Carbon deficit checks in high resolution and compensation under regional inequity

Abstract: Carbon compensation is an effective way of reducing carbon emissions. However, previous studies in this field have been limited and have not examined high-precision scientific carbon compensation under regional inequity. The present study examined initial carbon compensation in the grid and developed a new equitable carbon compensation model. Additionally, it modified the carbon compensation value for each province and analysed how land-use change affected carbon compensation. The results show that, after the modification, the entire carbon deficit reached 17.34×10^8 t C in 2015, representing a decrease of 14% compared with the initial carbon deficit. The area with negative carbon deficit values accounted for 36% of the whole area, concentrated mainly in the south, southwest and northwest. Without modification, the initial carbon compensation reached 537×10^8 USD, and only Yunnan, Sichuan and Hainan provinces being eligible to receive compensation. The final modified carbon compensation was approximately 20% of the initial values, and 11 provinces were eligible to obtain compensation. The other provinces responsible for paying the carbon compensation costs were typically concentrated in Central and Eastern China. Land-use changes in 2015 led to increases in the initial carbon compensation and modified carbon compensation of 3.74×10^8 and 0.13×10^8 USD, respectively. The per-unit land-use change caused greater increases in carbon emissions in China's big cities and the provinces in Central and East China. Some policies, such as macro-control by the central government, diversified forms and patterns of compensation, and auxiliary measures should be formulated/proposed.

Keywords: carbon deficit; carbon compensation; land-use change; regional inequity; China

1. Introduction

As the largest carbon emitter, China has promised to reach carbon neutrality by 2060. Increasing carbon sinks and reducing carbon emissions are key strategies to achieving this target. However, during this process, a large number of energy-intensive industries will be eliminated, meaning many people will lose their jobs. Furthermore, China has launched several national ecological restoration projects (Wang et al., 2021a), and obvious greening has been identified in the country (Liu et al., 2014; Lu et al., 2018). China's contribution to greening the world has accounted for a 25% increase in global leaf area, although it contains only 6.6% of global vegetated area (Chen et al., 2019). These measures will not only promote carbon sequestration but also affect people's survival (Wang et al., 2021a). Conversely, there are regions and enterprises in China that have emitted excessive amounts of carbon and consequently gained considerable economic profit. Wide inequities exist among the different regions in China; thus, people who have made sacrifices to reduce carbon emissions or increase carbon sinks need to receive payments from the beneficiaries, and carbon compensation appears to be an effective way to both promote emission reduction and eliminate inequity.

Previous studies have been conducted on compensation mechanisms, standards and patterns (Kollmuss et al., 2008; Li et al., 2013; Zhao et al., 2015b). Specific carbon compensation case studies have mainly addressed forest carbon compensation (Gregory et al., 2016; Guillaume et al., 2017), agricultural carbon compensation (Xiong et al., 2016), tourism carbon compensation (Fei, 2012), regional lateral carbon compensation (Miao et al., 2019) and carbon market design (Li et al., 2018). There are both economic and non-economic forms of compensation. The economic form accounts for the majority, the core of which is the compensation economy value calculation. There are different methods for evaluating carbon value, including the trade market method, the afforestation cost method, the income method and the carbon tax method (Lin & Ge, 2019). Among these, the trade market method is the most frequently used. Currently, according to data from China's carbon emissions trade website (www.tanpaifang.com/), the carbon emission trade price in

China is approximately 5.6–8.4 USD/t C, which is much lower than that in the European Union (EU). The per-unit carbon trade price is affected by various factors, such as the political attitude towards the implementation of carbon emission reduction policies, the market's supply and demand relationship, the energy price, the energy policy and the industry index (Fan & Todorova, 2017; Shen et al., 2020; Yin et al., 2019).

China's carbon emissions trade market is still yet to become mature. In July 2021, China began to expand its carbon emissions trade from the seven original carbon trading pilots to the whole of China, while the tradable industries boundary also expanded from the traditional power industry to many other sectors. Additionally, the first blue carbon trade project involving mangroves was successfully completed in Guangdong Province. This set a positive example to extend other carbon sink trade projects, which are not limited to forests but may also incorporate other carbon sinks items as well as grass and crops. This means that the study of carbon compensation in China will be more practical and meaningful.

