT (June 2009–May 2010) that is currently available and assessed China's biospheric carbon fluxes and fossil fuel emissions. To our knowledge, this is the first study to make use of GOSAT data products to quantify the carbon sequestration capacity of China's terrestrial ecosystems.

2 GOSAT data

GOSAT is the outcome of a joint effort by the Japan Aerospace Exploration Agency (JAXA), the National Institute for Environmental Studies (NIES), and the Ministry of the Environment (MOE). Its designed life expectancy is 5 years. GOSAT orbits around the globe with a polar sun-synchronous trajectory and flies at an altitude of approximately 666 km. The observation instrument onboard the satellite, the Thermal And Near-infrared Sensor for carbon Observation (TANSO), is composed of the Fourier Transform Spectrometer (FTS) and the Cloud and Aerosol Imager (CAI). TANSO–FTS obtains the spectral information from visible 0.76 μm to thermal infrared 14.3 μm. Compared with sensors onboard other satellites, TANSO–FTS has a higher signal-to-noise ratio and finer spectral and spatial resolutions [26]. The image data from TANSO–CAI are used to correct the effects of clouds and aerosols on the spectra obtained with TANSO–FTS. TANSO–FTS has two modes: normal pattern and orientation adjustable pattern. There are five modes for the FTS observation over lattice points, depending on the number of scans in the cross-track direction, namely, 1, 3, 5, 7, and 9. In normal 5 lattice point mode, the footprint is 158 km × 152 km at 30° latitude [27]. GOSAT returns to the same footprint every 3 days and collects 56,000 footprints globally, but only 2 %–5 % of the data are valid due to the requirements for clear-sky conditions [28]. However, the number of valid data points is still much larger than the number of ground monitoring stations.

There are 4 levels of data products (Levels 1–4) derived from GOSAT observations. Level 1 product contains spectra and radiances acquired by the satellite. The FTS SWIR Level 2 data provide the column abundances of CO_2 and CH_4 retrieved from Level 1 spectral observation data [29]. The FTS SWIR Level 3 product provides monthly global distributions of CO_2 and CH_4 calculated from the Level 2 data using the Kriging interpolation method. Zeng et al. [30] recently proposed an improved interpolation method, the spatiotemporal geostatistical method, which incorporates temporal variability for accurate prediction of regional CO_2 from Level 2 data. The Level 4 data product provides monthly CO_2 fluxes inferred from both the GOSAT Level 2 (X_{CO_2})retrievals and ground-based CO_2 monitoring data (GLOBALVIEW-CO_2), using a global atmospheric tracer transport model and a Bayesian inverse modeling scheme [27, 31, 32].

The L4A data product provides four fluxes, including three priori (imposed) CO_2 fluxes and a posteriori (optimized) surface CO_2 flux. The three priori fluxes include the fluxes of terrestrial biosphere (including biomass burning and forest fires), anthropogenic emissions, and ocean [33]. The optimized flux is the sum of the three priori fluxes plus flux correction to the priori flux determined via the optimization and obtained with inversion. The uncertainty of the optimized fluxes was reduced by up to 60 % using both the GOSAT (X_{CO_2})retrievals and the GLOBALVIEW data in the flux estimation [32]. The four fluxes are derived from an integrated global carbon cycle modeling system, including atmospheric tracer transport model (NIES-TM), anthropogenic emissions inventories, terrestrial biosphere exchange model, and oceanic flux model [32]. The NIES-TM was used to run forward simulations of atmospheric CO_2 for the inverse modeling of surface CO_2 fluxes. Monthly fossil fuel CO_2 emissions (combustion of fossil fuels and cement manufacturing) were obtained by integrating the high-resolution Open source Data Inventory of Anthropogenic CO_2 emission (ODIAC) dataset and the Carbon Dioxide Information Analysis Center's (CDIAC) dataset [32]. The carbon emissions from forest fire and biomass burning are from Global Fire Emissions Database (GFED 3.1). The ocean flux was estimated with a 4D variational assimilation system. The daily net ecosystem exchange (NEE) of CO_2 was predicted by the terrestrial biosphere exchange model VISIT (Vegetation Integrative Simulator for Trace gases). In the VISIT model, the physiological parameters were optimized by fitting model parameters to observe atmospheric CO_2 seasonal cycle, net primary production data, and a biomass distribution map using a Bayesian inversion approach [32].

