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LETTERS

The carbon balance of terrestrial ecosystems in China

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Global terrestrial ecosystems absorbed carbon at a rate of 1–4 Pg yr^{-1} during the 1980s and 1990s, offsetting 10–60 per cent of the fossil-fuel emissions[1,2]. The regional patterns and causes of terrestrial carbon sources and sinks, however, remain uncertain[1–3]. With increasing scientific and political interest in regional aspects of the global carbon cycle, there is a strong impetus to better understand the carbon balance of China[1–3]. This is not only because China is the world's most populous country and the largest emitter of fossil-fuel CO_2 into the atmosphere[4], but also because it has experienced regionally distinct land-use histories and climate trends[1], which together control the carbon budget of its ecosystems. Here we analyse the current terrestrial carbon balance of China and its driving mechanisms during the 1980s and 1990s using three different methods: biomass and soil carbon inventories extrapolated by satellite greenness measurements, ecosystem models and atmospheric inversions. The three methods produce similar estimates of a net carbon sink in the range of 0.19–0.26 Pg carbon (PgC) per year, which is smaller than that in the conterminous United States[5] but comparable to that in geographic Europe[6]. We find that northeast China is a net source of CO_2 to the atmosphere owing to overharvesting and degradation of forests. By contrast, southern China accounts for more than 65 per cent of the carbon sink, which can be attributed to regional climate change, large-scale plantation programmes active since the 1980s and shrub recovery. Shrub recovery is identified as the most uncertain factor contributing to the carbon sink. Our data and model results together indicate that China's terrestrial ecosystems absorbed 28–37 per cent of its cumulated fossil carbon emissions during the 1980s and 1990s.

In parallel with the recent economic boom in China, there has been a steep rise in energy demand, sustained by the use of fossil fuels. Fossil-fuel CO_2 emissions have thus climbed from 0.4 PgC yr^{-1} in 1980 to 1.5 PgC yr^{-1} in 2006, making China the largest emitter in the world[4]. Quantifying the carbon balance of Chinese ecosystems is necessary not only to assess the magnitude of the Northern Hemispheric and global sinks, but also to define new objectives for the management of terrestrial ecosystems in the context of the global impetus to slow the rate of CO_2 growth. In this study, we use three different methods: sample-based biomass and soil carbon inventories combined with remotely sensed vegetation greenness index, ecosystem models and atmospheric inversions of CO_2 concentration data (Methods), to assess the carbon balance of China during the 1980s and 1990s.

Forests cover ~14% of China. Analysis of the national forest inventory data (Methods) suggests that forest biomass carbon stock increased significantly during the 1980s and 1990s. This translates into a carbon sink of 0.058 ± 0.026 PgC yr^{-1} during the 1980s and one of 0.092 ± 0.044 PgC yr^{-1} during the 1990s (Table 1). A total amount of 1.65 ± 0.76 PgC has been sequestered into forest biomass since 1982. On an area basis, this accumulation of carbon in standing tree biomass (57 ± 26 gC m^{-2} yr^{-1}) is comparable to the US values (52–71 gC m^{-2} yr^{-1})[5] but is lower than in Europe (60–150 gC m^{-2} yr^{-1})[6]. In addition, bamboos are estimated to have accumulated 37 gC m^{-2} yr^{-1} (or 0.001 PgC yr^{-1}) during the 1990s[7]. In comparison with that in North America, the impact of forest fires on the Chinese forests' carbon balance is small, with an average emission of 0.003 PgC yr^{-1} between 1980 and 2000 (ref. 8).