Except for the carbon trade price, the basic data for determining carbon compensation is the carbon source/sink capacity. The evaluation of China's carbon sinks still has significant uncertainties, with the total amount varying widely between different studies. In most previous studies, carbon sink accumulations in China have been conducted around 0.1–0.4 Pg C/yr (Chuai et al., 2018; Wang et al., 2021b). However, a recent examination found a large Chinese land carbon sink of 1.11 ± 0.38 Pg C/yr during 2010–2016 (Wang et al., 2020). Therefore, the accuracy still needs to be improved with the help of increased field observations. Additionally, when using carbon sinks in carbon compensation, studies have usually quoted empirical coefficients or used the mean sink value of a certain ecosystem to study different regions, which has greatly exacerbated the errors. Using the amount of anthropogenic carbon emissions usually results in less bias, some studies have also examined carbon emissions at a grid scale in the spatial dimension. For example, the Carbon Dioxide Information Analysis Center (CDIAC) has provided carbon emission products with a resolution of $1° \times 1°$(CDIAC, 2020), the Emissions Database for Global Atmospheric Research (EDGAR) has provided carbon emission products since 1970 with a resolution of $0.1° \times 0.1°$(Crippa et al., 2018). These achievements can support addressing the carbon deficit on a more detailed scale. However, most studies are still carried out on the regional scale, and lateral compensations are usually made on the provincial scale in China (Miao et al., 2019; Wan et al., 2020; Yang et al., 2019).

Another problem that affects scientific compensation is regional inequity, in terms of both inter-regional differences and the influence of regional interactions. China's physical and geographical conditions differ greatly, with heavy precipitation and high temperatures in the southeast but the drier arid and semi-arid climate zones in the northwest. Such physical conditions create regional variations in terrestrial ecosystem carbon sinks. Large areas of the south and east have a high carbon sink capacity, while the capacity in the northwest is much lower (Pan et al., 2015). These physical conditions also make the distribution of populations and anthropogenic carbon emissions extremely spatially uneven, with the south and east (especially the coastal regions) having the most intensive emission concentrations (Li et al., 2020). Some carbon compensation research has been conducted with consideration of regional physical and socioeconomic differences, and the relative carbon deficit model was developed to modify regional carbon deficits (Wan et al., 2020; Yang et al., 2019).

With rapid economic and social development, regional interactions have become more frequent and more tightly linked. The multiregional input–output (MRIO) model is a widely used method to examine the economy and perform the associated environmental assessment among regions and sectors, and many researchers have used it to analyse embodied carbon emissions between regions and the resulting regional inequalities (Li & Li, 2022; Pan et al., 2018; Tian et al., 2020; Tramberend et al., 2019). Generally, previous studies have focused mainly on anthropogenic carbon emissions, and some have also included terrestrial carbon; for example, Chuai et al. (2021) formulated the theory that built-up land expansion in China is significantly affected by economic development and examined external regions' carbon storage loss as embodied in domestic trade. While, these are seldom used in carbon compensation research, if a model considers both regional interior differences and regional carbon interactions, the accuracy of regional inequity will be improved.

It is well known that land-use change can significantly affect regional carbon balance. Initially, scholars focused on whether there were significant differences in the influence on terrestrial ecosystems of carbon changes in vegetation and soil resulting from the capacity of carbon sequestration of different land-use types (Don, et al., 2011; Houghton, 1995; Lai et al., 2016). Generally, land-use change from land with a high biomass content will release carbon from terrestrial ecosystems. Some scholars also believe that as the carrier of anthropogenic activities, land-use change will also alter anthropogenic carbon emissions on the land surface (Fu et al., 2014; Zhang et al., 2018). The occupation of vegetated land (farmland, woodland and grassland) by built-up land is the most common land-transfer pattern in China (Ning et al., 2018) and generates a considerable amount of carbon emissions. Therefore, land-use control and optimisation will play critical roles in reducing carbon. Regarding carbon compensation, previous studies have not considered carbon changes resulting from changes in land use.

This research makes innovations according to the shortfalls discussed above. Its objectives include: (1) developing an inequity model able to consider interior regional differences and interactions and re-check carbon deficits, (2) modifying lateral regional carbon compensation values and (3) analysing land-use change and the associated carbon compensation and proposing certain policy implications. Such research is meaningful for both carbon emissions reduction and regional coordinated development.

