



Original Research

Global patterns and changes of carbon emissions from land use during 1992–2015



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ABSTRACT

Carbon emissions from land use (E_{LUC}) are an important part of anthropogenic CO_2 emissions, but its size and location remain uncertain, and our knowledge of the relationship between E_{LUC} and GDP remains partial. We showed that the carbon emissions directly caused by land use change (direct E_{LUC}) during 1992–2015 was 26.54 Pg C (1.15 Pg C yr⁻¹), with a decreased trend and a net reduction rate of -0.15 Pg C yr⁻¹. The areas that exhibited reductions were concentrated in South America, Central Africa, and Southeast Asia, and those with increments were scattered in Northwestern North America, Eastern South America, Central Africa, East Asia, and parts of Southeast Asia. For the indirect carbon emissions from the utilization of built-up land (indirect E_{LUC}), it manifested an upward trend with a total emission of 27.51 Pg C (1.2 Pg C yr⁻¹). The total value resulted by global E_{LUC} was $\$136.3 \times 10^9$ US, and the value of annual was equivalent to 3.7 times the GDP of the Central African Republic in 2015 ($\$5.93 \times 10^9$ US yr⁻¹). Among the 79 countries and regions considered in this study, 54 represented the upward GDP with increased emissions, and only 25 experienced GDP growth with emission reductions. These findings highlight the pivotal role of land use change in the carbon cycle and the significance of coordinated development between GDP and carbon emissions.

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1. Introduction

With the increased global warming, climate change mitigation has evolved from a future need to an urgent reality [40]. Since the increase of anthropogenic CO_2 emissions are one of the critical factors of global warming, continuous attention has been devoted to the issue of carbon neutrality [5,18,23]. Land use change is a crucial factor affecting the distribution of carbon emissions [12,10], and according to the study of Intergovernmental Panel on Climate Change (IPCC), about 11 % of CO_2 emissions in 2010 were triggered by land use change, second only to the burning of fossil fuels [22].

However, the complexity of land use leads to uncertainty about the magnitude and change pattern of carbon emissions from land use (E_{LUC}) [28,27]. Clarifying the patterns and changes of E_{LUC} is not only necessary to achieve carbon neutrality, but also important for an accurate understanding of the carbon cycle.

Several scholars have successfully examined E_{LUC} by using different spatial scales, but they were concentrated on provincial [41,9], state [11,45,19], and regional scales [1,15,46,10]. Few studies have been conducted on the global scale. In addition, extensive research has focused on a single ecosystem or a single type of land use [14,4,31]. The transformation and interactions between different systems or land use types have rarely been investigated. Current techniques of E_{LUC} estimation include the Bookkeeping (BK) model [14,13,6,2,26,4], Denitrification-Decomposition model [29,42,24], sample plotting [42,44] and the IPCC's recommended method [20]. Among these them, the method proposed by the IPCC takes into account both the direct carbon emissions caused by land

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use changes and the indirect carbon emissions stemming from energy consumption during land use and planning. Moreover, compared with other methods, the calculation process of this method is simpler and the sample requirements are less. Many researchers have obtained satisfactory results based on this method [38,25,48].

This study uses the method recommended by the IPCC to estimate the global E_{LUC} at different stages on the basis of land use and land cover change (LUCC) data from 1992 to 2015 and analyze its changes at different spatial-temporal scales. The relationship between indirect E_{LUC} and GDP in different countries is evaluated and the value loss caused by E_{LUC} is calculated. The aim is to provide theoretical and scientific bases for the further understanding of the global terrestrial carbon cycle and working towards solving the challenge of global warming.

2. Materials and methods

2.1. Data source

The LUCC data at 300 m spatial resolution were downloaded from the European Space Agency (<http://maps.elie.ucl.ac.be/geoportail/>) at the time span from 1992 to 2015. The reliability of this data has been confirmed in previous studies [30,32]. Soil profile data at 1 km spatial resolution were downloaded from the Harmonized World Soil Database (HWSD) (<http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>). A global biomass carbon map at 1 km spatial resolution was downloaded from the Carbon Dioxide Information Analysis Center (<https://cdiac.ess-dive.lbl.gov/>). Energy consumption data were obtained from the BP Statistical Yearbook of World Energy (<https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html>) and GDP data were acquired from the World Bank (<https://www.worldbank.org/>).

2.2. Methods

The research ideas and main steps of this paper are as following: first, the dynamic changes in the LUCC were obtained through spatial analysis. Second, the overlay analysis biomass carbon map and LUCC data to obtain biomass carbon density data of different land use types were acquired, and then used to get the change in vegetation storage. Third, based on the soil profile data and LUCC data, the organic carbon density of different soil types on different land use types was obtained and then the change of soil organic carbon storage (SOC) was calculated. Fourth, the change and distribution pattern of direct E_{LUC} were obtained based on the previous two steps. Fifth, the change of indirect E_{LUC} was obtained based on energy consumption data and the relationship between indirect E_{LUC} and GDP was discussed through statistical analysis (Fig. 1).

2.2.1. Analysis of land use and land cover change

Land use in 1992–2015 was analyzed by two-two overlays using the ArcGIS platform with five years as the time node (except for 1992–1995). The five study periods were divided into 1992–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015. The spatial change map of the land available for the five study periods was obtained. Next remote sensing images for 1992 and 2015 were analyzed by overlay, and a spatial change map of the land available for the entire study period was acquired. Table S1 shows the specific classification of the LUCC.

2.2.2. Calculation of carbon emissions induced by LUCC

Existing studies have suggested that changes in the vegetation

biomass and soil organic carbon storage are the main sources of E_{LUC} [48]. Therefore, E_{LUC} can be considered equal to the sum of the vegetation biomass and soil organic carbon (SOC) storage changes. The specific calculation formula according to IPCC [20] is as follows:

$$\Delta C = \Delta C_{BIO} + \Delta SOC_{30}, \quad (1)$$

where, ΔC is all of the carbon storage change caused by LUCC, ΔC_{BIO} is the vegetation biomass carbon storage change, and ΔSOC_{30} is the SOC storage change in the topsoil (0–30 cm). (1) Calculation of vegetation biomass carbon storage change.

The Global Biomass Carbon Map was plotted using GLC2000 (EU Science Hub). Therefore, this study used the subdivision type of the LUCC layer of 2000 and the map to perform an overlay analysis. The vegetation carbon densities of 37 land use types were extracted and their average values were used as the basis bio-carbon density data (Fig. S1). The vegetation biomass carbon storage change was also calculated according to the method recommended by the IPCC [20]. The calculation is as follows:

$$\Delta C_{BIO} = \sum_i [(D_{AFTERi} - D_{BEFOREi}) \times \Delta AREA_i], \quad (2)$$

where, ΔC_{BIO} is the vegetation carbon storage change during LUCC, D_{AFTERi} is the biomass carbon density on land use type i after the conversion, $D_{BEFOREi}$ is the biomass carbon density on land use type i before the conversion, $\Delta AREA_i$ is the conversion area, and i is the land use and land cover converted from one type to another.