Shrubland is a widely distributed biome type in China, covering ~20% of the country. However, information on the carbon balance

Table 1 | Carbon balance estimates of the Chinese terrestrial ecosystems using the different approaches

Method	Category		Period	Area (10^6 ha)	Carbon balance (TgC yr^{-1})	Ref.
Inventory–satellite-based estimation	Vegetation	Forest	1982–1993	124–132	58.4 ± 25.8	9
			1994–2003	132–143	92.2 ± 43.7	9
		Forest ave.			75.2 ± 34.7	
		Shrub	1982–1999	215	21.7 ± 10.2	This study
		Grassland	1982–1999	331	7.0 ± 2.5	10
		Bamboo	1981–1993	3.5	1.3 ± 0.9	7
		Subtotal			105.2 ± 48.3	
	Soil	Forest	1982–1999	130	4.0 ± 4.1	This study
		Shrub	1982–1999	215	39.4 ± 9.0	This study
		Grassland	1982–1999	331	6.0 ± 1.0	This study
		Crop	1980s, 1990s	120–160	26.0 ± 11	14, 15
		Subtotal			75.4 ± 25.1	
	Fire	Forest	1980–2000		−3.0	8
	Total				177 ± 73.4	
Process-based models	Vegetation		1980–2002		92 ± 74	This study
	Soil		1980–2002		75 ± 66	This study
	Total		1980–2002		173 ± 39	
Atmospheric inversion			1996–2005		350 ± 330	This study

Cropland has absorbed an additional 13.4 ± 0.9 TgC yr^{-1}, but we exclude this from an accounting of China's net terrestrial carbon sink because of its short turnover. Positive values indicate carbon sinks.

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of this important biome is very scarce. Across the conterminous United States, the 'encroachment' of shrubs was estimated to account for roughly one-third of the carbon sink[5]. Our estimation for China, relying on *in situ* biomass and satellite greenness information (Methods), indicates that shrubland biomass is a net sink of 0.022 ± 0.01 PgC yr^{-1} (10 ± 5 gC m^{-2} yr^{-1}), which is ~30% of the forest sink in the 1980s. This estimate is within the range of a previous estimation (0.014–0.024 PgC yr^{-1})[9].

For cropland[9] and grassland[10], respectively, the biomass stocks increased by 0.013 PgC yr^{-1} and 0.007 ± 0.002 PgC yr^{-1} during the 1980s and 1990s. However, carbon incorporated into plants is harvested at least once per year and released back as CO_2 into the atmosphere through the food web within the year[11]. This implies that this increasing crop biomass does not contribute to a net long-term sink.

Soils are the largest source of uncertainty in the terrestrial carbon balance of China (as well as in other regions of the world), as data from repeated inventories is lacking. We have developed an empirical regression method for scaling up soil carbon inventory data, and estimated spatio-temporal patterns of soil carbon changes (Methods). Over forests, shrublands and grasslands, we found a net sink in the soil. The largest soil carbon sink is found in shrublands (0.039 ± 0.009 PgC yr^{-1}) and the smallest sink is found in forests (0.004 ± 0.004 PgC yr^{-1}) (Table 1). This surprisingly small soil carbon sequestration in forests results from counterbalancing changes in evergreen and deciduous forest soils. Regional data indicate a large soil carbon accumulation in the evergreen forests of southern China (0.022 ± 0.008 PgC yr^{-1}) that is nearly offset by a net soil carbon loss in northern deciduous forests (0.018 ± 0.004 PgC yr^{-1}). Northern regions were exposed to a stronger warming trend[1] and also experienced net deforestation[12,13] during the 1980s and 1990s.

For the soil of croplands, a meta-analysis of data from 132 publications involving 23 soil groups and >60,000 soil sample measurements suggests that the topsoil organic carbon stock has been increasing at a rate of 0.015–0.020 PgC yr^{-1} (Supplementary Information)[14]. The magnitude of this sink is about one-half of the previous estimate (0.025–0.037 PgC yr^{-1})[15]. From these two estimates, we took a central value of 0.026 ± 0.011 PgC yr^{-1}.

Summarizing the estimates based on repeated carbon-stock inventories combined with satellite greenness information, we infer an average net carbon sink of 0.177 ± 0.073 PgC yr^{-1} in Chinese terrestrial ecosystems during the 1980s and 1990s. On average, 58% of this sink lies in the biomass and the rest in soil organic matter (Table 1).