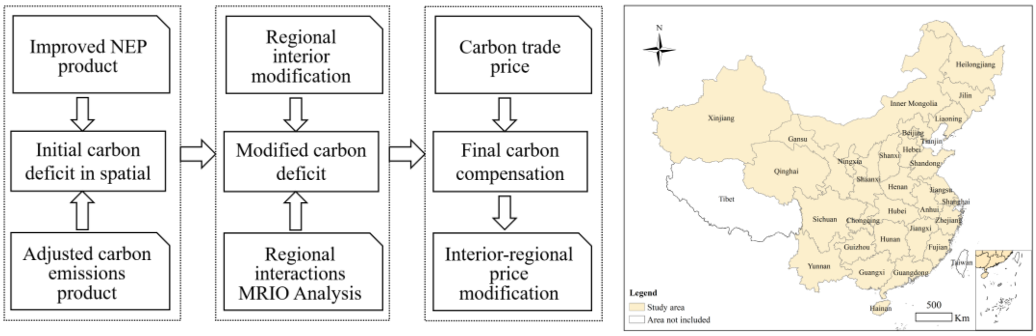
2. Data and methodology

2.1 Data

This study used MRIO data, data on the geographical distribution of carbon emissions, data on energy consumption among sectors and data on industry products and waste disposal. It also used carbon emission coefficients, net ecosystem productivity (NEP) and land-use data. The study was conducted in 2015, and all the selected data were from that year. The MRIO table was provided by the China Emissions Accounts and Datasets (CEADS) (https://www.ceads.net/), which contains the regional and sectorial links across China, including all 31 provinces except Hongkong, Macao and Taiwan (Zheng et al., 2020). Spatial carbon emissions data were obtained from the EDGAR dataset (Crippa et al., 2018) at a resolution of 0.1° × 0.1° (https://edgar.jrc.ec.europa.eu/). Provincial energy consumption data were provided by the *China Energy Statistical Yearbook 2016*, while industry product and waste disposal data were obtained from the provinces' respective statistical yearbooks. Carbon emissions coefficients were quoted mostly from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006) and partly from other studies (Zhao et al., 2015a). The 1-km NEP product was obtained from our previous research (Chuai et al., 2018). Land-use data were obtained from the Ministry of Natural Resources of the People's Republic of China and included, it is a statistical data for each province, with the land use types including the vegetated land (woodland, farmland and grassland), built-up land and unused land. Other economic and social data were obtained from the *China Statistical Yearbook*.

2.2 Research framework

This research employed the framework shown in Fig. 1(a). First, the total amount of carbon emissions from EDGAR for the whole of China is much closer to our calculation based on the domestic data as mentioned above, but bias exists for some provinces. Accordingly, we made adjustments for the EDGAR product according to our calculation result for provinces having bias. According to EDGAR product, we were able to calculate the carbon emissions amount for each province, and, we finally multiplied a coefficient calculated by the amount of statistical carbon emissions with the EDGAR emissions. Since the statistical data for carbon emissions did not include Tibet, Hongkong, Taiwan and Macao, the study area did not include these regions (Fig.1(b)). Second, the NEP was converted into a low resolution to match the EDGAR products' resolution, and the carbon deficit in spatial terms was checked within a resolution of 0.1° × 0.1°. In this study, the initial carbon deficit and carbon compensation are defined as the carbon deficit and compensation without consideration of regional interactions and regional interior modification. Third, the carbon emissions embodied in domestic trade were calculated using the MRIO model, and regional carbon emissions were modified by the trade-triggered carbon emissions among provinces. Fourth, carbon emissions and carbon sinks were further modified by regional interior differences, and the final carbon compensation value was evaluated using the trade market method. Here, the modified carbon deficit and carbon compensation indicate the carbon deficit and carbon compensation, which are modified by considering both the domestic trade and regional interior inequity, the details are shown in Eqs. (1)–(12).



(a) (b)

Fig. 1 (a) The research framework and (b) the distribution of the provinces

2.3 Analysis

2.3.1 Calculation of direct anthropogenic carbon emissions

The carbon emissions from energy consumption, industrial production processes and waste disposal were included in our calculations. The emissions coefficient method was used to calculate anthropogenic carbon emissions (Chuai et al., 2022).

2.3.2 Carbon emissions embodied in domestic trade

The carbon emissions closely linked with the domestic trade considered here included agriculture, commerce, and industry. The MRIO model based on environment expansion was used to calculate the carbon emissions embodied in China's domestic trade at the provincial scale. We excluded the column and row with Tibet from the matrix as we lacked the data on carbon emissions in Tibet.

Based on the fundamental relationship given in the MRIO table, a balanced input–output relationship is expressed by Eq. (1):

$$AT + F = T \tag{1}$$

$$T = (I - A)^{-1} F\,. \tag{2}$$

where A is the direct consumption coefficients matrix, T refers to the total output matrix, and F is the final use matrix. I is an $n \times \times n$ identity matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix. The carbon emissions embodied in domestic trade among provinces were calculated by Eq. (3):

$$C = l(I - A)^{-1} F\,. \tag{3}$$

where l represents the direct carbon emissions intensity vector, and C is the amount of carbon emissions embodied in domestic trade among provinces. The MRIO analysis was conducted by the using the MATLAB software.