In this study, we used the GOSAT Level 4A product (V02.01) to derive the posterior biosphere flux ($NEE_{posterior}$) by subtracting fossil fuel and ocean fluxes from the total optimized flux. The biomass burning emissions were not excluded, because the current version (V02.01) of GOSAT L4A product does not provide this data layer. The posterior biosphere flux ($NEE_{posterior}$) exhibited unreasonable carbon sources in many areas, because the biomass burning emissions were not subtracted. Therefore, for cells with positive posterior NEE values (carbon release) and negative prior NEE values (net carbon uptake), we replaced the posterior values with prior NEE (NEE_{prior}). We then used the resulting adjusted NEE fluxes (NEE_{adj}) to assess the magnitude and distribution of Mainland China's carbon sink. We also used the fossil fuel emissions data included in the GOSAT L4A product to quantify the fossil fuel emissions at the national and regional levels and assessed the carbon offsetting capacity of terrestrial ecosystems.

3 China's carbon sink: magnitude and distribution

We assessed the magnitude and distribution of China's terrestrial carbon sink from June 2009 to May 2010 using GOSAT L4A data. Our results show that China's terrestrial ecosystems provided a carbon sink of -0.21 Pg C a^{-1}. Our estimate is within the ranges of two previous estimates (-0.19 to -0.26 Pg C a^{-1} [3], -0.18 to -0.24 Pg C a^{-1} [34]) but is about twice as much as another previous estimate (-0.096 to -0.106 Pg C a^{-1} [4]) (Table 1). This suggests that the magnitude of China's carbon sink still remains uncertain. This also likely suggests that the terrestrial sink in China has been increasing due to large-scale afforestation, vegetation restoration, and rising air temperatures in recent decades [35].

The estimate of the global terrestrial carbon sink for the past two decades is typically around -2 Pg C a^{-1} [37–39]. According to our estimate, China's terrestrial carbon sink accounts for about 10.5 % of the world's total sink. China's carbon sink was lower than that of the conterminous United States (-0.30 to -0.58 Pg C a^{-1} [40]) mainly because the U.S. forest area is almost double that of China (3.14×10^6 km^2 for the U.S. and 1.71×10^6 km^2 for China, [41]). The size of China's carbon sink was comparable to

Table 1 Magnitude of China's carbon sink estimated from GOSAT data and other methods

Biosphere fluxes (Pg C a^{-1})	Period	Reference
-0.21	2009–2010	This study
-0.18 to $-0.$ 24 (mean -0.21)	1961–2005	[34]
-0.19 to -0.26	1980–2000	[3]
-0.096 to -0.106	1981–2000	[4]
0.32 to -0.25 (mean -0.07)	1981–1998	[36]

Negative values indicate carbon sinks

or slightly higher than that of Europe (−0.135 to −0.205 Pg C a^{-1}, [42]). This indicates that there is substantial potential to increase the size of China's carbon sink by increasing the forest area through afforestation and reforestation.