(2) Calculation of SOC storage change

On the basis of soil profile data obtained from the World Soil Database HWSD 1.21 and previous studies, the organic carbon densities of 36 soil types (Table S2) were calculated [8,36,37,39,47]; Potma [Gonçalves_et_al_2018,47]. The average carbon density of each soil type was used as the basis for the calculation (Fig. S2). According to the IPCC's primary method [20], the calculation for the change in soil organic carbon storage is as follows:

$$\Delta SOC_{30} = \sum_{i,S} (SOC_{D_{is}} \times F_{IMPACTi} \times \Delta AREA_{is}), \quad (3)$$

where, ΔSOC_{30} is the change in SOC storage, $SOC_{D_{is}}$ is the SOC density of land type i with soil types, $F_{IMPACTi}$ is the impact factors of SOC change during LUCC [34], and $\Delta AREA_{is}$ is the transformed area of land use type i with soil types.

2.2.3. Calculation of indirect carbon emissions from LUCC caused by energy consumption

In order to develop the economy, the utilization and planning of land, especially built-up land, will indirectly generate carbon emissions. These emissions can be estimated by the carbon emission coefficient of energy consumption [43,45]. Therefore, this study uses the indirect E_{LUC} method to calculate carbon emissions [20]. The specific formula is as follows:

$$E = \sum_{i=1}^n E_i \times M_i \times \varepsilon_i, \quad (4)$$

where, E is the total amount of carbon emissions caused by energy consumption; E_i is the consumption of i energy; M_i is the energy conversion coefficient of i energy to standard coal; and ε_i is the carbon emission coefficient of i energy, in which coal accounts for 0.7559 tC/t, petroleum accounts for 0.5857 tC/t, and natural gas accounts for 0.4483 tC/t.

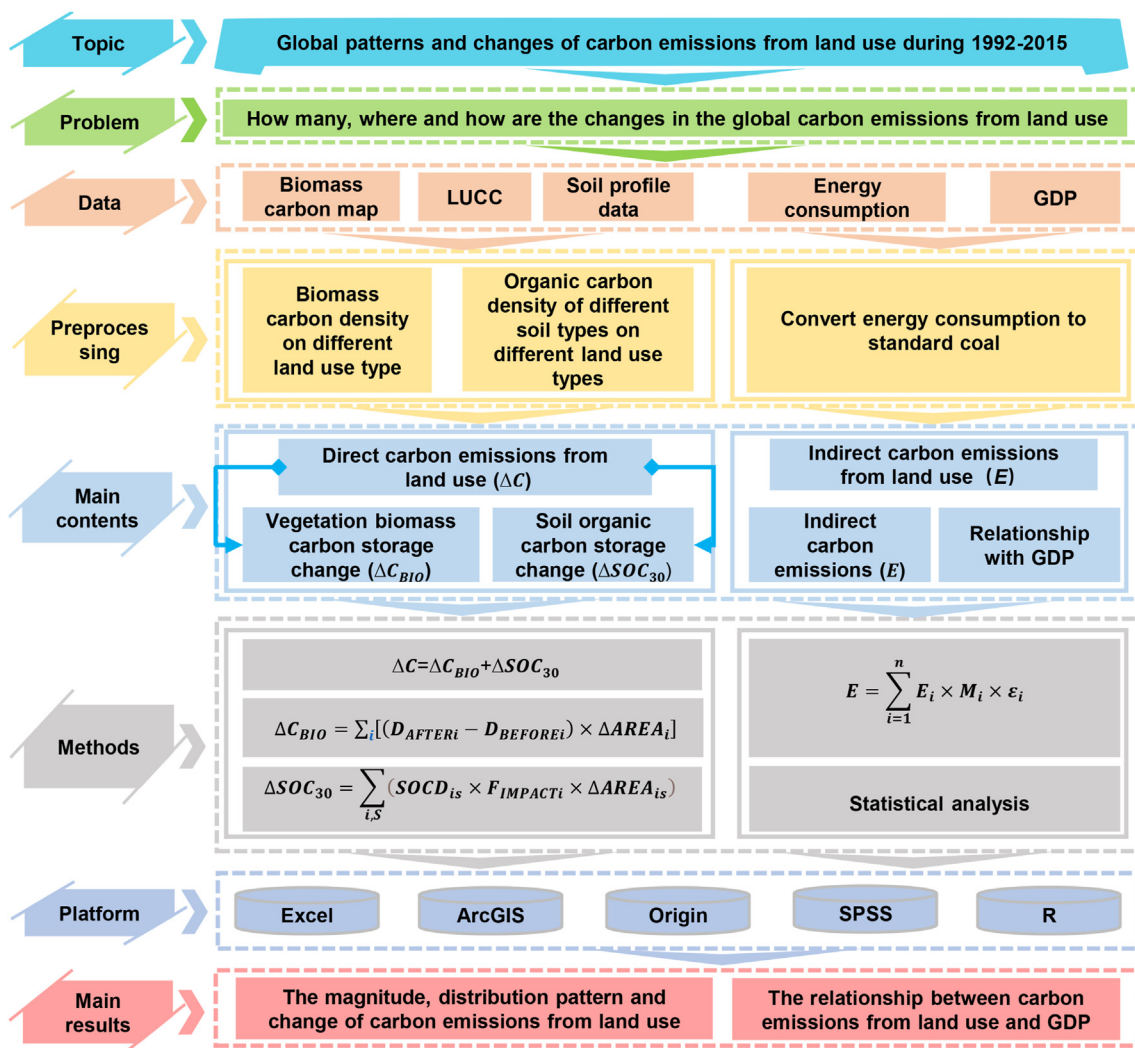


Fig. 1. Technique flowchart.

2.2.4. Analysis of the relationship between GDP and carbon emissions

GDP is an important indicator for measuring the social and economic development level of a country or region, and studies have shown that carbon emissions have a notable relationship with the level of social and economic development [3,7,33]. In order to analyze the relationship between carbon emissions and GDP, this study first calculated the changes in indirect carbon emissions and total GDP of 79 countries and regions in the world from 1992 to 2015. Then obtained the Pearson correlation coefficient of the two based on the SPSS platform.

3. Results

3.1. Dynamic change in LUC

Land use in the global terrestrial system is dominated by other land, forest and grassland, while the areas of wetland and built-up land are relatively small (Fig. 2). As indicated in Fig. S3 and Table S3, cropland showed an overall increasing trend during the entire study period, with an increase of 65.85×10^6 ha, mainly due to the conversion of forest (2.87 %) and grassland (2.02 %) to cropland. However, from the perspective of each research period, cropland

showed a change characteristic of initially increasing then decreasing. Specifically, the increase in cropland was the most obvious during 1995–2000 with an increase of 43.63×10^6 ha. However, the area of increase gradually decreased subsequently, and the area of cropland during 2010–2015 decreased by 1.41×10^6 ha. That is, the increasing trend of cropland throughout the study period was mainly due to the increase from 1995 to 2000. The forest area showed a decreasing trend, with a reduction of 30.18×10^6 ha throughout the study period.