2.3.3 Modified carbon deficit and compensation

According to the MRIO analysis, regional carbon emissions were modified by the amount of carbon emissions embodied in domestic trade, as shown below:

$$C_{ei} = C_i + (C_{i-import} - C_{i-export})\,. \tag{4}$$

C_{ei} represents the carbon emissions modified by the domestic trade in region *i*, C_i is the actual carbon emissions in region *i*, and $C_{i-import}$ and $C_{i-export}$ are the total carbon emissions that region *i* triggered to all the other regions in China and the reverse amount that other regions triggered to region *i*, respectively, obtained from C in Eq. (3).

If we do not consider the inter-regional differences, the initial carbon deficit and carbon compensation can be calculated using the following equations:

$$C_{di} = C_{ei} - C_{si} \tag{5}$$

$$ACC_{di} = C_{di} \times P_c \tag{6}$$

where C_{di} is the actual carbon deficit of region *i*, C_{si} is the regional carbon sink (t C/a), and ACC_{di} is the payment for the carbon compensation of region *i*. Additionally, P_c is the unit trading price of carbon emissions. Based on the based on current conversion exchange rate between the USD and Renminbi (RMB), this is approximately 27.17 USD/t C (data from China's carbon trade network: www.tanjiaoyi.com/).

For the consideration of inter-regional ecological background differences, the ecosystem service value (*ESV*) was used to modify regional carbon sinks (Wan et al., 2020) as follows:

$$C_{rdi} = C_{ei} - C_{si} \times \alpha_i \tag{7}$$

$$\partial_i = 1 + (ESV_i - \overline{ESV}) / \overline{ESV} \tag{8}$$

where C_{rdi} is the first modified carbon deficit of region *i*, and α_i is the regional modified coefficient carbon sink. The terms ESV_i and $\overline{ESV}$ are the *ESV* for region *i* and the mean value for all regions, respectively. We produced the *ESV* across China using the method proposed by Xie et al. (2017).

Then, regional populations and land were considered to make further modifications:

$$\eta_i = \frac{P_i \times L_i}{\sum P_i \times L} \tag{9}$$

$$C_i = C_{rdi} - \eta_i \sum C_{rdi} \tag{10}$$

here, η_i is the regional carbon compensation coefficient, which is calculated from P_i (population in region *i*) and L_i (land area in region *i*), and C_i is the final modified carbon deficit for region *i*.

Finally, considering the differences in regional economic development, the carbon compensation coefficient was used to calculate the final carbon compensation as follows:

$$ACC_i = C_i \times P_c \times \theta_i \tag{11}$$

$$\theta_i = G_i / G_{\mathrm{T}}(1 + ae^{-bt}) \tag{12}$$

where ACC_i is the final carbon compensation value of region *i*, θ_i is the carbon compensation coefficient of region *i*, G_i represents the gross domestic product (GDP) of region *i*, G_T represents the national GDP, *a* and *b* are constants numerically equal to 1, and *t* is the national Engel coefficient.

2.3.4 Carbon compensation variations from land-use change

To calculate the carbon compensation variations from land-use change, the first step is to determine the carbon emissions caused by land-use change. The calculation process is as follows:

$$\mathrm{C}_{i-change} = \sum_{j=1}^{n} L_{j-begin} \times D_j - \sum_{j=1}^{n} L_{j-end} \times D_j \tag{13}$$

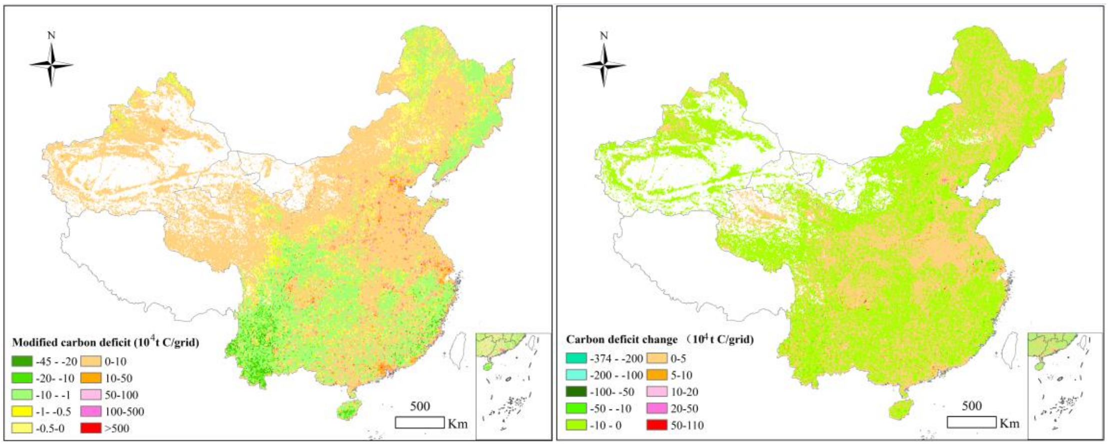
where $\mathrm{C}_{i-change}$ represents the carbon emissions caused by land-use change in province *i*; $L_{j-begin}$ and L_{j-end} are the areas of land-use type *j* at the start and end of 2015, respectively; and D_j is the carbon sink or carbon emissions capacity of land-use type *j* in 2015.