The spatial distribution of the annual biosphere flux (Fig. 1) shows that the magnitude of regional carbon sinks varied with geographic region. A large part of China was nearly carbon neutral. The annual biosphere fluxes in the east were generally higher than those in the west. Regionally, the carbon sinks were largest in Northwest China (−0.085 Pg C a^{-1}), Southwest China (−0.050 Pg C a^{-1}), and South China (−0.033 Pg C a^{-1}) (Fig. 2). The sink in Northwest China accounted for 39.7 % of the entire sink of the country. The sink in Northwest China was mainly located in the western part of Xinjiang and the Loess Plateau. Ecological restoration projects in this ecologically vulnerable region have led to a significant increase in forested areas and ecosystem carbon sequestration [43]. Despite the large land area of Northwest China and the contributions of ecological restoration projects, the magnitude of the sink in the region most likely has been significantly overestimated. Southwest China and South China account for 24.5 % and 4.7 % of the national land area, respectively, and are characterized by large forest cover and warm and wet climate conditions. Together, the sink in Southwest China and South China accounted for 38.6 % of the entire sink of the country. During the study period, Southwest China experienced a severe spring drought [44]; therefore, the biosphere flux in Southwest China (−0.050 Pg C a^{-1}) was probably slightly lower than the normal level for this region. Intermediate sinks were provided by Central China (−0.016 Pg C a^{-1}) and Northeast China (−0.016 Pg C a^{-1}). The smallest sink was provided by East China (−0.008 Pg C a^{-1}) and North China (−0.005 Pg C a^{-1}). North China is characterized by semiarid and arid continental climates and is dominated by grasslands, which contributes the least carbon sink in China.

We also examined the monthly variations in biosphere flux for different geographic regions (Fig. 3). As expected, China's terrestrial ecosystems generally absorbed carbon from April to September. The nationally averaged monthly NEE varied from −0.285 Pg C $month^{-1}$ in August to 0.179 Pg C $month^{-1}$ in December. The regional flux exhibited relatively low seasonal variations in South China which is dominated by evergreen forests, but large variations in Southwest China and Northeast China. A large area of Southwest China is distributed with mixed forests and grasslands, and the annual

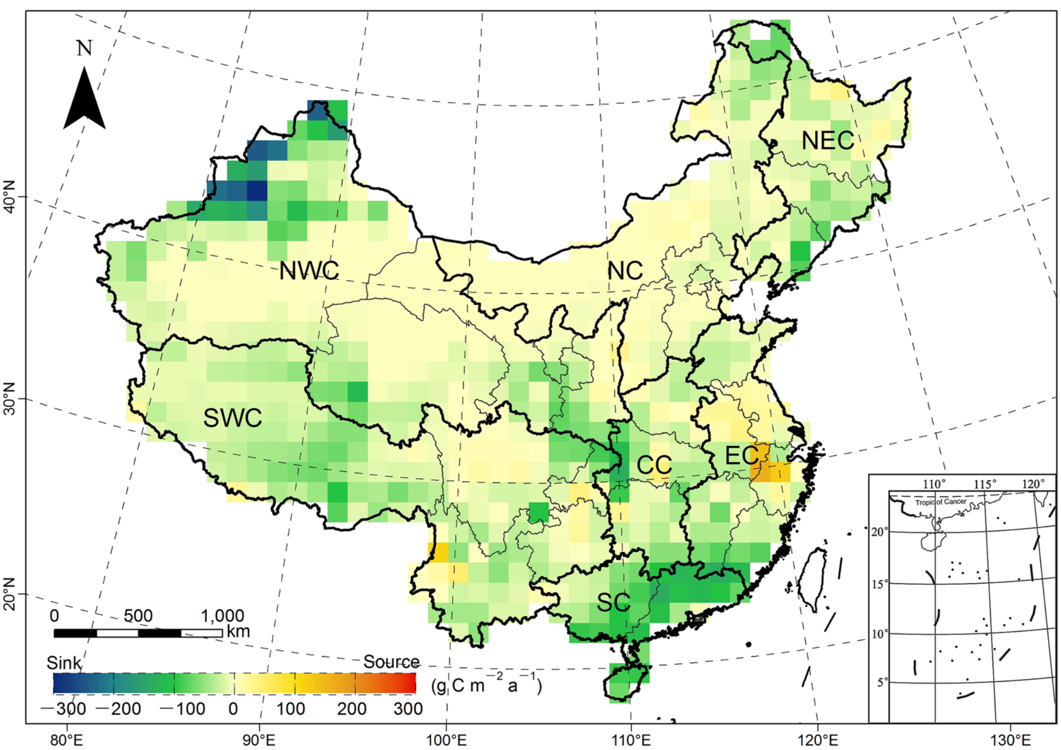

Fig. 1 Annual biosphere flux of Mainland China's terrestrial ecosystems derived from the adjusted biosphere flux (NEE_{adj}) based on GOSAT data for the period June 2009–May 2010. The seven geographic regions are: Northeast China (NEC), North China (NC), Northwest China (NWC), East China (EC), Central China (CC), Southwest China (SWC), and South China (SC)