Next we used the results of an ensemble of atmospheric inversions to verify results of the inventory–satellite method. Inversions over China are poorly constrained by a regionally scarce atmospheric network (there are only nine sites in northern Asia). They are also sensitive to transport-model errors[16] and to biases in the assumed fossil-fuel emissions[17]. Each inversion in our ensemble solves for fluxes on the transport-model grid (200 km; see Methods), which minimizes the aggregation bias in regional flux estimations[18]. Although their uncertainties are large on the regional scale, it is important to include inversions in an assessment because this method provides an independent estimation and encompasses all surface sources and sinks of CO_2, whereas there is a risk of omitting important processes or ecosystems (for example wetlands and urban ecosystems) in the inventory method. The mean result of the inversion ensemble over the period 1996–2005 is a net CO_2 uptake of 0.35 PgC yr^{-1}, with a random error returned by the inversions of ± 0.33 PgC yr^{-1}, an error range of 0.05 PgC yr^{-1} corresponding to the spread (s.d.) of the ensemble of sensitivity tests in which the inversion set-up is varied and an additional error of ± 0.19 PgC yr^{-1} due to uncertainty in assumed fossil-fuel emissions (Supplementary Information). This estimation is comparable to the result of ref. 19 (run ID/version s96_v3.1), in which, with a different inverse set-up, a mean carbon sink over China of 0.46 PgC yr^{-1} was obtained for the period 1996–2005 (Supplementary Information).

The inversion sink of atmospheric CO_2 in ecosystems ($N_{CO_2} = 0.35$ PgC yr^{-1}) is twice as large as the inventory–satellite-based carbon sink ($N_C = 0.177$ PgC yr^{-1}). Part of this discrepancy can be reconciled when accounting for 'lateral fluxes' (LF, Fig. 1a)[20].