From the perspective of each research period, except for the increase in the forest area in the two stages of 2000–2005 and 2005–2010, the corresponding area for the other three stages decreased. The largest reduction of 21.71×10^6 ha occurred in 1995–2000 and it accounted for 71.94 % of the value for the entire study period. From the perspective of land use change, the reduction in the forest area was mainly caused by the conversion of cropland (2.87 %) and grassland (1.99 %). Grassland showed a decreasing trend during the entire study period, and the reduction area was 34.39×10^6 ha, which was primarily due to the conversion of grassland to cropland (2.02 %) and forest (2.16 %). In the study period, except for the increase in 2010–2015, all four stages showed decreasing trends. The most obvious stage of change was during 1995–2000, which showed a reduction of 23.12×10^6 ha, an

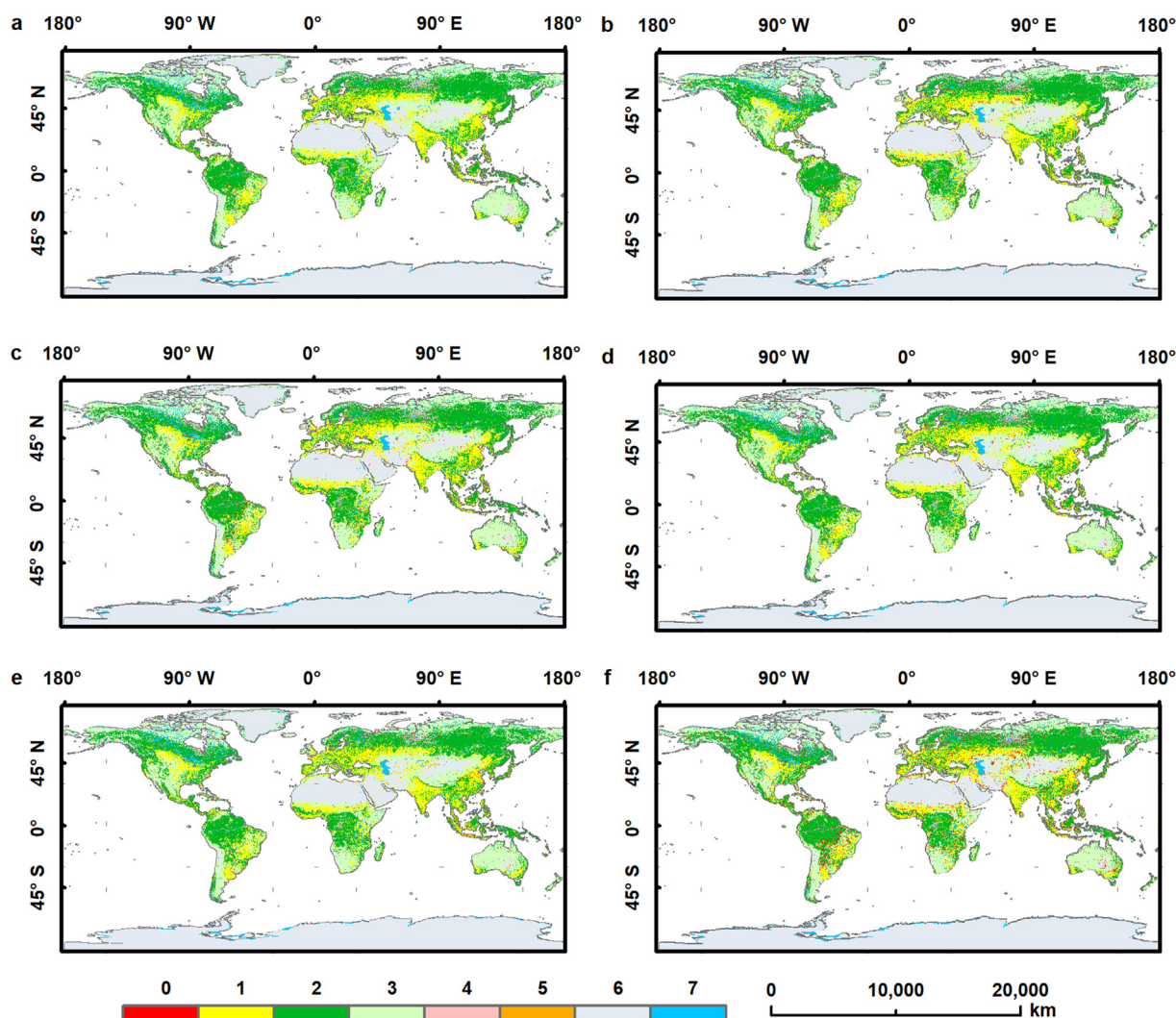


Fig. 2. Land use spatial change during each stage. In the figure, from a to f are the land use spatial changes during 1992–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2015, and 1992–2015, respectively. 0 represents the area where land use changes, and 1–7 represents cropland, forest, grassland, wetland, built-up land, other land and water.

amount that accounted for 67.23 % of the value for the entire research phase. Wetland showed a decreasing trend throughout the study period, and the reduction area was 18.49×10^6 ha, which was mainly caused by the conversion to forest (9.49 %). The area of each stage for wetland was also reduced, which is consistent with the overall characteristics. The most obvious reduction of 7.98×10^6 ha was from 2000 to 2005 and accounted for 43.16 % of the whole research period. Built-up land showed an increasing trend during the study period, with an increase of 36.66×10^6 ha, which was primarily generated by the conversion of cropland (0.94 %) to built-up land. The trend of change for built-up land at each stage was consistent with the overall trend. The largest increase of 13.31×10^6 ha was from 2000 to 2005 and accounted for 36 % of the overall change. Other land and water also showed a decreasing trend throughout the study period, with reduction areas of 18.25×10^6 ha and 1.18×10^6 ha, respectively. Other land was mainly converted to grassland (1.26 %), and water was mainly converted to forest (1.40 %) and other land (1.21 %). The most obvious change in other land, a decrease of 8.32×10^6 ha, occurred during 2005–2010, and it accounted for 45.59 % of the value for the entire study period. The reduction in water was mostly related to reductions in 2000–2005 and 2005–2010. From a spatial

perspective, areas with changes in land use were relatively fragmented, and the alterations in Australia, Central South America, Western Asia, and Eastern Europe were relatively concentrated and obvious.

3.2. Vegetation biomass carbon storage change

As shown in Table S4, the total change in vegetation carbon accumulation during 1992–2015 was 21.74 Pg C and the annual average change was 0.95 Pg C. The increase in carbon storage was 8.33 Pg C and the increase rate was $0.36 \text{ Pg C yr}^{-1}$. The vegetation carbon storage decreased by 13.41 Pg C with a reduction rate of $0.58 \text{ Pg C yr}^{-1}$, which was 1.6 times the increase rate. The overall carbon storage of vegetation showed a decreasing trend. The net change was -5.09 Pg C and the annual average net change was -0.22 Pg C . The reduction of vegetation carbon storage was mainly caused by the decrease in forest carbon storage, whereas the increase in such storage was mainly due to the increase in carbon storage in cropland and grassland (Fig. 3g).