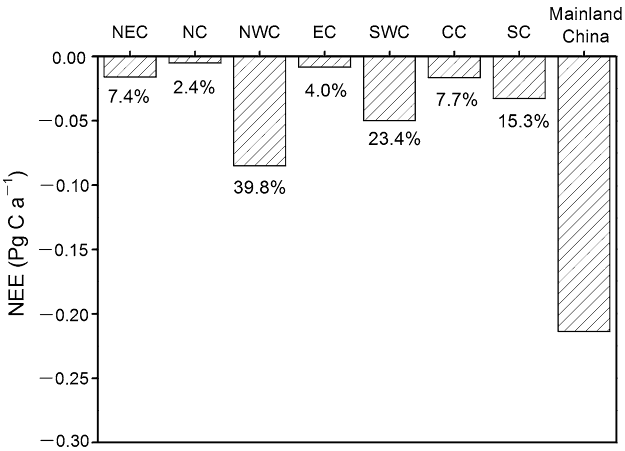

Fig. 2 Magnitude of the regional carbon sinks (NEE_{adj}). The *numbers below the bars* represent the percentages that the regional carbon sinks account for the nationwide carbon sink. The seven geographic regions are the same as in Fig. 1

flux varied from −0.075 Pg C month^{-1} in August to 0.052 Pg C month^{-1} in December. A large area of Northeast China is mixed forests and croplands, and the annual flux varied from −0.059 Pg C month^{-1} in July to 0.026 Pg C month^{-1} in November.

4 Fossil fuel emissions and carbon offsets by ecosystems

Our results show that the fossil fuel CO_2 emissions in China were 1.90 Pg C a^{-1} for the period June 2009–May 2010. Spatially, the eastern half of China had higher emissions than the western half, with the highest emissions occurring in the northeastern provinces (Fig. 4a). The biosphere fluxes and emissions in China showed different patterns along two typical transects (A–B and C–D). For the transect A–B (northwest–southeast transect representing gradients from low precipitation to high precipitation and from low population density to high population density, Fig. 4b), biosphere fluxes and fossil fuel emissions both increased and higher biosphere fluxes occurred at 112°–115° longitude and higher fossil fluxes occurred at 116°–117° longitude. For the transect C–D (northeast–south transect representing gradients from cold regions with shorter growing seasons and extensive use of heating during the winter to warm regions with longer growing seasons and less use of heating, Fig. 4c), biosphere fluxes were almost consistently low except for areas lower than 30°N, while fossil fuel emissions showed large variations for areas lower than 42°N.

East China and North China were the largest two regional emitters (0.57 and 0.41 Pg C a^{-1}, respectively) and together, accounted for 51.6 % of the country's total emissions. Approximately 1.5 % and 1.2 % of the emissions were offset by net ecosystem carbon uptake in the two regions, respectively. Northeast China, Central China, and South China had intermediate fossil fuel carbon emissions and the terrestrial ecosystem offset 7.8 %, 8.2 %, and 16.8 % of the emissions, respectively. The high CO_2 emissions in Northeast China were attributed to extensive fossil fuel burning and biomass combustion, industrial and agricultural activities, and residential heating. Northwest China and Southwest China had the lowest fossil emissions of 0.17 and 0.16 Pg C a^{-1}, respectively, and the terrestrial ecosystem offset 51.5 % and 31.8 % of the emissions, respectively. The western parts of China had low emissions due to low population densities and less-developed economies. Southwest China is covered by large areas of forests and thus could sequester more carbon from the atmosphere. The terrestrial ecosystems in Northwest China offset 51.5 % of fossil fuel emissions due to the relatively low fossil fuel emissions and a relatively high carbon sequestration capacity in the Loess Plateau. The offsetting percentage of Northwest China was likely overestimated, because the magnitude of the regional carbon sink was likely significantly overestimated.