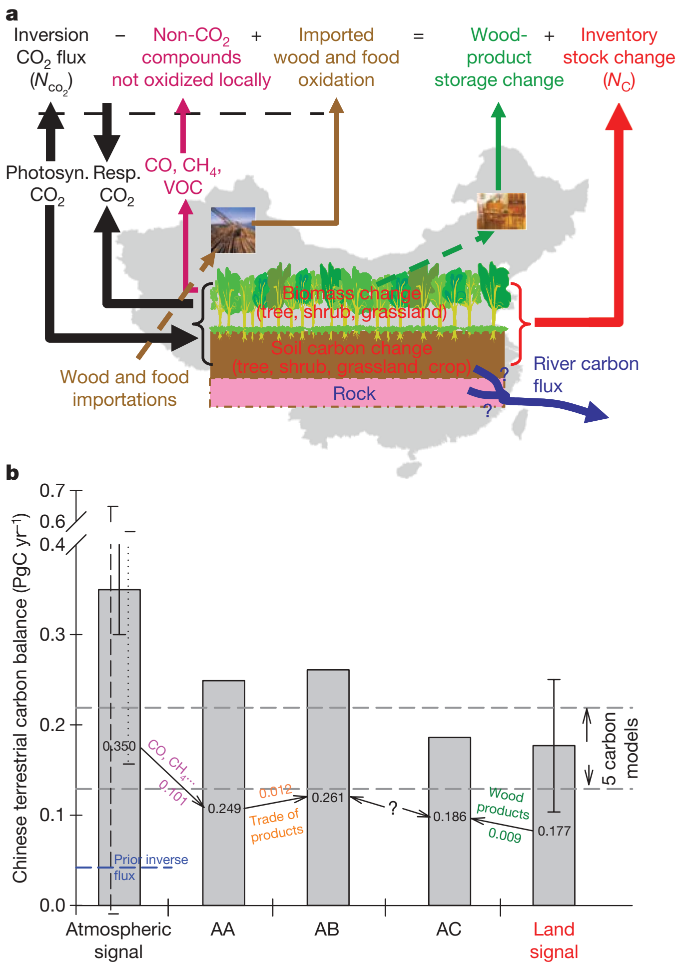

Figure 1 | Carbon balance estimates of terrestrial ecosystems in China. **a,** The link between inventory–satellite-based terrestrial-biosphere carbon balance (N_C) and atmospheric inversion modelling estimation (N_{CO_2}). The two can be related by $N_C = N_{CO_2} - \mathrm{LF}$, where LF (lateral flux) denotes processes causing CO_2 fluxes with the atmosphere that are not accounted for by N_C. Lateral fluxes include (1) carbon fixed by photosynthesis but returned to the atmosphere by non-CO_2 compounds, that is, emissions of CO, CH_4 and volatile organic compounds (VOCs); (2) carbon associated with the fate of wood and food products; and (3) carbon exported from ecosystems by rivers. **b,** The carbon balance of the Chinese terrestrial biosphere estimated by atmospheric inversion modelling, ecosystem models and inventory analysis. AA, a carbon sink of 0.350 Pg yr^{-1} estimated by atmospheric inversions minus a carbon loss of 0.101 PgC yr^{-1} in non-CO_2 gaseous compounds (CO, CH_4 and VOCs) leaves a net carbon sink of 0.249 PgC yr^{-1}. AB, the net carbon sink in AA plus imported carbon (0.012 PgC yr^{-1}) through trade of wood and food products produces a total carbon sink of 0.261 PgC yr^{-1}. AC, inventory-based estimate (0.177 PgC yr^{-1}) plus carbon accumulation (0.009 PgC yr^{-1}) in wood products generates a total carbon sink of 0.186 PgC yr^{-1}. The black solid and dashed lines indicate inversion-model uncertainty corresponding to the estimated random error in the spread (s.d.) of an ensemble of sensitivity tests (± 0.05 PgC yr^{-1}) and the inversion procedure (± 0.33 PgC yr^{-1}), respectively. The dotted line indicates uncertainty in fossil-fuel emission in China (20% or ± 0.19 PgC yr^{-1})[4]. The blue dashed line shows the prior inverse flux (0.04 PgC yr^{-1}). The grey horizontal dashed lines indicate the range of carbon balance estimated by ecosystem models. A positive value indicates a net carbon uptake. The transport of carbon by Chinese rivers to the ocean was not counted in LF, because we do not know if this carbon is eroded from old soil pools or if it constitutes a fraction of the current CO_2 sink being channelled to rivers (Supplementary Information).

We estimate from atmospheric chemistry databases[21] that anthropogenic and biogenic emissions of non-CO_2 compounds over China are 0.118 PgC yr^{-1}. Roughly 14% of these emissions are converted to CO_2 in the boundary layer[20], leaving a corresponding lateral flux of 0.101 PgC yr^{-1}. We used international trade statistics[22] to estimate that 0.008 PgC yr^{-1} of wood products and 0.004 PgC yr^{-1} of food products are imported into China and oxidized into an annual CO_2 source of 0.012 Pg yr^{-1} (Supplementary Information). The carbon balance of domestic wood products, which was not included in the inventory method, was also considered[5]. These wood-product pools in China are found to accumulate 0.009 PgC yr^{-1} (Supplementary Information). In summary, the atmospheric CO_2 inversion sink (N_{CO_2}) is reduced by the lateral fluxes from 0.35 PgC yr^{-1} to 0.261 PgC yr^{-1}, which corresponds to carbon sinks in ecosystems (Fig. 1b).

Finally, we used results from five process-based ecosystem models[23] to quantify the effect of changes in CO_2 and climate on the carbon balance of China (Methods). Despite differences in their settings and parameters, the five models consistently locate a net carbon sink over China between 1980 and 2002, ranging from 0.13 PgC yr^{-1} to 0.22 PgC yr^{-1} with an average of 0.173 ± 0.039 PgC yr^{-1}. In good agreement with the inventory–satellite-based mean sink apportionment, the models partition the sink to be mostly in biomass (~53%) and otherwise in soils (Table 1). The fact that the carbon sink produced by models is close to the inventory–satellite-based estimation, even though models do not account for land-use changes in their settings, tentatively suggests that climate and CO_2 are important drivers that can explain the entire observed sink magnitude, or that land-use effects of regionally opposite sign compensate each other on the scale of countries and result in a small net contribution of land-use change. These two hypotheses call for a more in-depth regional analysis, given below.