At the various research stages, the most obvious change in vegetation carbon storage occurred from 1995 to 2000 (Fig. 3c). First, the total change in vegetation carbon storage was 7.49 Pg C

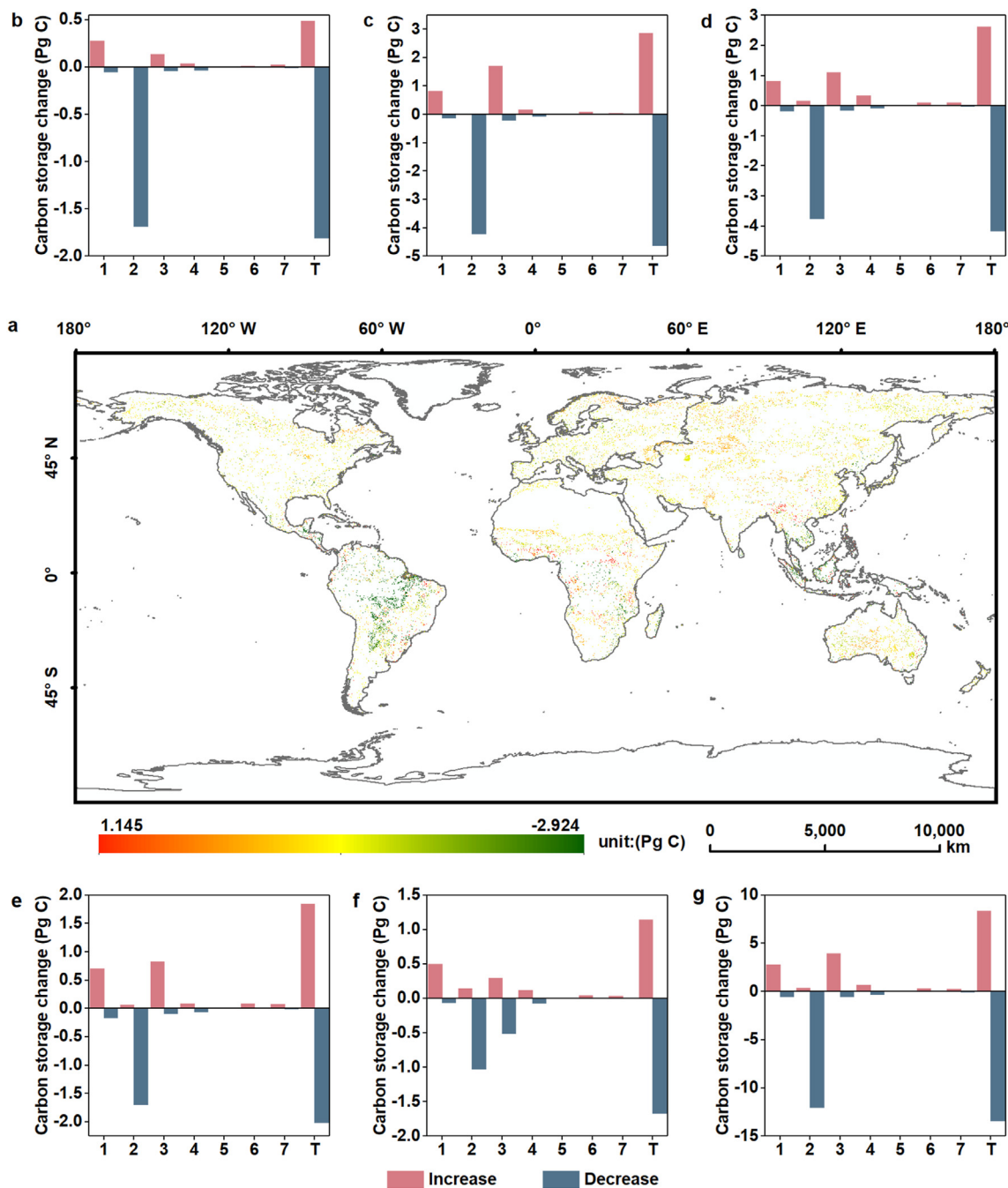


Fig. 3. Spatial distribution pattern of vegetation carbon storage in each stage. In the figure, a is the spatial change in 1992–2015, and from b to f, are the changes of vegetation carbon storage of different land use types during 1992–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2015, and 1992–2015, respectively. 1–7 represents cropland, forest, grassland, wetland, built-up land, other land and water; T represents total.

and the annual average change was 1.2 Pg C. Specifically, the increase was 2.86 Pg C and the increase rate was 0.57 Pg C yr⁻¹. The decrease was 4.63 Pg C and the decrease rate was 0.93 Pg C yr⁻¹. The decrease rate was 1.62 times the increase rate. During this period, the net carbon storage of vegetation decreased by 1.32 Pg C, which accounted for 34.83 % of the net change in vegetation carbon storage during the entire study period and the annual average net change rate was -0.35 Pg C yr⁻¹. Second, from 2000 to 2005, the vegetation carbon storage increased by 2.63 Pg C and the increase rate was 0.53 Pg C yr⁻¹. The total reduction was 4.17 Pg C and the

reduction rate was 0.83 Pg C yr⁻¹ (Fig. 3d). The decrease rate was 1.59 times the increase rate. The net change in vegetation carbon storage during this period was -1.54 Pg C, which accounted for 30.3 % of the entire study period, and the annual average net change rate was -0.31 Pg C yr⁻¹. Third, the vegetation carbon storage increased by 0.49 Pg C in 1992–1995 and the rate was 0.16 Pg C yr⁻¹. The reduced vegetation carbon storage was 1.81 Pg C, the rate was 0.6 Pg C yr⁻¹, and the reduction rate was 3.7 times the increase rate (Fig. 3b). At this stage, the net carbon storage of vegetation was reduced by 1.32 Pg C, which means that the vegetation carbon was

reduced at a rate of $0.44 \text{ Pg C yr}^{-1}$ during this period. The two stages of 2005–2010 and 2010–2015 were relatively insignificant (Fig. 3e and f). From 2005 to 2010, the average annual net change of vegetation carbon storage was only -0.17 Pg C and the annual average net change was as low as -0.03 Pg C . This outcome is consistent with the trend of land use change.

From a spatial perspective, the reduction of vegetation carbon storage in South America was the most pronounced, especially in Central Brazil, Central Bolivia, most of Paraguay, and Northern Argentina. Southeast Burundi, the western part of Tanzania, most of Malawi, and the northwestern part of Mozambique also showed a significant downward trend. Australia showed an increase in the middle and a decreasing trend on both sides. The increase in vegetation carbon storage in Asia was obvious and mainly concentrated in Northern Kazakhstan, Central Pakistan, and Northwestern China. The increase in Europe was mainly in Eastern Europe, especially in Russia (Fig. 3a).

3.3. SOC storage change

Soil carbon accumulation generally increased primarily due to increased carbon accumulation in cropland and grassland soils (Fig. 4). As indicated in Table S4, the total change in soil carbon accumulation from 1992 to 2015 was 4.81 Pg C and the annual average change was 0.21 Pg C . The total reduction was 1.07 Pg C with a reduction rate of $0.21 \text{ Pg C yr}^{-1}$; The soil carbon storage increased by 3.74 Pg C with an increase rate of $0.75 \text{ Pg C yr}^{-1}$, which was 3.49 times the decrease rate. During the entire study period, the net carbon storage increased by 2.66 Pg C and the annual average net increase was $0.12 \text{ Pg C yr}^{-1}$.

