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China's carbon sinks from land-use change underestimated

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The size and attribution of the regional net carbon flux from land-use change (LUC) activities (E_{LUC}) are often highly debated, especially in regions such as China, which has experienced decades-long extensive reforestation activities. Here, using a LUC dataset incorporating remote-sensing and national forest inventory data with two modelling approaches, we show that E_{LUC} in China shifted from a carbon source to a sink in the 1990s, contributing to a net cumulative CO_2 removal of 2.0 Pg C during 1981–2020. From 2001 to 2020, the average E_{LUC} was −0.14 Pg C yr^{-1}, accounting for over one-third of the national land carbon sinks. Forest-related LUC activities contributed greatly to national carbon fluxes, while non-forest-related activities played a dominant role in certain areas. Our findings suggest that the carbon sinks from LUC activities in China may be largely underestimated in global assessments, underscoring the need to develop region-specific modelling for evaluation and potential regulation.

Land-use change (LUC)-induced carbon emissions (E_{LUC}, net of carbon emissions and removals due to all anthropogenic activities considered) are responsible for roughly one-third of global anthropogenic carbon emissions since industrialization[1]. Although its contribution has decreased in recent decades, E_{LUC} still accounts for an important share of the global carbon budget, constituting 11% of anthropogenic emissions during 2012–2022[2]. The gross fluxes of LUC (that is, gross sources and sinks) are even larger, suggesting considerable potential for emission reductions[3]. Land-based climate mitigation is crucial for achieving the climate targets set by the Paris Agreement, drawing increasing scientific and political attention in recent years[4,5]. At the UN Framework Convention on Climate Change COP 26 in 2021, 141 countries pledged to halt forest loss and land degradation by 2030[6]. A robust evaluation of the national LUC carbon budget is required to adequately represent the specific land-use management and conservation efforts of each region[7].

Some LUC activities, such as deforestation, emit carbon dioxide (CO_2) into the atmosphere, while others, such as reforestation, absorb CO_2 through the regrowth of secondary vegetation and rebuilding soil carbon stocks. This dual role acts as both an anthropogenic carbon source and sink, and results in LUC-induced carbon fluxes that are spatially intertwined and contribute to the terrestrial carbon sinks[8]. There are no global- or regional-scale observational constraints for distinctly separating E_{LUC} from natural terrestrial carbon sinks[1,8]. Thus, models have been developed for estimating LUC-induced carbon fluxes, such as book-keeping models and dynamic global vegetation models (DGVMs)[9,10]. The lack of a single valid definition and approach for calculating E_{LUC} leads to its inherent uncertainty[1]. The E_{LUC} estimate provided by the global carbon project (GCB2022)[2] is assigned low confidence, with a 68% likelihood that the actual E_{LUC} lay within ±0.7 Pg C yr^{-1} of the estimated value (1.2 Pg C yr^{-1} during 2012–2021)[2]. While studies may agree well at the global level regarding the magnitude of E_{LUC}, regional divergences across models or approaches are often large but masked by ensemble statistics[2,3]. The regional LUC-related carbon budget is highly influenced by local data inputs

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(for example, land transitions) that are hardly represented in global estimates[11,12]. For instance, opposite trends (decreasing versus increasing) or even direction (sinks versus sources) could be observed with different LUC data, in Southeast Asia[11] and the United States[12].

Over the past decades, rapid economic development has led to dramatic land-use changes in China. The extensive clearing of forests and grasslands for industrialization and agriculture has released terrestrial stored carbon into the atmosphere. Meanwhile, since the late 1970s, China has launched decades-long ecological restoration projects to restore degraded ecosystems, achieving the largest reforestation area globally according to the nineth national forest inventory[13]. These projects could sustainably enhance terrestrial carbon stocks and sinks[13]. To mitigate climate change and pursue sustainable development, China has pledged to reach peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060[14]. The government has provided a clear timetable and implementation framework for achieving these 'dual carbon' goals (carbon peaking and carbon neutrality)[15]. Forest sector is explicitly involved in the regulations and pledges made in the climate change mitigation portfolio; for example, reaching a national forest cover of ~25% by 2030[14,15]. Therefore, a detailed E_{LUC} estimation is essential for both scientific understanding of the regional carbon cycle and for the development of land-based emission reduction strategies.

Currently, studies have estimated the land carbon fluxes of China from various perspectives, using different tools and data sources[16–18]. Owing to differences in definitions, components and forcing data used in these assessments, great variations and inconsistent temporal behaviours are expected in results[16–18]. These disagreements suggest that the role of the LUC sector in contributing to regional carbon budgets has not been clearly defined, which limits the potential policy implications regarding land planning and management[4,5]. Recently, great progress has been made in constraining E_{LUC} uncertainties, such as mapping emissions from global models to country-reported emissions data[4] and evaluating model results against biogeophysical observations[19]. Harmonizing multiple sources from modelling, observations and inventories has been considered a well-tested solution[20,21]. Tools such as book-keeping models and DGVMs can estimate spatially explicit LUC-related carbon fluxes, with the book-keeping approach able to further attribute LUC-induced fluxes to specific LUC activities[2,10]. As for LUC data-driven models, the large-scale inventories provide unique bottom-up information that complements satellite-based remote-sensing products, ensuring that spatiotemporal dynamics of land-use activities are captured[16,22,23].

In this study, we estimate spatially explicit LUC-induced carbon fluxes in China during 1981–2020, by using an enhanced LUC dataset (land-use change dataset, LUCD) and two different carbon accounting approaches (book-keeping and DGVMs). The new LUCD reconciles remote-sensing data with the national forest inventory to capture spatiotemporal dynamics of historical LUC activities[22]. The book-keeping model (Land-Use Change Emissions, LUCE), together with a DGVM (the Integrated Biosphere Simulator, IBIS), allows for flexibility of tracking LUC components while capturing transient environmental changes[24]. We further present LUC-associated flux components to gain detailed insights into impacts of LUC activities on the carbon budget in China. Our objectives are: (1) to provide an accurate and detailed estimate of LUC-induced carbon fluxes in China for the period 1981–2020 and (2) to identify the contributions of regional E_{LUC} to total land carbon sinks in China, which help to acknowledge and potentially inform land management and conservation in other similar regions.