Figure 2 provides carbon balance estimations on the scale of large regions in China. On this scale, the inversion fluxes are associated with large random errors with regional differences partly controlled by the prior flux setting and the uncertainties in assumed fossil-fuel emissions. The regions with the largest carbon sinks are southwest China (0.048 PgC yr^{-1}, or 43 gC m^{-2} yr^{-1}; Fig. 2i) and southeast China (0.044 PgC yr^{-1}, or 67 gC m^{-2} yr^{-1}; Fig. 2g), which respectively account for 22% and 20% of the total country area. Analysis of the five ecosystem models' output suggests that up to 77% and 71% of the respective sinks in these two regions can be explained by climate change and rising atmospheric CO_2. In northeast China (Fig. 2a), both inventory–satellite-based fluxes (0.003 PgC yr^{-1}) and inversions (0.005 PgC yr^{-1}) show a small source, whereas the five ecosystem models driven by rising CO_2 and climate imply a sink (0.018 PgC yr^{-1}). From these differences, we tentatively deduce that 0.021–0.023 PgC must be lost annually by overharvesting and degradation of forests[13], which is close to a previous estimate of 0.027 PgC yr^{-1} (ref. 12). The inversion method and the inventory–satellite method show large discrepancies over north China (Fig. 1d). In this region, ~60% of the land area is cropland. The larger sink