First, the most obvious stage of change was during 2000–2005 (Fig. 4d). During this period, the total amount of soil carbon change was 1.42 Pg C . The increase in soil carbon was 1.16 Pg C and the increase rate was $0.23 \text{ Pg C yr}^{-1}$. The total reduction was 0.26 Pg C and the reduction rate was $0.04 \text{ Pg C yr}^{-1}$. The increase rate was 6.07 times the decrease rate. The total net change in soil carbon storage was 0.9 Pg C , and the annual average net change was 0.18 Pg C , which accounted for 33.6% of the entire study period. Second, from 2005 to 2010 (Fig. 4e), the total change in soil carbon accumulation was 1.33 Pg C . Specifically, the increased soil carbon was 1.11 Pg C and the increase rate was $0.22 \text{ Pg C yr}^{-1}$. The reduced soil carbon was 0.23 Pg C and the decrease rate was $0.05 \text{ Pg C yr}^{-1}$. This increase rate was 4.8 times the decrease rate. The net change in soil carbon storage was 0.88 Pg C and the annual average net change was 0.18 Pg C , which accounted for 32.94% of the total carbon accumulation change during the entire study period. The least obvious change occurred during 2010–2015 (Fig. 4f), where the total amount of soil carbon change was only 0.43 Pg C . Soil carbon increased by 0.3 Pg C and the increase rate was $0.06 \text{ Pg C yr}^{-1}$. The decrease was 0.13 Pg C at a rate of $0.03 \text{ Pg C yr}^{-1}$. The increase rate was 2.31 times of the decrease rate. The total net change in soil carbon was 0.17 Pg C and the annual average net change was 0.03 Pg C , which accounted for only 6.34% of the change in soil carbon storage during the entire study period.

The areas where soil carbon was spatially reduced were concentrated in Central Brazil in the South American state, the east of Bolivia, most of Paraguay, and Northern Argentina. The soil carbon in Eastern Australia was also significantly reduced. A significant reduction also occurred in Asia (mainly in Cambodia, Malaysia, Indonesia in Southeast Asia), China's coastal areas in East Asia, and Northeastern Kazakhstan in Central Asia. The regions with an obvious increase in soil carbon concentration were concentrated in Africa, mainly in countries on both sides of the equator. Eastern European countries also collectively showed an increasing trend (Fig. 4a).

3.4. Carbon emissions induced by LUCC

The total change in E_{LUC} from 1992 to 2015 was 26.54 Pg C and the average annual change was 1.15 Pg C . The increase was 12.06 Pg C and the increase rate was $0.52 \text{ Pg C yr}^{-1}$. The decrease was 14.48 Pg C and the decrease rate was $0.63 \text{ Pg C yr}^{-1}$. The decrease rate was 1.2 times the increase rate. The change in carbon storage caused by land use showed a decreasing trend with a net decrease of 2.42 Pg C and a rate of $-0.15 \text{ Pg C yr}^{-1}$ (Table S4). As indicated by Fig. 5, the principal reason for increased carbon storage were variations in cropland and grassland, whereas reduced carbon storage was chiefly stimulated by changes in forest carbon storage.

At each stage, the total carbon storage in 2005–2010 was 5.19 Pg C and the annual average rate of change was $1.04 \text{ Pg C yr}^{-1}$. The increase was 2.95 Pg C and the increase rate was $0.59 \text{ Pg C yr}^{-1}$. The decrease was 2.24 Pg C and the decrease rate was $0.45 \text{ Pg C yr}^{-1}$. This means that the increase rate was 1.31 times the decrease rate. The net change in carbon storage at this stage was 0.71 Pg C and the annual average net change was 0.14 Pg C . In addition to the increasing trend of carbon storage in 2005–2010 (Fig. 5e), carbon storage decreased during the rest of the period. The 1995–2000 period had the most obvious phase of reduction (Fig. 5c), in which the total carbon storage change was 8.86 Pg C . The increase accounted for 3.87 Pg C and the increase rate was $0.77 \text{ Pg C yr}^{-1}$. The decrease was 4.99 Pg C and the decrease rate was approximately -1 Pg C yr^{-1} . The increase rate was 1.3 times the decrease rate. The total carbon storage decreased by 1.13 Pg C and the annual average net change was -0.23 Pg C , which accounted for 46.51% of the entire study period. The next obvious phase occurred in 1992–1995 (Fig. 5b), during which the total carbon storage change was 2.72 Pg C . The increase accounted for 0.81 Pg C and the increase rate was $0.27 \text{ Pg C yr}^{-1}$. The reduction rate was 1.91 Pg C and the decrease rate was $-0.64 \text{ Pg C yr}^{-1}$. The decrease rate was 2.36 times the increase rate. During this period, the total carbon storage decreased by 1.10 Pg C and the average annual net change was -0.37 Pg C , which accounted for 45.48% of the entire study period. The changes in 2000–2005 and 2010–2015 were relatively insignificant (Fig. 5d and f). The total net changes were -0.65 Pg C for 2000–2005 and -0.35 Pg C for 2010–2015. The average annual net changes were -0.13 Pg C for 2000–2005 and -0.07 Pg C for 2010–2015. The increases were 3.78 Pg C for 2000–2005 and 1.44 Pg C for 2010–2015. The rates were $0.76 \text{ Pg C yr}^{-1}$ for 2000–2005 and $0.29 \text{ Pg C yr}^{-1}$ for 2010–2015. The reductions were 4.43 Pg C for 2000–2005 and 1.8 Pg C for 2010–2015. The rates were $-0.89 \text{ Pg C yr}^{-1}$ for 2000–2005 and $-0.36 \text{ Pg C yr}^{-1}$ for 2010–2015. The decrease rates were 1.17 times the increase rates for 2000–2005 and 1.25 times the increase rates for 2010–2015.

As for the spatial distribution pattern, it was basically similar to the distribution pattern of soil and vegetation carbon storage. The low-value areas were mainly concentrated in Northwestern Brazil in South America, Northern Bolivia, the Democratic Republic of the Congo in Africa, Indonesia and Malaysia in Asia, and the southeastern coast of China. The high-value areas were primarily distributed in Northwestern and Southeastern Canada, Northeastern and Southeastern parts of South America, Guinea-Côte d'Ivoire-Nigeria-South Sudan in Africa, and Myanmar, Thailand, Central China, and Russia in Asia.