At the national scale, the terrestrial ecosystems offset 11.1 % of the fossil fuel emissions. Our results showed that

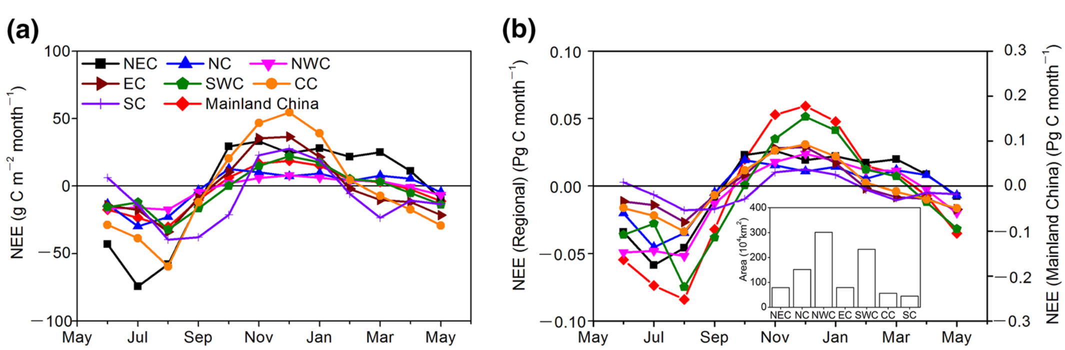

Fig. 3 Monthly variations of biosphere fluxes (NEE_{adj}) for different geographic regions and China from June 2009 to May 2010. **a** Spatially averaged monthly NEE (g C m^{-2} month^{-1}). **b** Spatially integrated monthly NEE (Pg C month^{-1}). The seven geographic regions are the same as in Fig. 1

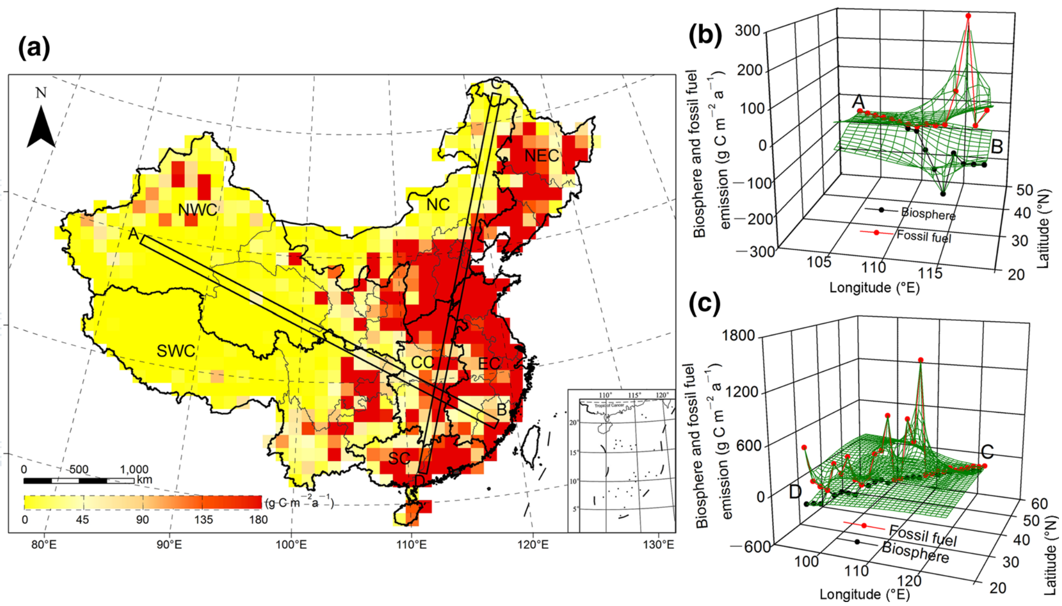

Fig. 4 **a** Spatial distribution of annual fossil fuel emissions in China. **b** Annual biosphere fluxes and fossil fuel emissions along Transect A–B. **c** Annual biosphere fluxes and fossil fuel emissions along Transect C–D