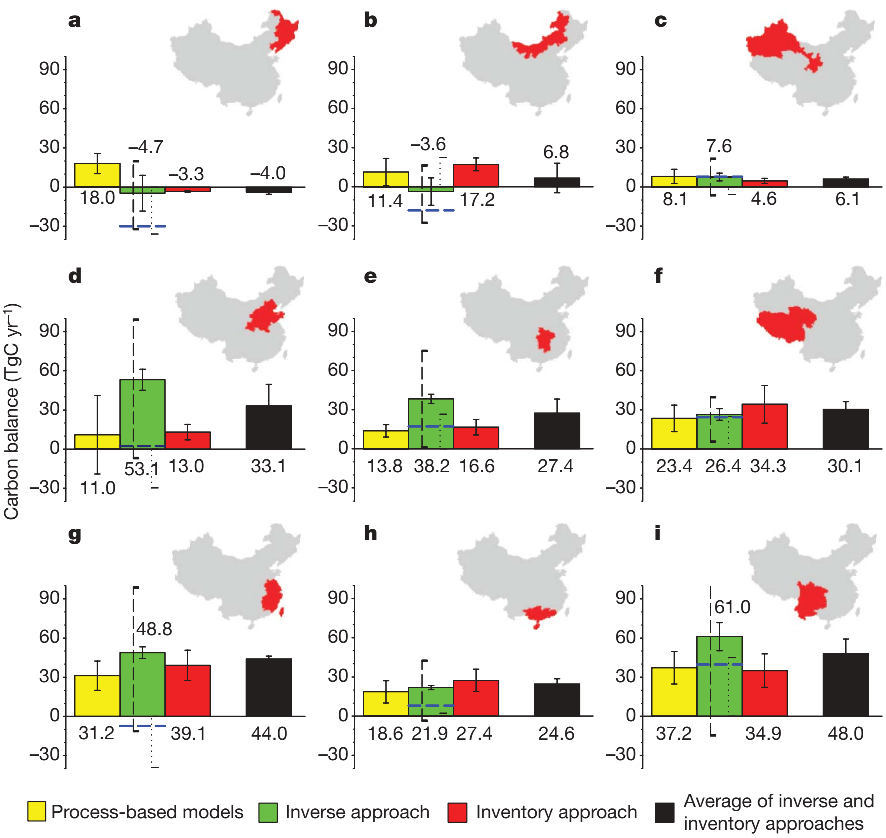

Figure 2 | Carbon balance in the nine regions of China. **a**, Northeast China; **b**, Inner Mongolia; **c**, northwest China; **d**, North China; **e**, central China; **f**, Tibetan plateau; **g**, southeast China; **h**, South China; **i**, southwest China. Estimates from atmospheric inversion modelling have been adjusted by the spatial patterns of carbon losses in non-CO_2 gaseous compounds (CO, CH_4 and VOCs); other parts of lateral carbon fluxes have not been considered, owing to lack of information about their spatial patterns. In addition, owing to lack of information about the magnitude of the regional agriculture soil carbon sink, we simply calculate it as the product of the total agricultural soil carbon sink for China and the fraction of the whole country corresponding to regional area in agriculture. The black solid and dashed lines indicate inversion modelling uncertainty corresponding to the estimated random error in the spread (s.d.) of an ensemble of sensitivity tests and the inversion procedure, respectively. The dotted lines indicate the difference in fossil-fuel emissions between this study and ref. 31, and begin at zero. The blue dashed lines show the prior inverse flux. A positive value indicates a net carbon uptake. On this scale, the inverse estimates also rely on the *a priori* spatial distribution of the carbon fluxes.

deduced by inversion may in fact reflect atmospheric CO_2 fixed by crop plants, the pertaining biomass being harvested and moved away from that region by trade circuits[11].

Several factors can account for the carbon-sink spatial distribution inferred above. First, summer precipitation in China has significantly increased, which may have benefited vegetation growth[24]. Second, large-scale reforestation and afforestation programmes have been active since the 1980s, which makes China the greatest acreage with plantations, constituting about one-quarter of the global plantation area[25]. These plantations resulted in an increase of forest biomass carbon stocks[26]. For example, in the southern regions (Fig. 2e, g, h), afforestation and reforestation programmes are one of the main causes of regional carbon uptake. Because none of the ecosystem models take into account the effects of such land-use changes, the model-simulated carbon sink is consistently 25% less than estimates derived from the inventory–satellite method, and is 42% less than the atmospheric inversion sink.

Third, changes in energy production systems in rural areas and movement of rural population to cities have decreased the collection of fuel wood, accelerating the recovery of shrublands. In the past 30 years, firewood, charcoal, and crop straw that had been used as major energy supplies in most rural areas have been steadily replaced by the use of fossil fuel (mainly coal). This transition, which increased fossil-fuel emissions while decreasing the reliance on biotic fuels[24], may be one cause of the inferred shrubland carbon accumulation, although this sink is the most uncertain component of the entire Chinese carbon balance.

Finally, crop production increased markedly between 1950 and 1999 (ref. 27), which augmented the amount of residue and root input to the soil. Before the 1980s, crop residues were used as a source of fuel in rural areas, but this practice has strongly decreased[28]. Recent trends in agricultural practice throughout China give evidence for a decreasing removal of crop residues and an expansion of reduced and zero tillage, which are likely to cause an increase in carbon sequestration[14,15].

In conclusion, terrestrial ecosystems in China are found to be a net sink of 0.19–0.26 $PgC\,yr^{-1}$ during the 1980s and 1990s (Figs 1 and 3). This sink is less than that of 0.30–0.58 $PgC\,yr^{-1}$ in the conterminous United States[5] but is comparable to that of 0.14–0.21 $PgC\,yr^{-1}$ in geographic Europe[6,20] (Fig. 3). On an area basis, the sink magnitude in China (20–27 $gC\,m^{-2}\,yr^{-1}$) is similar to that in Europe (16–24 $gC\,m^{-2}\,yr^{-1}$) but lower than that in the United States (33–63 $gC\,m^{-2}\,yr^{-1}$) (Fig. 3). Fossil-fuel use in China produced cumulative emissions of 14.1 PgC into the atmosphere between 1980 and 2000 (ref. 29). Our data suggest that ~28–37% of China's CO_2 emissions from burning fossil fuels have been removed by carbon accumulation in its terrestrial biosphere, which is comparable to the United States (20–40%)[30] but larger than in Europe (12%)[6]. Despite net carbon sequestration due to increased afforestation and vegetation restoration, the percentage of fossil-fuel CO_2 emissions offset by terrestrial ecosystems will decrease in the future because of the dramatic acceleration in emissions driven by economic growth. Also, uncertainty in fossil-fuel emission is by far the dominant factor in the uncertainty in the overall Chinese carbon balance. Future trends in emissions and sinks will be of great international concern and a big challenge for China will be to take action to reduce its carbon emissions in the future.