E_{LUC} shifting to net sink

Over the past four decades (1981–2020), the E_{LUC} for China changed from a net carbon source to a net sink since the early 1990s (Fig. 1). In the 1980s, consistent across multiple models used, LUC alone contributed to net carbon emissions, range 0.1–0.28 Pg C yr^{-1}. However, the annual E_{LUC} has rapidly declined since and turned negative, indicating

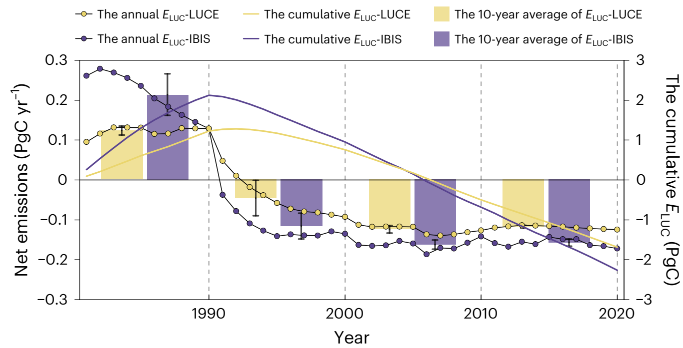

Fig. 1 | The net carbon fluxes from LUC activities in China during 1981–2020. The bars show 10-year averages from LUCE and IBIS, with error bars indicating standard deviation ($n = 10$). The left axis shows the annual E_{LUC}, while the right axis shows the cumulative E_{LUC}.

the creation of a net carbon sink. Since 2000, E_{LUC} remained relatively stable at around −0.142 Pg C yr^{-1} (−0.122 ± 0.008 Pg C yr^{-1} for E_{LUC}-LUCE and −0.161 ± 0.01 Pg C yr^{-1} for E_{LUC}-IBIS) (Fig. 1). By around 2005, the cumulative E_{LUC} also turned negative, indicating that LUC has acted as a net carbon sink of 7.3 Pg CO_2 during 1981–2020 (6.2 Pg CO_2 based on E_{LUC}-LUCE and 8.4 Pg CO_2 based on E_{LUC}-IBIS) (Fig. 1).

Spatially, both models showed similar estimates of annual E_{LUC}, with most areas showing emissions in the 1980s, gradually transitioning to weak sinks starting in the 1990s (Fig. 2a–f). Over the past four decades, more than half the total national areas had LUC-induced carbon sinks (56% in Fig. 2i and 54% in Fig. 2j). Over 40% of the pixels (49% in E_{LUC}-LUCE and 42% in E_{LUC}-IBIS) showed a significant decline in E_{LUC} ($P < 0.05$) over time (Fig. 2k,l), strongly contributing to the shift of the E_{LUC} of China from a carbon source to a carbon sink (Supplementary Fig. 1). About 22% of pixels (21% in E_{LUC}-LUCE and 23% in E_{LUC}-IBIS) exhibited a significant increase in E_{LUC} ($P < 0.05$, Figs. 2k,l), although the associated carbon fluxes were much weaker (Supplementary Fig. 1). The distribution patterns of the 10- and 40-year averages of E_{LUC}, were broadly similar between LUCE and IBIS models (Fig. 2). A considerable number of pixels had weak E_{LUC}, either positive or negative, mainly located in northwest China and the Qinghai-Tibet Plateau, while stronger carbon sinks were mainly observed in eastern and southern China (Fig. 2 and Supplementary Fig. 2). Although the LUCE and IBIS estimates showed broadly comparable magnitudes, trends and spatial distributions, some differences were observed. The annual E_{LUC} estimated by LUCE was relatively lower than that by IBIS, and these differences could be attributed to accounting boundaries, modelling processes and assumptions between the two approaches. For instance, the book-keeping models often exclude the loss of additional sink capacity incorporated in transient DGVMs[1,7,21].

Comparing with other estimates

Previous studies, either global or regional, have reported much higher emissions and lower sinks from LUC activities in China, particularly in the past two to three decades (Fig. 3a). For the 1980s, there was a consensus that LUC was a net carbon source, with cumulative emissions of ~1.7 Pg C from both the GCB2022 (an average of three book-keeping models) and this study (the average of two approaches) (Supplementary Fig. 3). Afterwards, there was a clear inconsistency in the understanding of the role of LUC activities in the carbon budget across studies[2,16–18]. During 2001–2020, estimates from ref. 18 and the BLUE model[2] showed LUC as a carbon source of ~0.08 Pg C yr^{-1}. In contrast, GCB2022 estimated LUC as a small carbon sink (−0.0014 ± 0.016 Pg C yr^{-1}) (ref. 2), as did ref. 17 (−0.073 Pg C yr^{-1}). Our estimate of carbon sinks from LUC activities is even higher, at −0.1414 ± 0.008 Pg C yr^{-1}, with the national greenhouse gas inventory (NGHGI)[4] showing the highest sinks at −0.242 Pg C yr^{-1}. Previous studies suggested that