China's terrestrial ecosystems play a significant role in slowing down the buildup of CO_2 in the atmosphere and have implications for carbon and climate policymaking. Globally, terrestrial ecosystems offset 10 %–60 % of fossil fuel emissions during the 1980s–2000s [38, 39, 45–48]. Regionally, ecosystems in Europe offset 7 %–12 % of fossil fuel emissions in 1995 [42], and ecosystems in the U.S. offset 40 % in the 2000s [49]. China's offset ratio is comparable to that in Europe. Global fossil fuel emissions increased by 29 % from 2000 to 2008 due to the fact that the largest fuel emission source shifted from oil to coal [50], and lowered the percentage of fossil fuel emission offset by ecosystems. The offset percentage likely also decreased in China since the 1980s despite the increase in the forest carbon sink as a result of forest plantations.

The future carbon offsetting capacity of China's terrestrial ecosystems will depend on the trends of fossil fuel emissions and changes in the magnitude of the terrestrial carbon sink. On the one hand, fossil fuel emissions will most likely continue to increase within the next decade or so, although in the long run, China's path to low-carbon development will likely slow down the increase in fossil fuel emissions. On the other hand, ecological restoration and rehabilitation projects, including forest plantations and "grain for green", will continue to increase forest cover and ecosystem carbon sequestration capacity. Future climate change, including rising air temperature and atmospheric CO_2 concentrations and increases in the frequency and severity of extreme climate events and disturbances, will add additional uncertainty in projecting the carbon offsetting capacity of China's terrestrial ecosystems (Fig. 5).

5 Uncertainty in sink estimates

There are several sources of uncertainty to our estimates of biosphere fluxes, although we used the GOSAT data product based on the state-of-the-art satellite observations of CO_2 concentrations. In this study, we assessed the magnitude and distribution of China's carbon sink using the adjusted NEE derived mainly from the posterior ($NEE_{posterior}$) (Fig. 6a) and partly from the prior (NEE_{priori}) (Fig. 6b) fluxes of the GOSAT data product. $NEE_{posterior}$ exhibited unreasonable carbon sources in some areas of Southwest China, East China, North China, and Northeast China, likely because biomass burning emissions were not subtracted. Agricultural fires, such as crop-residue burning, are very active during the fire season and near regions with high levels of biomass burning, such as in South China [51] and North China Plain [52]. The adjusted biosphere flux (NEE_{adj}) included emissions from the biomass burning and forest fires that could not be subtracted for the Level 4A product (V02.01) that we used, which could certainly lead to uncertainty in our estimate of the carbon sink. Moreover, $NEE_{posterior}$, and thus NEE_{adj}, exhibited large differences in the spatial distribution of carbon fluxes and the magnitude of regional carbon sinks from NEE_{prior}, particularly for Northwest China (Fig. 6c). The large net carbon uptake in the northern portion of Northwest China for $NEE_{posterior}$