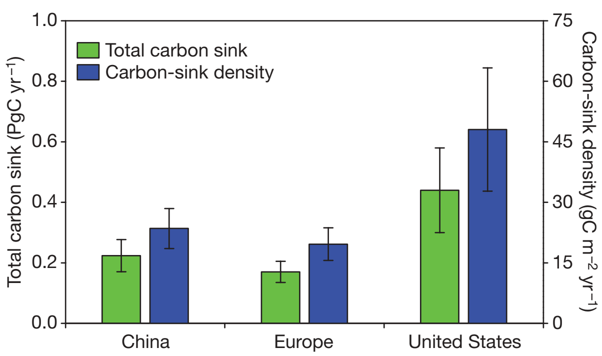

Figure 3 | Terrestrial-biosphere carbon sink and its density in China, compared with those in geographic Europe and the conterminous United States. The carbon sinks of geographic Europe and the conterminous United States are based on refs 6 and 5, respectively. The error bars for China and geographic Europe are based on the mean atmosphere-based estimate (top) and the mean land-based estimate (bottom), and those for the conterminous United States are based on the upper and lower limits of the carbon sink estimated in ref. 5.

METHODS SUMMARY

The inventory–satellite method of estimating carbon-stock changes is based on a large data set of field measurements and extensive forest and soil inventories combined with remote-sensing greenness index trends during the 1980s and the 1990s. Results from the inventory–satellite method are verified by atmospheric inversions that use CO_2 concentration measurements and rough first-guess information about the flux seasonality. Then the outputs of five ecosystem models are analysed to attribute the potential contribution of rising CO_2 concentrations and climate change to the observed regional carbon sources and sinks, including to the carbon storage apportionment between live biomass and soil organic matter pools.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.P., J.F., P.C. and P.P. designed the research; J.F. performed the forest inventory data analysis; S.P. performed the shrub biomass analysis; Y.H. performed the cropland soil carbon storage analysis; S.P. and T.W. performed the soil inventory data analysis; S.P., P.C. and T.W. performed later carbon flux analysis; P.P., P.C. and S.P. performed the inversion modelling analysis; S.P., S.S. and P.C. performed the terrestrial biogeochemical modelling analysis. All authors contributed to the interpretation of the results and the writing of the paper.

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METHODS

Inventory–satellite-based estimation. We used repeated and extensive inventories for forest, and field measurements combined with remote-sensing information for shrubland, to estimate the trends in carbon stocks. For forest, we analysed individual data from the National Forest Resource Inventory, collected from ~200,000 permanent and temporary sample plots from 1977–2003 (refs 26, 32). Specific expansion factors were applied to each forest type to convert tree volume to total biomass (Supplementary Information). For shrubland, we estimated the change in living biomass carbon stocks on the basis of an empirical regression of shrub biomass data from 34 sites against the normalized difference vegetation index (NDVI) data from the NOAA-AVHRR satellites[33,34] (Supplementary Information). Likewise, using data from the national grassland resource survey[35] and crop yield census[36], combined with NDVI data, we estimated changes in the biomass of grasslands and croplands (Supplementary Information).

To quantify changes in soil organic carbon (SOC) over the past two decades, we developed an approach for estimating soil carbon storage of different ecosystems by integrating climate data (temperature and precipitation)[37], NDVI data and ground-based soil inventories data from 2,473 soil profiles collected during 1979–1985 by the national soil carbon survey[38] (Supplementary Information). The underlying assumption is that trends in litter input can be inferred from trends in NDVI, and that changes in decomposition of SOC are driven by temperature and precipitation. To estimate the SOC changes in agricultural soils, we performed a meta-analysis on data from 132 publications encompassing 23 soil groups and >60,000 soil sample measurements (Supplementary Table 5)[14].