3.5. Indirect carbon emissions from LUCC

In 1992–2015, the global indirect E_{LUC} showed an upward trend. Among the three types of energy consumption, carbon emissions from oil and coal dominated the indirect E_{LUC} . The largest carbon

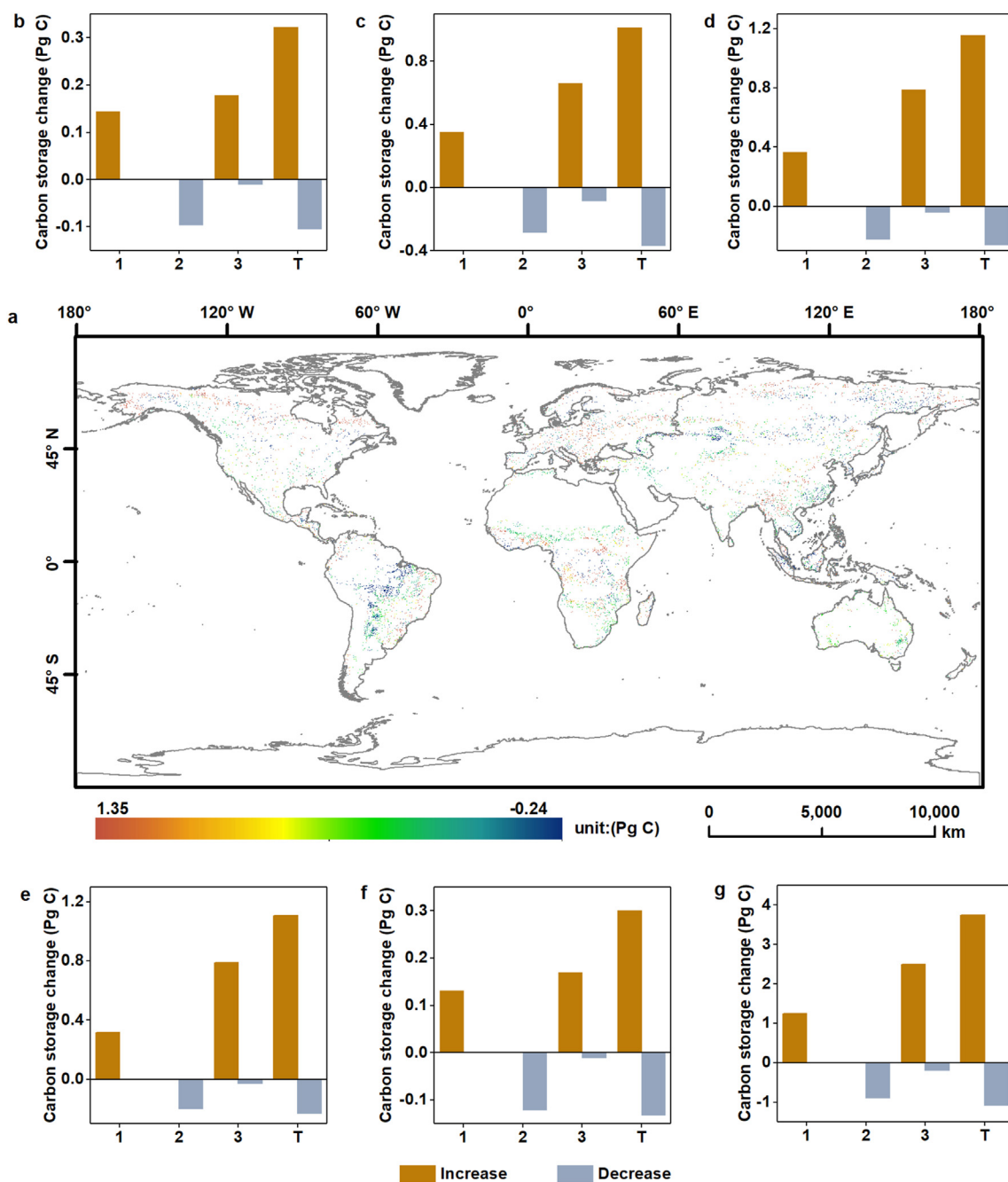


Fig. 4. Spatial distribution pattern of SOC storage in each stage. In the figure, a is the spatial change in 1992–2015, and from b to f, are the changes of SOC storage of different land use types during 1992–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2015 and 1992–2015, respectively. 1–3 represents cropland, forest, and grassland; T represents total.

emissions involved oil before 2005. However, carbon emissions from coal gradually surpassed oil, making coal consumption the largest type of energy consumption after 2005. In addition, obvious downward trends occurred in the three types of energy consumption in 2009, an outcome that may be due to the 2008 global economic crisis. As indicated by Table S5, the total global indirect E_{LUC} from 1992 to 2015 was 27.51 Pg C and the average annual emission was 1.2 Pg C. From the perspective of energy consumption types, the largest emissions involved coal, with a total emission of 11.26 Pg C which accounted for 40.92 % of the total emissions and with an average annual emission of 0.49 Pg C. Coal was followed by oil, with a total discharge of 11.04 Pg C, which accounted for 40.13 % of the total emissions. The average annual emission of oil was

0.48 Pg C. The smallest emissions were from natural gas, with a total emission of 5.21 Pg C, accounting for 18.95 % of the total emissions and having an average annual emission of 0.23 Pg C. In terms of time, the largest emission was in 2015 for a total emission of 6.72 Pg C, which accounted for 24.44 % of the total emissions. The second largest emission was in 2010, with a total discharge of 6.34 Pg C, which accounted for 23.04 % of the total emissions. The smallest emission was in 1992, during which the emission was only 4.31 Pg C, which accounted for 15.67 % of the total emissions. The indirect E_{LUC} in different countries exhibited varying trends in different periods (Fig. 6).

In 1992, the United States emitted a total of 1008.29×10^6 t C of carbon and ranked first in the world in terms of carbon emissions.