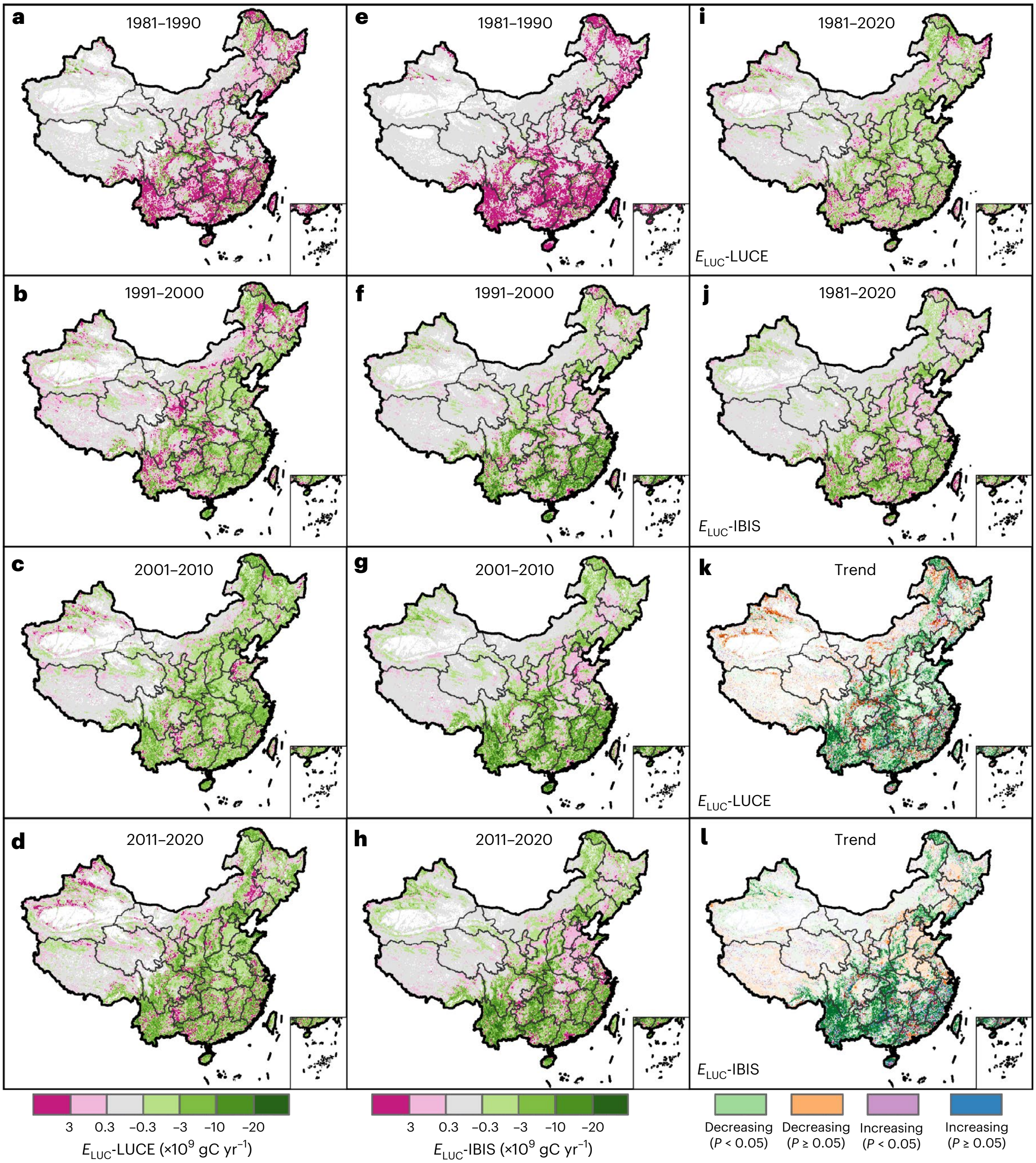

Fig. 2 | The estimated E_{LUC} over time and space. **a**–**h**, The 10-year average of E_{LUC} from LUCE (**a**–**d**) and IBIS (**e**–**h**) for 1981–1990 (**a**,**e**), 1991–2000 (**b**,**f**), 2001–2010 (**c**,**g**) and 2011–2020 (**d**,**h**). **i**,**j**, The 40-year average of E_{LUC} from LUCE (**i**) and IBIS (**j**). **k**,**l**, The interannual trends by LUCE (**k**) and IBIS (**l**).

most discrepancies between the E_{LUC} estimated by NGHGIs and those from book-keeping models and DGVMs are largely due to conceptual differences. The NGHGIs, following IPCC guidelines, used a broader definition of managed lands, resulting in larger areas of managed forest[4]. These comparisons denoted that E_{LUC} estimates that considered forest inventories, including NGHGI[7], refs. 4,16 and this study, consistently suggested that LUC in China has been a net carbon sink in recent decades (Fig. 3a,b), primarily due to decreasing deforestation rates and expanded reforestation efforts over the past half century[16,22]. This revealed the critical nature of LUC transition data in regional E_{LUC} estimates (Fig. 3a,b).

During 1981–2020, the gross reforestation area reached 195 Mha, while the gross deforestation area was 103 Mha, resulting in a net forest increase (92 Mha) mainly in southern China, outside the Sichuan Basin, and to a lesser extent in northern China (Fig. 3c). Notably, over half the reforestation activities (60%) occurred before the twenty-first century, indicating that these new forests were relatively young (20–40 years old). In contrast, deforestation declined significantly during this period, at a rate of 0.07 Mha yr^{-1} (P < 0.05). These forest-related LUC activities suggest that the existing forests of China, particularly the newly established ones, may continue to function as carbon sinks in the near future[25]. However, global LUC data provided by LUH2-GCB2022 suggested that the intensity of forest-related LUC activities was comparatively low, with an overall decrease in forest area (Fig. 3d). LUH2-GCB2022 estimated a gross reforestation area of 30 Mha during 1981–2020, with 70% of this occurring in later years (2001–2020). Meanwhile, gross deforestation reached 60 Mha, with forest loss at a rate of 0.75 Mha yr^{-1}. These forest losses mainly occurred in northeastern, southeastern and Tibetan Plateau regions of China (Fig. 3d). When using the LUH2-GCB2022 dataset to drive the LUCE and IBIS