Atmospheric inversions. On the basis of observed atmospheric CO_2 gradients and the integrating power of atmospheric transport, inversions provide estimation of the net land–atmosphere CO_2 exchange, including fossil CO_2 fluxes and other land CO_2 fluxes. Until recently, inversions solved for flux at coarse resolution, typically ~10–15 land regions over the globe. At such coarse resolution, the estimate of China's carbon balance is hampered by uncertainty in the assumed first-guess flux error covariance[39]. Recent developments of inversions with fluxes solved at the spatial resolution of the transport-model grid (100–300 km) provide better insights into regional CO_2 fluxes[18,40]. The lack of stations near China (Supplementary Fig. 2) and the difficulties transport models have representing continental stations are two limitations of the performance of this method. Because inversions solve for the net CO_2 flux, the inferred ecosystem CO_2 flux depends on the assumed fossil CO_2 emissions (these errors in emissions translated into errors in ecosystem fluxes shown in Figs 1b and 2). Monthly net CO_2 fluxes were inverted using 75 atmospheric stations and the LMDz global transport model, using the first-guess flux magnitude and error covariance from an ecosystem model, following the methodology described in ref. 18 and Supplementary Information.

Ecosystem modelling estimates. We processed the results of five global ecosystem models[23] to quantify the effect of CO_2 and climate change on the carbon balance of China. These five models are the HyLand (HYL) model[41], the LPJ model[42], the ORCHIDEE model[43], Sheffield–DGVM[44] and TRIFFID[45]. All models describe the surface fluxes of CO_2, water and the dynamics of water and carbon pools in response to climate change and rising atmospheric CO_2 concentration. However, the formulation (and number) of processes primarily responsible for this exchange differ among models (Supplementary Information). In comparison with inventory measurements, ecosystem models have the advantage of calculating soil carbon and biomass changes in a consistent way, by scaling up processes with spatially explicit data on climate, vegetation and soil types. However, we did not include these model results as a way of providing 'best estimates' of the carbon balance because none of the models explicitly considers changes in land use and land management. Instead, we exploited the model results (1) to deliver an independent check of the above-versus below-ground sink partitioning and (2) to isolate the impacts of rising CO_2 concentrations and climate versus land use and management on the regional scale.

Each model was initialized using a pre-industrial mean monthly climatology derived from the CRU data set[46] and an atmospheric CO_2 concentration of 296 p.p.m., until carbon pools reached steady-state equilibrium. They were then run to 2002 with transient climate forcing[46] and historical atmospheric CO_2 concentration data[47]. We note that none of the models were driven by the satellite-derived NDVI data; thus, their results can be considered to be independent of the data-oriented method based on inventory and satellites.

Uncertainty analysis. Uncertainties in the results of the inventory–satellite method (except the crop soil carbon sink) were estimated on the basis of repeated measurements of permanent sample plots or the residual (or fitting) error of regression. For the forest biomass carbon-stock estimation, three major error sources (sampling, measurement and regression errors) were recognized[48–50]. Among these sources, most of the propagated error is due to sampling error in sample plot selection. Similar to the approach of ref. 50, we calculated the national sampling errors in estimating the growing-stock volume change of China's forests during the 1980s and 1990s to be 41.2% and 44.5% (two standard errors, or the approximate 95% confidence interval; for details, see Supplementary Table 2), respectively, which are quite close to the estimate of 39.6% for eastern US forests[50]. In addition, the error caused by converting growing-stock volume into biomass carbon stock was estimated at ~3% at the national level[51]. Therefore, the absolute uncertainties in estimating the forest carbon sink for the two decades are 25.8 $TgC\,yr^{-1}$ (out of 58.4 $TgC\,yr^{-1}$) and 43.7 $TgC\,yr^{-1}$ (out of 92.2 $TgC\,yr^{-1}$), respectively (Table 1).

The uncertainties of the ecosystem models, reflected by their use of different parameterizations of ecosystem processes, are expressed as 1 s.d. of five different model results (Table 1). The uncertainties in the inversion-model-derived means of China's carbon fluxes were based on the estimated random error in the inversion procedure, the spread (s.d.) of an ensemble of sensitivity tests and the systematic error due to assumed fossil-fuel emissions[4,31] (see Figs 1b and 2 and Supplementary Information). The random error describes the degree to which the estimated fluxes are constrained by the atmospheric measurements, and the spread indicates the contribution of different prior assumptions to the range of flux estimates (in this study we do not consider potential biases of the transport model).

The source data and methods are described in detail in the Supplementary Information.

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