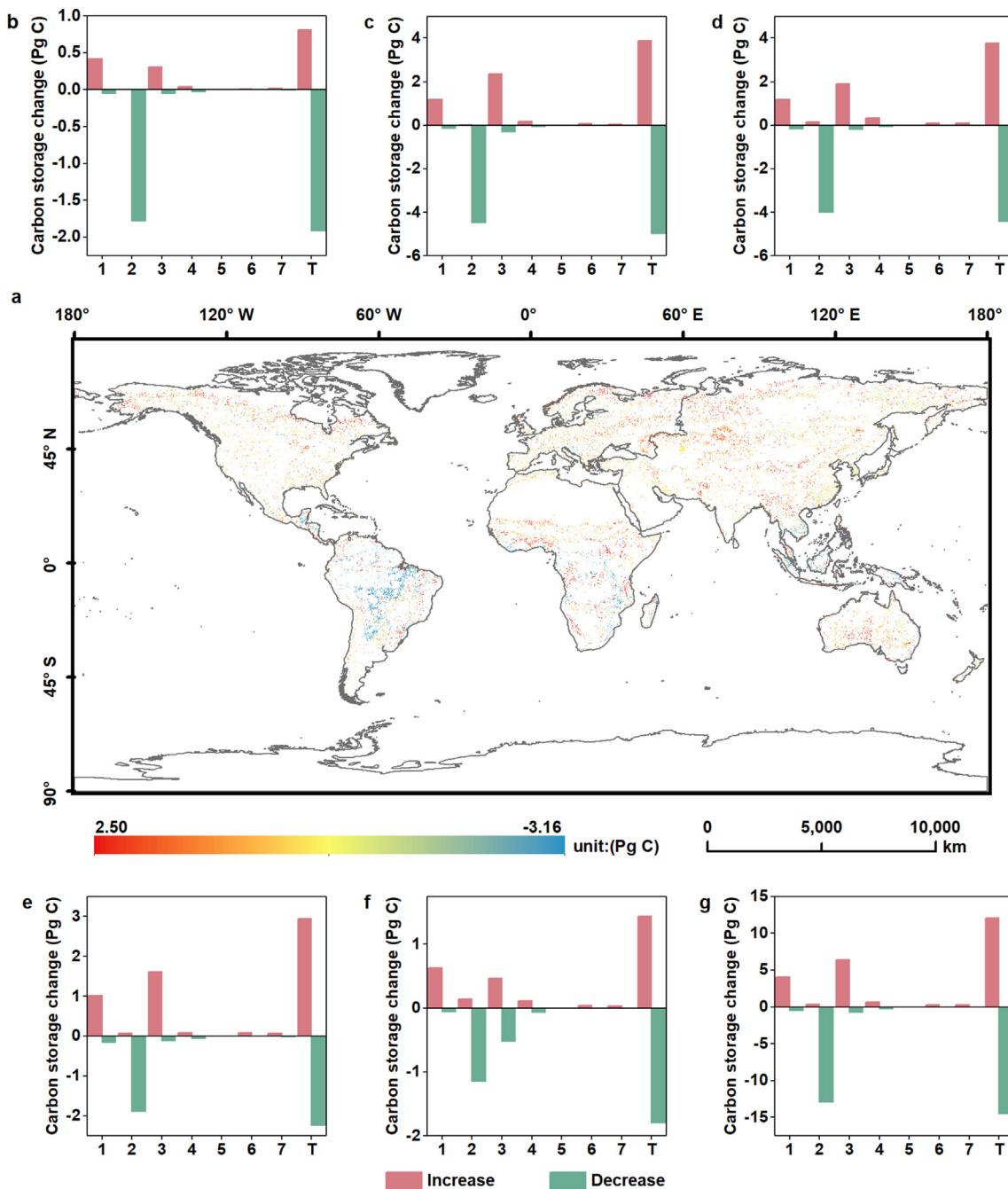


Fig. 5. Spatial-temporal distribution pattern of E_{LUC} in each study period. In the figure, a is the spatial change in 1992–2015, and from b to f, are the changes of E_{LUC} of different land use types during 1992–1995, 1995–2000, 2000–2005, 2005–2010, 2010–2015, and 1992–2015, respectively. 1–7 represents cropland, forest, grassland, wetland, built-up land, other land and water; T represents total.

China's emission was 588.70×10^6 t C, which was only 58.39 % of the US carbon emission. This status quo continued until 2000; Since 2005, China's total indirect E_{LUC} (1344.88×10^6 t C) has begun surpassing that of the US (1191.57×10^6 t C), thereby becoming the world's largest carbon emitter. In 2015, China's indirect E_{LUC} was 1994×10^6 t C, which was 1.87 times that of the US (1069.62×10^6 t C), and accounted for 41.62 % of the global (4791.28×10^6 t C) indirect E_{LUC} . In addition to China, India and Brazil's indirect E_{LUC} also steadily increased, and the two were listed in the top 10 countries in terms of global indirect E_{LUC} . In 2015, the emissions in these two countries were 431.38×10^6 t C (India) and

116.97×10^6 t C (Brazil). The increase rates were 295.98×10^6 t C (India) and 65.79×10^6 t C (Brazil), and the growth rates were 12.87×10^6 t C yr⁻¹ (India) and 2.86×10^6 t C yr⁻¹ (Brazil).

4. Discussion

4.1. Comparison of estimated results with other results

Determining the amount of carbon emissions accurately is a prerequisite for further analysis. Among the many methods of estimating E_{LUC} , the BK model has been widely used as a classic

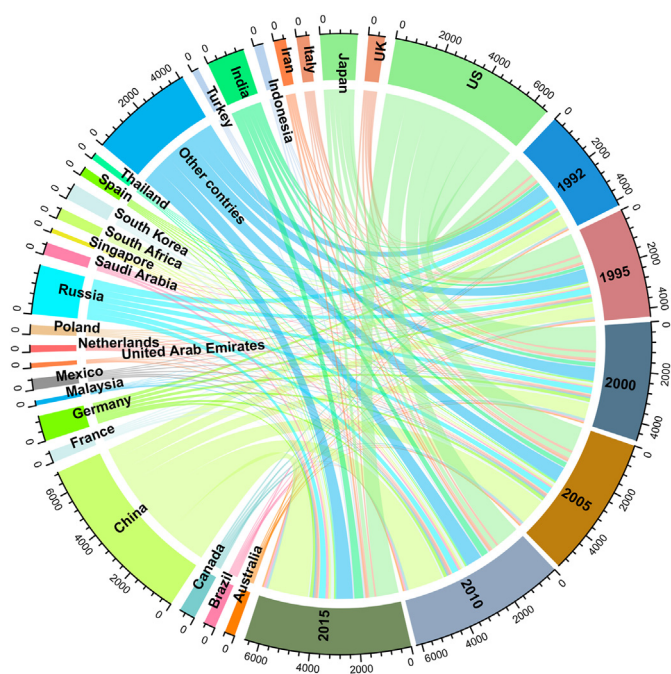


Fig. 6. Indirect E_{LUC} in countries around the world (unit: 10^6 t C).

model. The model involves annual time series accounting consisting of collecting various data and summarizing empirical data. The advantage of the BK model is that it systematically considers the basic ecological process of the carbon cycle caused by land use change. However, obtaining the parameters and characteristics of these processes is difficult. Whether these parameters and features are representative or not remains doubtful. By contrast, the IPCC recommended method used in this study requires less data, involves a simpler sample, and is a more straightforward approach to estimate carbon emissions. Comparison of several studies on BK and other models (such as CASA and DGVMs) revealed that the calculated LUCC carbon flux is close to other research results at the same spatial scale and is within the error range (Table 1). The results of this work are proven to demonstrate high precision and the reliability of the method is strong.

4.2. Relationship between carbon emissions and GDP

Research on the relationship between economic development and carbon emissions is of great practical significance, especially in clarifying the carbon emission reduction tasks of various countries and realizing the coordinated and sustainable development of socio-economy and the ecological environment. Pearson's correlation analysis results depicted that the changes in indirect E_{LUC} and GDP changes in the 79 countries and regions studied in this article

Table 1
Comparison of fluxes of E_{LUC} between our results and other studies.

Research period	Method	Carbon flux (Pg C yr^{-1})	Reference
1990–2009	BK	1.14 ± 0.18	[16]
2006–2015	BK	1.11 ± 0.35	[17]
2005–2014	BK/CASA/DGVMs	0.9 ± 0.5	[28]
2008–2017	BK/DGVMs	1.5 ± 0.7	[27]
1980–2012	BK	1.13	[35]
1992–2015	GIS + IPCC method	1.15	This study

Notes: BK = bookkeeping models; CASA=Carnegie-Ames-Stanford Approach (CASA) biogeochemical model; DGVMs = Dynamic global vegetation models.

were overall significantly positively correlated with a correlation coefficient of 0.65. Comparing the total changes between the two, it can be seen that while the GDP of most countries increases, indirect E_{LUC} are also increasing (Fig. 7a). That means these countries should assume important responsibilities in dealing with global warming. But we can still see that the 25 countries and regions, including Russia, Ukraine, the United Kingdom, Germany, and Italy, have increased their GDP and reduced their indirect E_{LUC} (Fig. 7b). This result manifested that these countries were also aware of the importance of protecting the environment and preventing climate warming while increasing their GDP. At the same time, their development model can be used as a reference for other 54 countries and regions.