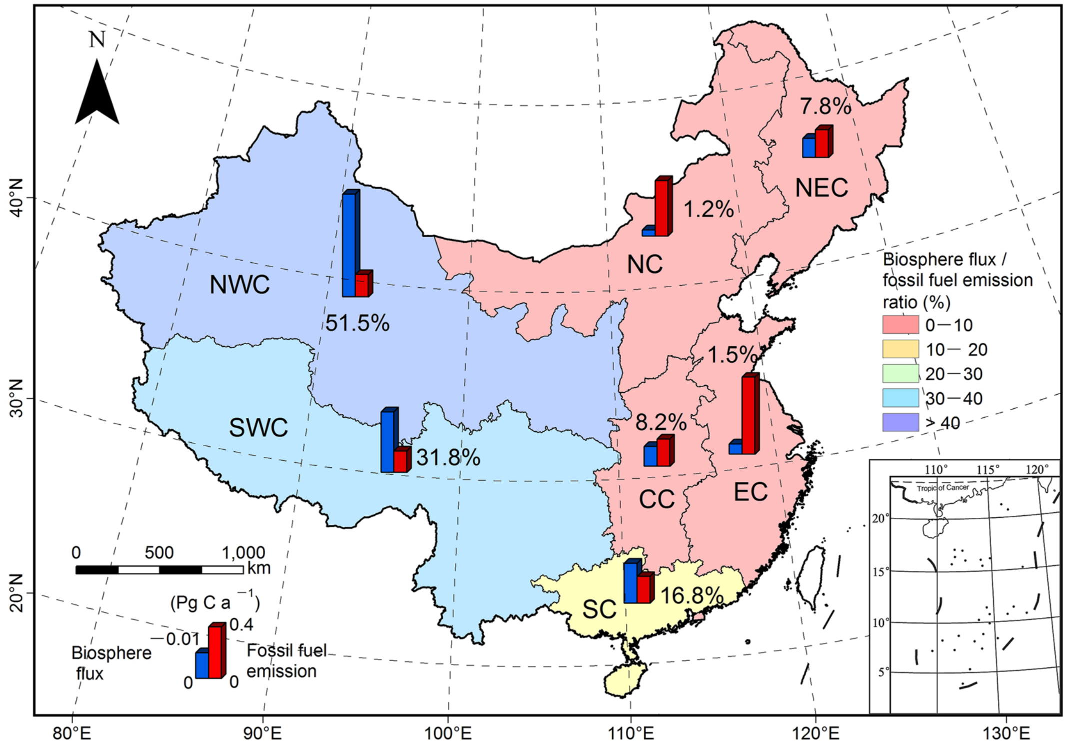

Fig. 5 Regional carbon sinks and fossil fuel emissions in China. The *ratios* indicate the percentages (%) of fossil fuel emissions that were offset by the biosphere carbon sink. The seven geographic regions are the same as in Fig. 1

was likely significantly overestimated because of the limitations and uncertainty of the inversion.

Our estimates of China's carbon sink also have other sources of uncertainty. There are likely large uncertainties in the fossil fuel emissions used in the inversion [32]. The accuracy of the posterior biosphere flux ($NEE_{posteriori}$) is also related to the quality of observed GOSAT X_{CO_2} data and the inverse modeling schemes [32]. The GOSAT instrument has measurement errors in measuring CO_2 concentrations [7], although the errors are relatively small (<2 ppm; [19–21]). Moreover, the accuracy of the GOSAT data product is higher in regions with dense GOSAT footprints, but larger uncertainties exist for regions with sparse GOSAT footprints. The uncertainty in the model parameters and the structure of the integrated global carbon cycle modeling system used to derive the GOSAT Level 4 data product could also lead to uncertainty in the biosphere flux estimates.

All these above sources of uncertainties can lead to uncertainties in our carbon sink estimates. Although our estimates were generally consistent with previous estimates based on independent approaches, there is still substantial uncertainty in the magnitude and distribution of China's carbon sink. Our study shows that further research is needed to reduce the uncertainty in the posterior biosphere flux.

Despite the uncertainty of the GOSAT data product, GOSAT could significantly improve our knowledge of the CO_2 fluxes over terrestrial areas. In the near future, more carbon satellites will be launched for global CO_2 studies. For example, GOSAT-2, a GOSAT successor, is planned to be launched in 2017 [33]. NASA's Orbiting Carbon Observatory (OCO-2) is also specifically designed for making high-precision measurements of CO_2 [53] and is expected to be launched in 2015 [54]. China plans to launch TanSat (Tan-carbon in Chinese) in 2015, which is designed to monitor CO_2 in Sun-Synchronous orbit with (X_{CO_2}) precisions of 1–4 ppm over regional scales [55]. The Institute of Environmental Physics (IUP) of the University of Bremen, Germany, is currently conducting studies for a future greenhouse gas satellite mission called CarbonSat (Carbon Monitoring Satellite), which is scheduled to be launched around the end of this decade [56]. These future satellites will likely provide more valuable data for assessing carbon sinks/sources at regional to global scales.