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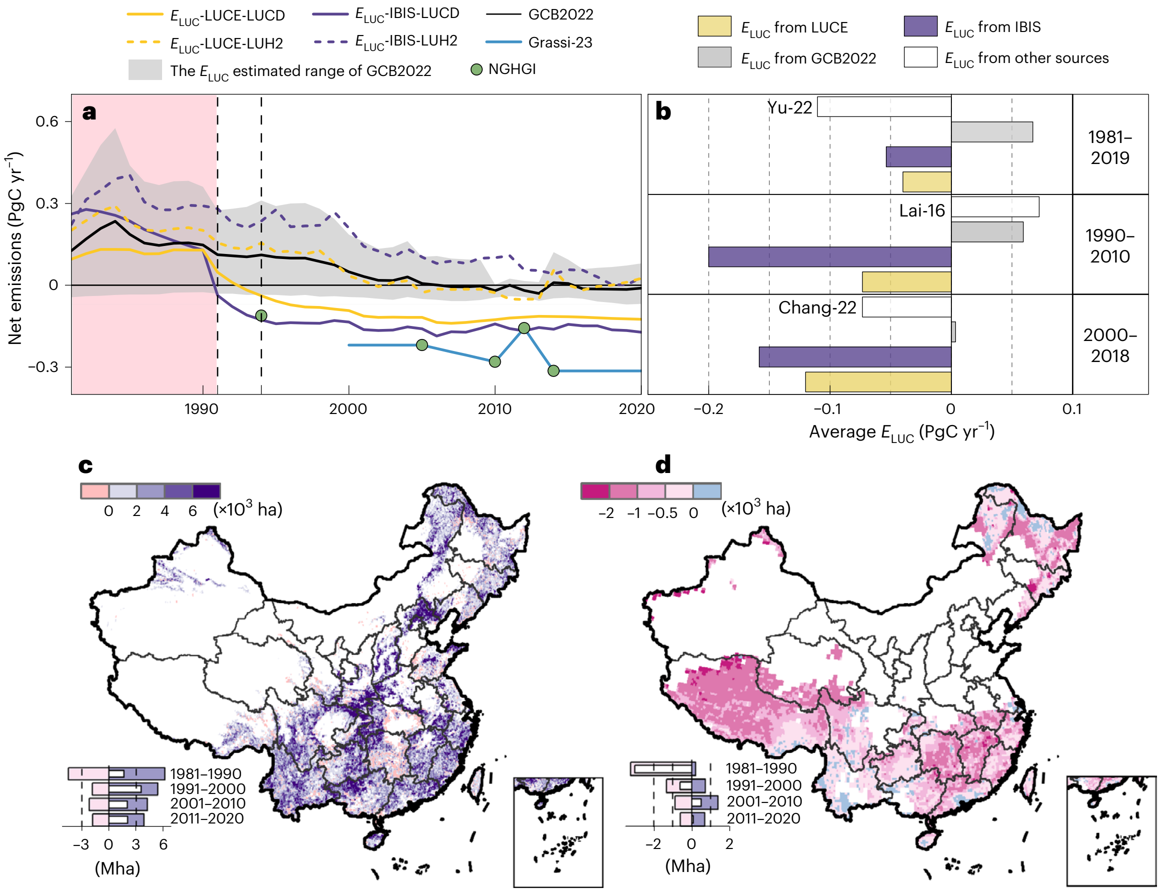

Fig. 3 | The estimates provided in this study and other studies. **a**, The annual E_{LUC}, with a shaded area showing the estimated range of the three book-keeping models (HN2017, BLUE and OSCAR) from GCB2022 (ref. 2). Both Grassi-23 and NGHGI are E_{LUC} estimates derived from ref. 4. **b**, The averaged E_{LUC} over different time periods. Yu-22, Chang-22 and Lai-16 are E_{LUC} estimates derived from refs. 16–18, respectively. **c**,**d**, The spatial distribution of forest changes during 1981–2020 in this study (**c**) and in the LUH2-GCB2022 (**d**). The coloured bars show the area of forest loss (negative) and gain (positive), with white bars showing the net change in **c** and **d**. Note that E_{LUC}-LUCE-LUCD and E_{LUC}-LUCE-LUH2 represent the estimated E_{LUC} by LUCE using LUC data from LUCD and LUH2-GCB2022 (ref. 2), respectively; E_{LUC}-IBIS-LUCD and E_{LUC}-IBIS-LUH2 represent the estimated E_{LUC} by IBIS using LUC data from LUCD and LUH2-GCB2022 (ref. 2), respectively.

models, both E_{LUC} estimates (E_{LUC}-LUCE-LUH2 and E_{LUC}-IBIS-LUH2) failed to show substantial carbon sinks in recent decades (Fig. 3a). The E_{LUC} estimated from LUCE for 2011–2022 was −0.0084 Pg C yr^{-1}, while IBIS estimated 0.043 Pg C yr^{-1}; the size of both results were close to those from GCB2022 (ref. 3). Thus, the poor representation of the LUC history from global datasets and modelling limited the ability to fully evaluate LUC-induced carbon fluxes in regions such as China[24,26].

In addition to changes of land-use types, land management practices of forests, croplands and pastures also affect regional carbon fluxes[7]. Controlling wildfires, pests and diseases could reduce forest carbon loss, but these disturbances are less intense in China and their impacts on overall LUC-induced carbon fluxes are relatively small[25]. As in traditional book-keeping models[2,3,10], harvest, including wood products being harvested and subsequent forest regrowth, is considered a common forest management practice[3]. These wood products can decompose over time and are typically viewed as carbon sources from a carbon budget perspective, while the following forest regrowth gradually restores the ecosystem and acts as a carbon sink[3]. The sum of these two carbon fluxes makes up the net carbon flux resulting from harvest activities, representing the balance between the carbon released from wood products and the carbon sequestered during regrowth[3]. The net carbon flux from harvest activities in China during 1981–2020, as estimated by the LUCE model, was 28 ± 14.7 TgC yr^{-1} (Supplementary Fig. 4a). With this update, the estimated E_{LUC} with LUCE still indicated that LUC transitioned from a carbon source to a carbon sink in the 1990s, with the sink size stabilizing at around −0.1 ± 0.018 Pg C yr^{-1} in the twenty-first century (Supplementary Fig. 4b). This still showed a much greater sink than that from GCB2022 with a nearly neutral impact (−0.0014 ± 0.016 Pg C yr^{-1}). Overall, harvest activities, as one component of carbon flux, had a limited impact on the scale of E_{LUC} change in China. Note that we did not explicitly simulate carbon fluxes resulting from cropland management practices, such as tillage and fertilization, but their effects on carbon exchanges were implicitly included in the LUCE parameterization framework[3]. Grazing had a dual impact for pasture carbon storage, and its role depended heavily on the intensity of the carbon removed[27]. Given large uncertainties, grazing-related factors were not currently considered in this study. Nevertheless, in some parts of Northwest China, non-forest LUC activities substantially influenced carbon fluxes (Fig. 4c,d). Therefore, an explicit assessment of grazing-related carbon fluxes could provide valuable insights for pasture management in the context of climate change[27].