The carbon trading market is a novel way to solve the problem of greenhouse gas emission reduction represented by CO_2 , it treats carbon emission rights as a commodity for trading. For instance, the loss of carbon emissions caused by global land use change can be calculated with the average carbon price of the EU market of $\$28 \text{ US tC}^{-1}$ in 2019 (Table S6). During 1992–2015, the net value of global E_{LUC} was $\$136.3 \times 10^9 \text{ US}$ and the rate was $\$5.93 \times 10^9 \text{ US yr}^{-1}$. The net value caused by direct E_{LUC} was $\$68.79 \times 10^9 \text{ US}$ and the net value caused by indirect E_{LUC} was $\$67.51 \times 10^9 \text{ US}$, which accounted for 50.47 % and 49.53 % of the total net value, respectively.

4.3. Deficiencies and prospects

From the land use perspective, this study estimated global E_{LUC} changes from 1992 to 2015 by using the IPCC recommended method, revealed the spatial and temporal evolution characteristics of E_{LUC} , and discussed the relationship between E_{LUC} and GDP. This research has certain practical significance, but limitations still exist. Specifically, the following aspects are still insufficient.

- (1) Although previous studies have confirmed the reliability of this method, some uncertainty about the technique remains. First, this study estimated E_{LUC} change based on the assumption that the carbon density is unchanged. In reality, carbon density is constantly changing. In addition, when calculating the soil carbon accumulation change, only three types of land (cropland, forest, and grassland) were considered in this work. Using mutual conversion between types, the other four were disregarded. These problems may result in inaccurate calculation results.
- (2) This work analyzed the spatial and temporal evolution characteristics of E_{LUC} from 1992 to 2015 in stages. The research has important guiding significance for understanding the carbon cycle of terrestrial ecosystems, but the internal conversion mechanism of the carbon cycle has not been discussed in depth. Most carbon in the soil comes from vegetation litter. Ideally, the reduction of vegetation carbon should be equivalent to the increase in soil carbon. The results of this study indicate that the net carbon accumulation of vegetation is reduced by 5.09 Pg C and the net carbon accumulation of soil is increased by only 2.66 Pg C. Where is the additional 2.43 Pg C of vegetation reduction? Was it in the atmosphere or something else?
- (3) This work analyzed the relationship between E_{LUC} and GDP and converted the net carbon loss during the research period from the carbon trading angle. The research has a certain reference value in clarifying the energy conservation and emission reduction tasks of various countries. However, this study only discussed the relationship between global GDP and indirect E_{LUC} from the perspective of total changes. The influence of other factors, such as differences in national conditions, natural conditions, and industrial structure, have

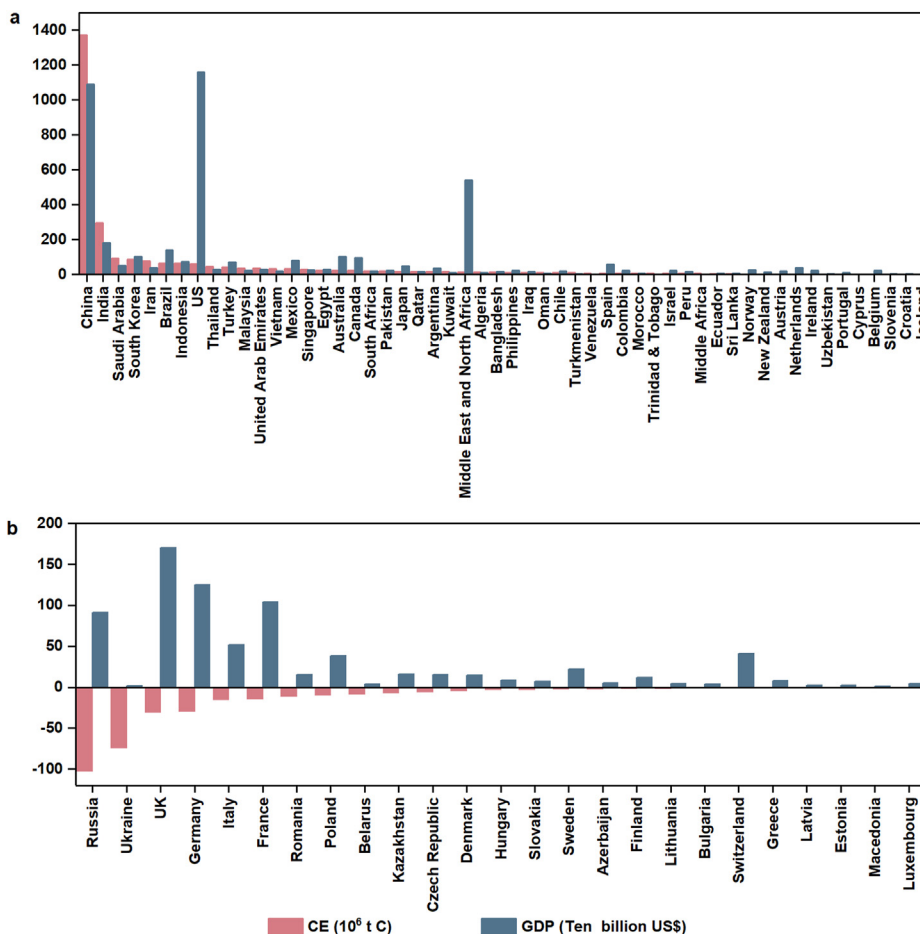


Fig. 7. Relationship between indirect carbon emissions (CE) and GDP in global countries and regions. In the figure, a represents that GDP increases and CE also increases, and b represents that GDP increases while CE decreases.

not been considered. Moreover, the driving mechanism of carbon emissions remains unclear. What is the main control factor? What is the contribution rate? These queries will be the main focus of future research.

In summary, in the future, we will further analyze the internal transformation mechanism of carbon emissions and reveal the driving factors of its spatial and temporal evolution. We will subsequently conduct simulation prediction and risk warning for future trends of global carbon emissions, with the aim of providing scientific basis and technical support in response to global warming.

5. Conclusions

It is found that during the study period, vegetation carbon storage decreased, accompanied by an increase in SOC storage. Regarding the total amount of direct E_{LUC} change, it achieves the level of 26.54 Pg C. The study also revealed specific areas where E_{LUC} increased and decreased, which could give further insight into the carbon reduction targets. It is noteworthy that this paper highlights the calculation of indirect E_{LUC} , which has been overlooked in terms of previous studies. Furthermore, we have made a preliminary discussion on the relationship between indirect E_{LUC} and GDP, it is concluded that they are not necessarily a positive correlation. This discovery breaks the traditional understanding that carbon emissions will increase with economic growth. The results give in-depth

demonstrations and call attention to the accounting for E_{LUC} , which will provide important implications in understanding the carbon cycle mechanism, initiating carbon reduction countermeasures, achieving carbon neutrality, and mitigating global warming.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ese.2021.100108>.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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