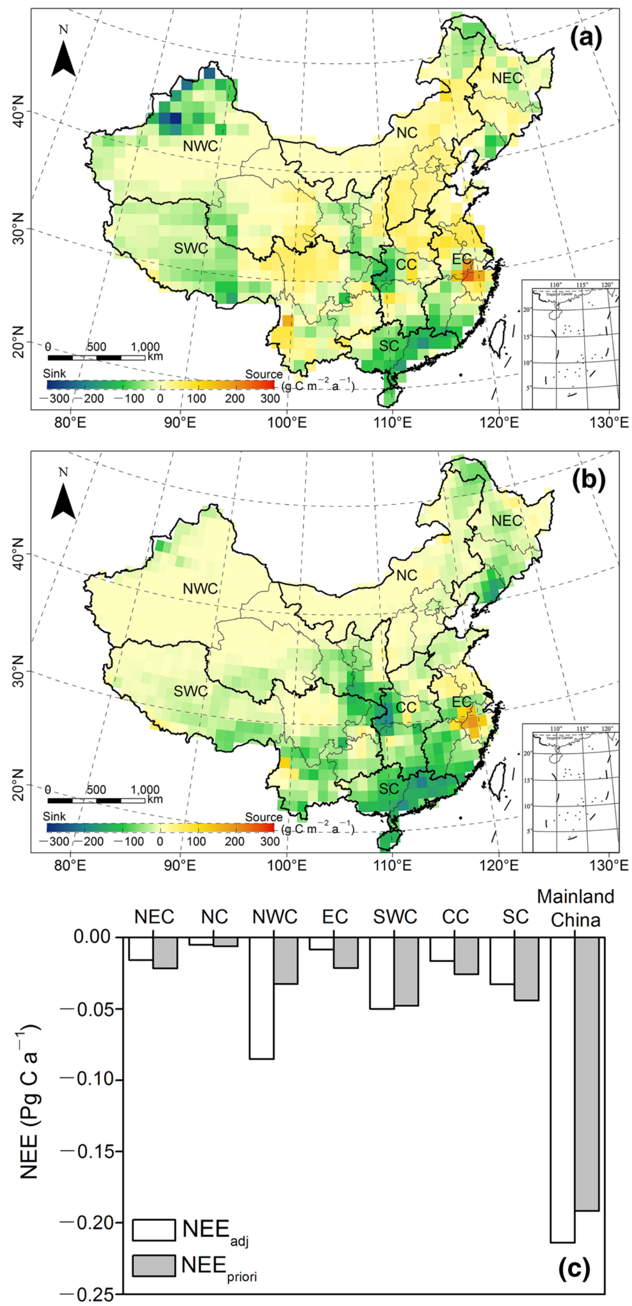

Fig. 6 Comparison of posterior and prior biosphere flux in China for the period June 2009–May 2010. **a** Posterior biosphere flux ($NEE_{posterior}$). **b** Prior biosphere flux (NEE_{prior}). **c** Comparison in regional carbon sinks between adjusted and prior flux estimates. The seven geographic regions are the same as in Fig. 1

6 Conclusions

The successfully launched GOSAT provides a unique global dataset of net monthly CO_2 fluxes (GOSAT Level 4A data product) for studying major greenhouse gases such as CO_2 and CH_4. We assessed the carbon sink and fossil fuel emissions of China using this dataset. China's terrestrial ecosystems provided a carbon sink of -0.21 Pg C a^{-1}. The consumption of fossil fuel in China produced CO_2 emissions of 1.90 Pg C a^{-1}, and 11.1 % of which were offset by net ecosystem carbon uptake. Our results show that China's terrestrial ecosystems play a significant role in offsetting fossil fuel emissions and slowing down the buildup of CO_2 in the atmosphere. Our study offers a new perspective on the magnitude and distribution of China's terrestrial carbon sink and fossil fuel emissions. In the meanwhile, our analysis also shows that the GOSAT Level 4A data product has significant uncertainty, and further research is needed to reduce the uncertainty in our estimates of both magnitude and spatial distribution of the carbon sink.

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