Contributions by LUC activity

Among LUC activities, forest-associated categories, including deforestation and reforestation, dominated national LUC carbon fluxes, while non-forest-related LUC contributed to regional carbon fluxes (Fig. 4a and Supplementary Fig. 5). During 2001–2020, 71% of gross sources and 78% of gross sinks were attributed to deforestation and reforestation, respectively (0.135 ± 0.007 and −0.246 ± 0.003 Pg C yr^{-1}). Forest-dominated pixels, those with forest-related activities contributing >50% to gross fluxes, were widely distributed across eastern China, the Northeast Plain and the North China Plain that are mostly occupied

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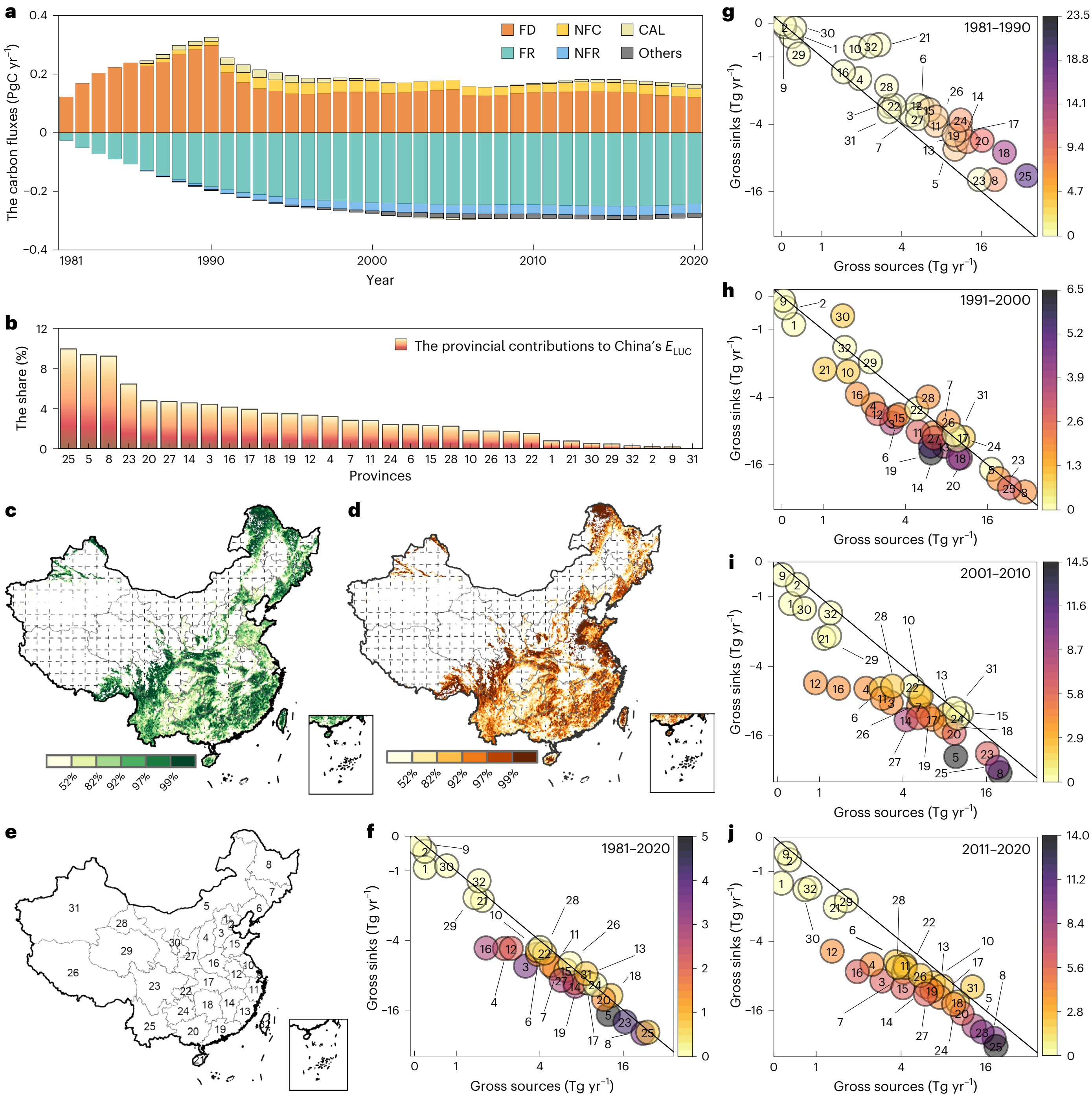

Fig. 4 | The components of gross carbon fluxes and provincial contributions. **a**, Carbon fluxes from different LUC activities. LUC included six categories: deforestation (FD), non-forest conversion (NFC), reforestation (FR), non-forest reconstruction (NFR), conversions between anthropogenic land (CAL) and others. **b**, The provincial contributions to China's E_{LUC} during 2001–2020. **c**, The contributions of deforestation to gross carbon sources, with dashed lines showing regional fluxes dominated by non-forest-related LUC activities. **d**, The contributions of reforestation to gross carbon sinks, with dashed lines showing regional fluxes dominated by non-forest-related LUC activities. **e**, The spatial distribution and code of provinces in China (also see codes in Fig. 5c). **f**–**j**, The gross carbon sources, sinks and net emissions over the 40-year period (**f**) and over the 10-year periods (**g**–**j**), for 1981–1990 (**g**), 1991–2000 (**h**), 2001–2010 (**i**) and 2011–2020 (**j**). The colour of circles indicates the relative size of the provincial net carbon flux, with circles to the right of the dark line representing carbon sinks and circles on the other side representing carbon sources. The values within the correspond to province codes. The gross sources, sinks and net emissions in this figure are estimated with LUCE.

by agricultural lands. Additionally, some of these forest-dominated pixels were also found in parts of the Tianshan Mountains region in northwestern China, where annual precipitation typically exceeded 400 mm (Fig. 4c,d)[26]. Non-forest-related LUC contributed substantial carbon fluxes in certain areas (Supplementary Fig. 5), including several provinces in northwestern China (for example, Xinjiang and Qinghai) where forest cover has been rather limited (Supplementary Fig. 5).

Provinces with larger gross fluxes also had larger net fluxes from LUC activities, in terms of either 10- or 40-year average (Fig. 4). Yunnan, Heilongjiang, Inner Mongolia and Sichuan (coded 25, 8, 5 and 23,

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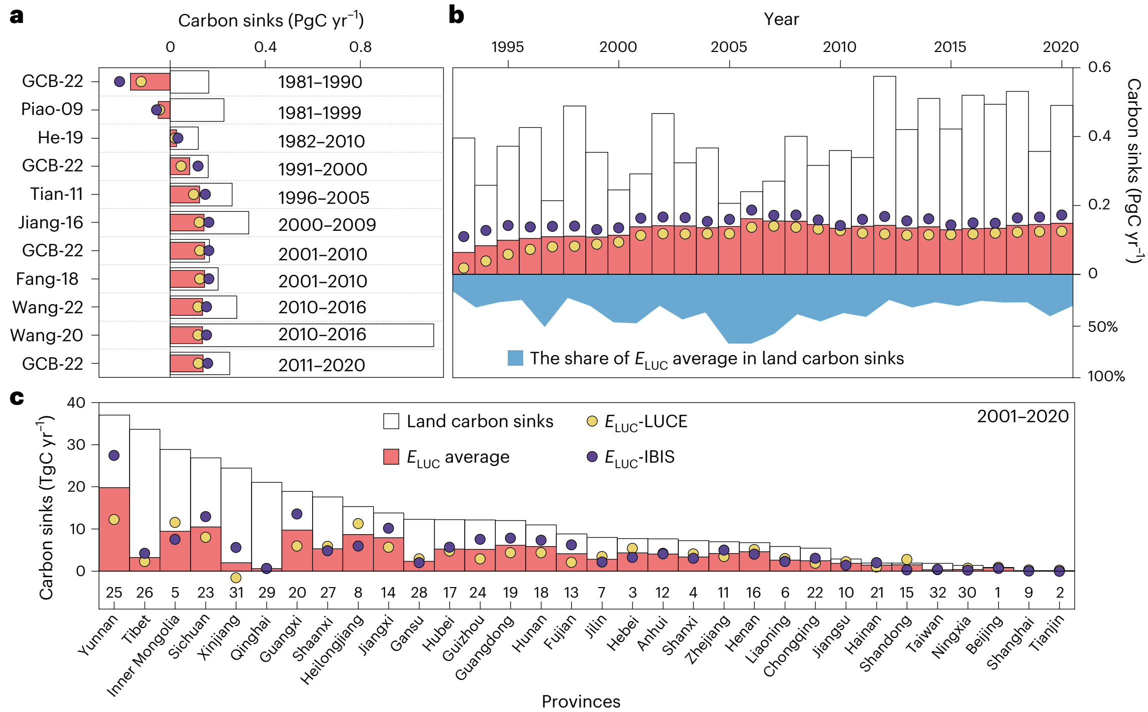

Fig. 5 | The contributions of the E_{LUC} to total land carbon sinks in China. a, The E_{LUC} shares in land carbon sinks reported in different studies. **b**, The annual E_{LUC} and the E_{LUC} average shares in land carbon sinks. **c**, The E_{LUC} shares in provincial land carbon sinks (2001–2020). The blank bars in **a** show estimates of land carbon sinks from different reports, with GCB-22, Piao-09, He-19, Tian-11, Jiang-16, Fang-18, Wang-22 and Wang-20 referring to refs. 2,28–34, respectively. The blank bars in **b** and **c** show land carbon sinks estimated by IBIS[24]. The values on the horizontal axis in **c** represent the province codes that correspond to Fig. 4e.

respectively) consistently exhibited large gross and net fluxes throughout the study period, contributing greatly to national LUC-induced fluxes (Fig. 4f). Over the past two decades (2001–2020), about 35% of gross and net fluxes were attributed to these four provinces. Specifically, Yunan had the highest E_{LUC} contribution (10%), followed by Heilongjiang (9%), Inner Mongolia (9%) and Sichuan 6% (Fig. 4b). It should be noted that >70% of gross fluxes in the three provinces (Yunnan, Sichuan and Heilongjiang) came from forest-related LUC activities, while non-forest-related LUC activities accounted for 58% of gross sources and 33% of gross sinks in Inner Mongolia (Supplementary Fig. 5). In contrast, the northwestern provinces of Xinjiang, Qinghai and Tibet (coded 31, 29 and 26, respectively) accounted for only 8% of gross sources and 6% of gross sinks. Overall, non-forest-related LUC dominated gross fluxes only in a few provinces (for example, Qinghai and Ningxia) (Supplementary Fig. 5). These findings suggested that efforts to mitigate LUC emissions should prioritize provinces/regions with higher gross/net fluxes, such as southwest and northeast China. In areas contributing low emissions, the best opportunities for mitigation are enhancing land-based carbon sinks.

Discussion

Since the 1990s, E_{LUC} in China has functioned as a carbon sink, contributing substantially to the overall land carbon sinks of China (Fig. 5). However, in the early 1980s to 1990s, LUC was a net source of emissions offsetting a large portion of land sinks, as also evidenced by other studies[28–30]. Hence, the contributions of the national E_{LUC} to the net land sinks were smaller when considering the 1980s (Fig. 5a). On the contrary, the national E_{LUC} excluding the 1980s contributed to >40% of total land sinks, except for the extremely large carbon sinks in very few studies[31–34]. Focusing on land sinks during 2001–2020, as estimated using the IBIS model, the land carbon sinks of China ranged from 0.21 to 0.57 Pg C yr^{-1}, with an average of 0.4 Pg C yr^{-1} (Fig. 5b). Nationally, the contribution of E_{LUC} to land carbon sinks was 38% during 2001–2020 (33% and 44% for the E_{LUC}-LUCE and the E_{LUC}-IBIS, respectively), peaking at 67% around 2005 (Fig. 5b). At the provincial level, the top two provinces with the largest land carbon sinks (>30 TgC yr^{-1}), Yunnan and Tibet, showed completely different E_{LUC} shares, with >50% in Yunnan and only 10% in Tibet (Fig. 5c). This suggested that the land carbon sink of Yunnan was mostly from newly established ecosystems, while that of Tibet was from existing ecosystems.

The changing role of LUC activities in land carbon sinks can be attributed to a series of ecological projects implemented by the Chinese government since the late 1970s[13]. Although it is difficult to identify and associate specific LUC activities for each projects, their impacts on carbon fluxes are implicitly included in our E_{LUC} estimates, using a reconstructed LUC dataset that integrates national forest inventory data. Southwest China (including Yunnan, Guizhou, Guangxi, Sichuan and Chongqing, coded as 25, 24, 20, 23 and 22, respectively) is a large contributor to national E_{LUC}. Following the implementation of various ecological projects (for example, the Natural Forest Protection Project and The Grain for Green Program)[13], the deforestation rate in this region during 2011–2020 was halved compared to the 1980s, dropping from 1.4 to 0.7 Mha yr^{-1}. Consequently, associated carbon emissions have been reduced by 45% from 81 to 45 TgC yr^{-1}. At the same time, the region has been afforested at a rate of 1.6 Mha yr^{-1}, resulting in a net increase in forest area of 30 Mha. These growing forests continuously absorb CO_2 from the atmosphere, doubling the associated carbon sinks from −36 to −82 TgC yr^{-1}. While many ecological projects are initially designed to prevent and combat land degradation[35], the nature-based actions resulted in carbon gains from LUC activities, thereby contributing to terrestrial carbon sinks[16,36]. For example, in the northern and central provinces, including Hebei, Shanxi and Shaanxi, increased forest areas (Fig. 3c) coincided with known ecological restoration projects, for example, the Beijing-Tianjin Sand Source Control Project and Three-North Shelter Forest Program[37].

As climate policies progress from pledges to implementation, increasing interest is in tracking progress at the country level[4]. One sector of particular importance is LUC, accounting for 25% of the emission reductions pledged by countries in their nationally determined contributions[4,38]. While NGHGIs are often used for global inventory reporting, integrating LUC inventory data with updated modelling approaches (for example, Global Carbon Project (GCP)) could help to harmonize flux estimates with national flux inventories, offering more consistent and potentially more actionable information for policy-makers[3]. Additionally, region-specific modelling, with both data inputs and models specifically parameterized and benchmarked with regionally specific data, is necessary for evaluation of the role of LUC in meeting national and regional climate targets (for example, Nationally Determined Contributions) and sustainable development goals. Robust flux estimations can better inform policy-makings and regulations and assist in planning and managing climate region-specific LUC activities. It will also promote land-use activities that contribute to climate mitigation and the protection and enhancement of the natural capital of the nation[14,20].

There are a few intertwined issues with E_{LUC} estimations, including the low quality of LUC maps, the underperformance of most models for management processes, the inconsistent boundary definitions across methods, and uncertainties of vegetation and soil carbon stocks[2]. It is important to emphasize that, while LUC-induced carbon fluxes are occurring, there is so far no general agreement on a single valid approach to assess the LUC-induced carbon fluxes[1]. The methodological choices and assumptions required to attribute these fluxes to LUC activities depend on the research goals and data availability. Cross-model intercomparisons are helpful for understanding the strengths and limitations of different approaches and improving overall LUC emission estimates. Reconciling several data sources will reveal a more robust picture of LUC-induced fluxes by incorporating models, observations and inventory data[3,4]. Although LUC data in this study may better represent historical land transition trajectories, they might still lack the ability to directly distinguish between anthropogenic and natural processes, adding uncertainties to estimates of anthropogenic carbon fluxes. Additionally, some important flux components from anthropogenic LUC activities are still missing, such as those related to pasture grazing, agricultural land management and wetland drainage. Given the growing importance of E_{LUC} for climate mitigation strategies, further efforts should be dedicated to improving regional E_{LUC} estimations.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-025-02296-z.

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Methods

Land-use change dataset

Accurate, well-defined and spatially explicit LUC data are a prerequisite for E_{LUC} estimation. In this study, we first reconstructed a forest cover dataset (0.01°) by integrating both national forest inventory and multiple remote-sensing datasets[22]. This dataset could capture the dynamic changes of forest cover in China since 1980. Second, fully classified annual China land cover data[39] were used to determine other land-use types in non-forest areas, which ensured that our full dataset could capture the trajectories of all LUCs. Finally, the assimilated dataset was aggregated to 0.1° for model simulations and LUC information was derived from gross transition data. Specifically, this dataset (LUCD) offered annual, gridded land-use and LUC information in China at a 0.1° spatial resolution spanning the years 1980–2021. The LUCD contained five land-use categories (forests, shrubs, croplands, pastures and bare land) and ten subcategories, including four forest types (evergreen coniferous forests, evergreen broadleaf forests, deciduous coniferous forests and deciduous broadleaf forests), two crop types within the cropland category (C3 and C4) and two pasture types within the pasture category (C3 and C4) and provided all associated land-use transitions between those categories (Supplementary Table 1). The LUCD provides spatially explicit LUC information over the past four decades, capturing the historical changes of forest coverage in China as recorded in the inventory, for example, forest cover has increased considerably from 12% in 1980 to the current 24% (refs. 22,24).

Dynamic global vegetation model

DGVMs are frequently used to estimate carbon fluxes from LUC activities in model ensembles to attain more robust results[2]. This study used IBIS to delve into the effects of LUC activities on terrestrial carbon sinks. The model, initially designed to simulate biophysical and physiological processes across diverse terrestrial ecosystems[40], has been greatly improved by incorporating several new processes[41,42]. These enhancements have enabled its successful application in estimating land carbon sink and LUC-induced carbon fluxes in China[24]. The IBIS model also features among the models used in the GCP for the annual estimation of the global terrestrial carbon budget[2]. Following the convention in global carbon budget, in this study, the E_{LUC} was quantified as the difference of net biome production (NBP) between two paired simulations, with LUC (scenario S3) and without LUC (scenario S2) included (that is, $E_{LUC} = NBP_{S3} - NBP_{S2}$). Both simulations were driven by transient CO_2 concentration and climate data over 1980–2021.

The IBIS has been validated specifically for using in China in earlier studies, with good performance for simulating vegetation biomass and carbon fluxes (that is, vegetation gross primary production, ecosystem respiration and net ecosystem production)[43,44]. In this study, the IBIS was further localized, in terms of both data forcing and model parameterization[24], to better represent regional conditions in China. We adopted locally interpolated climate data from meteorological stations and measurement-based soil properties datasets as driving data[45]. The IBIS version used here was further optimized with parameterization[46,47]. Validation against two observation-based datasets in China revealed that the vegetation biomass estimates showed overall good performance ($R^2 = 0.77$; Supplementary Fig. 6a)[46]. The national soil carbon density estimated by IBIS was comparable with observation (10.26 versus 7.19 kgC m^{-2})[47], but less so at the grid cell scale ($R^2 = 0.12$; Supplementary Fig. 6b). The underperformance of soil carbon has long been regarded as one of the common issues for DGVMs to be further improved[3,24].

Book-keeping modelling

Since ref. 10 quantified carbon fluxes from LUC activities with a book-keeping approach, several book-keeping models have been built and are widely used to estimate the global and regional E_{LUC} (refs. 3,10). Book-keeping models are forced with land-use transitions and built upon carbon densities, along with temporal response curves for different ecosystems following a land-use transition. In this study, we used a recently developed book-keeping model, Land-Use Change Emissions (LUCE), to estimate carbon fluxes from LUC activities in China, including gross sources, gross sinks and net fluxes[3]. The LUCE model is one of the four book-keeping models adopted in recent GCP for estimating annual E_{LUC} globally[48]. It uses the book-keeping approach for global and regional applications, aiming to document the distribution of LUC-induced emissions and removals over time. The model focuses on subgrid gross land-use transitions and the associated carbon fluxes by explicitly considering grid carbon density changes (particularly vegetation). The model has the capability to estimate temporal carbon emissions (gross and net) at the grid level, enabling the identification of contributions over time and space, for example, emissions hotspots, dominant years or dominant LUC activities[3].

As a parametric model of carbon tracking, both LUC data and carbon data are key inputs to force the LUCE model. The former identifies the locations and intensities of LUC activities, while the latter describes the amount of carbon stored in different LUC events. Together, they determine the magnitude of LUC-induced carbon exchanges[3]. In this study, we adopted gross transition from LUCD to force LUCE model for better simulating the carbon dynamics resulting from LUC activities. Following the framework of the LUCE model, we categorized different LUC transition data into corresponding simulation processes (for example, clearing and abandonment). Traditional book-keeping models were built upon fixed carbon densities, regardless of environmental effects, which has been argued to contribute to differences in estimates across model approaches[3,19,21]. In this study, we proposed an approach to overcome the current issue in LUC carbon budgets, by capturing transient environmental conditions (for example, CO_2 and climate) using the natural vegetation carbon density outputs from the IBIS model under corresponding LUC scenarios as LUCE inputs. This approach can provide consistent estimates between book-keeping models and DGVMs[7,21]. Biomass carbon densities for anthropogenic land types still followed previous practices, with 5 or 3 tC ha^{-1} for crop and 10 tC ha^{-1} for pasture[3]. Given the poor spatiotemporal representation of the DGVMs (including IBIS), soil carbon densities were derived from the default settings of the LUCE[3]. In general, the forest had the highest soil carbon density, followed by shrubs and pastures, with the croplands having the lowest soil carbon density. Note that we did not specifically account for carbon fluxes from land transition between pastures and shrubs, considering their similar carbon stocks[3].

The analyses and comparisons of different simulations

This study presented historical LUC-induced carbon fluxes over the past four decades (1981–2020), including gross sources (from LUCE), gross sinks (from LUCE) and the net fluxes (from both LUCE and IBIS). The spatially explicit results were aggregated to estimate LUC fluxes at both national and provincial levels (with both LUCE and IBIS) and reanalysed to identify emission hotspots and contributions by LUC activities (with LUCE only). To separate flux components corresponding to different processes, LUC activities associated with carbon fluxes were analysed by six categories in the LUCE results (Supplementary Table 2): deforestation, including conversion types of forests to shrubs, anthropogenic lands (cropland and pasture) and bare land; non-forest conversion, including conversion types of shrubs to cropland and bare land; reforestation, including conversion types of shrubs, anthropogenic lands (cropland and pasture) and bare land to forests; non-forest reconstruction, including conversion types of cropland and bare land to shrubs; conversions between anthropogenic land, including conversion types between cropland and pasture; others refers to land-use transitions between the anthropogenic land (crop and pasture) and bare land.

To highlight impacts of the LUC data, we also derived LUC information from another dataset, the LUH2 dataset. This dataset is widely regarded as the primary source of long-term LUC data, and often adopted by global studies concerning climate, carbon and biodiversity[49]. In this study, the LUH2 dataset used in the GCP (LUH2-GCB2022) was adopted to reconstruct historical land-use activities, and this dataset offered global, annual, gridded LUC information at a quarter-degree spatial resolution spanning the years 850–2022[3]. The dataset provided transition information between five land-use types, and contained reconstruction data including wood harvest and shifting cultivation, covering all land-use activities with or without LUC. Following the same protocol, we drove the IBIS model and LUCE model with the gross transition data from the LUH2-GCB2022. In particular, we estimated carbon fluxes from harvest activities based on the LUCE model, to illustrate its effect on the E_{LUC} of China. In addition, all trends of time series in the context were detected by the Mann–Kendall trend test[3], while the magnitude of the trend was calculated by the Sen's slope[3]. The main findings regarding temporal and spatial carbon fluxes are also accessible on an online repository[50].

Data availability

The primary results presented in the study are available via Figshare at https://doi.org/10.6084/m9.figshare.28252124 (ref. 50). The original LUCD dataset created by ref. 22 is available at https://doi.org/10.12199/nesdc.ecodb.rs.2023.015. The IBIS land carbon sinks estimated by ref. 24 are available at https://doi.org/10.1016/j.scib.2023.11.016. The LUH2-GCB2022 data and carbon fluxes estimates from H&N2017, BLUE and OSCAR are derived from GCB2022 (ref. 2). The archive of GCB can be accessed through https://globalcarbonbudget.org/. The multiyear provincial administrative boundary data for China come from the Resources and Environmental Science Data Registration and Publishing System[51]. Any other data requests can be addressed to the corresponding author Z.Q.

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Author contributions

Conceptualization: Z.Q., W.Y. and S.P. Methodology: Z.Q., W.Y., J.G.C. and S.P. Resources: Z.Q., W.Y., U.M. and X.W. Data curation: Y.Z., X.X. and X.L. Formal analysis: Y.Z., X.X. and Z.Q. Visualization: Y.Z. and Z.Q. Supervision: Z.Q. and W.Y. Project administration: Z.Q. Writing—original draft: Y.Z. and Z.Q. Writing—review and editing: all authors.

Competing interests

The authors declare no competing interests.

Additional information

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