Then, $\mathrm{C}_{i-change}$ can be used to replace C_{di}, the initial carbon compensation without modification can be calculated by Eq. (6), and $\mathrm{C}_{i-change}$ can be used to replace C_{rdi}. The final carbon compensation after modification can be calculated by Eqs. (10)–(12).

3. Results

3.1 Modified carbon deficit and changes

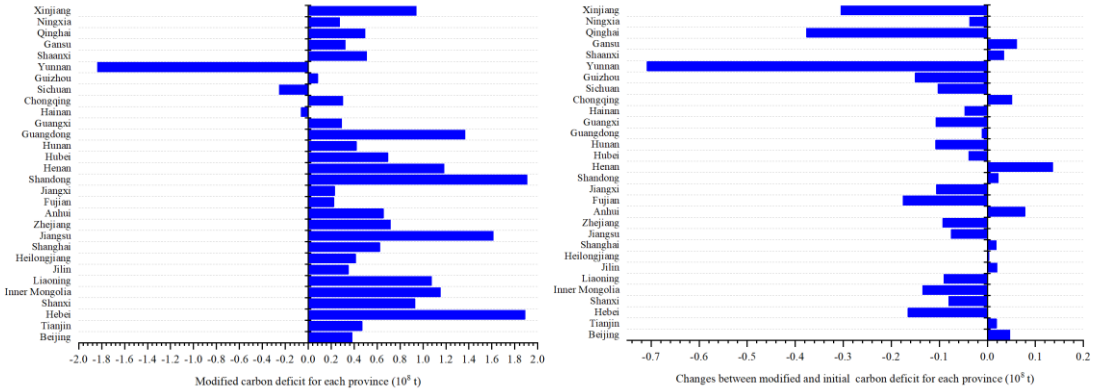
The modified carbon deficit was calculated using Eq. (10). Fig. 2(a) shows that, after the modification, the entire carbon deficit reached 17.34 × 10^8 t C in the year 2015, representing a decrease of appropriately 2.42 × 10^8 t C compared with the initial carbon deficit without modification. The area with positive carbon deficit values accounted for 63.97% of the area shown in Fig. 2(a); higher values were more concentrated in the east and especially in the Circum Bohai Sea economic sphere and the Yangtze River/Pearl River economic zones. The remaining area, which was mainly concentrated in the south, southwest and northwest, should receive carbon compensation. The changes shown Fig. 2(b) reveal that 38.1% of the area needs to increase its carbon deficit after modification, with this area being mainly concentrated in Central, Eastern and Southern China. The area with decreased carbon compensation has a wide distribution across China, especially in the south, west, north and northeast.



(a) (b)

Fig. 2 (a) Modified carbon deficit and (b) the changes compared with the initial carbon deficit (in 2015

Fig. 3 shows that the three provinces of Yunnan, Sichuan and Hainan have negative carbon deficits. This means they have more carbon sinks than carbon sources, especially Yunnan (−1.8 × $10^{.8}$ t C). Yunnan also had the highest carbon deficit decrease compared with its initial carbon deficit (−0.78 × 10^8 t C). For provinces with positive carbon deficits, Shandong has the highest (1.91 × 10^8 t C), followed by Hebei, Jiangsu, Guangdong, Henan, Inner Mongolia and Liaoning, with values varying between 1.9 × 10^8 and 1.08 × 10^8 t C. The other provinces have positive carbon deficits lower than 1 × 10^8 t C. After modification, 19 provinces exhibited a decreases in their carbon deficits. After Yunnan, the provinces of Qinghai and Xinjiang had the second- and third-highest decreases. Fujian, Hebei, Guizhou and Inner Mongolia had similar decrease values ranging from −0.18 × 10^8 to −0.13 × 10^8 t C. For the 11 provinces with carbon deficit increases, the increases were much lower. Henan had the highest increase at 0.14 × 10^8 t C, while the others were all lower than 0.1 × 10^8 t C.



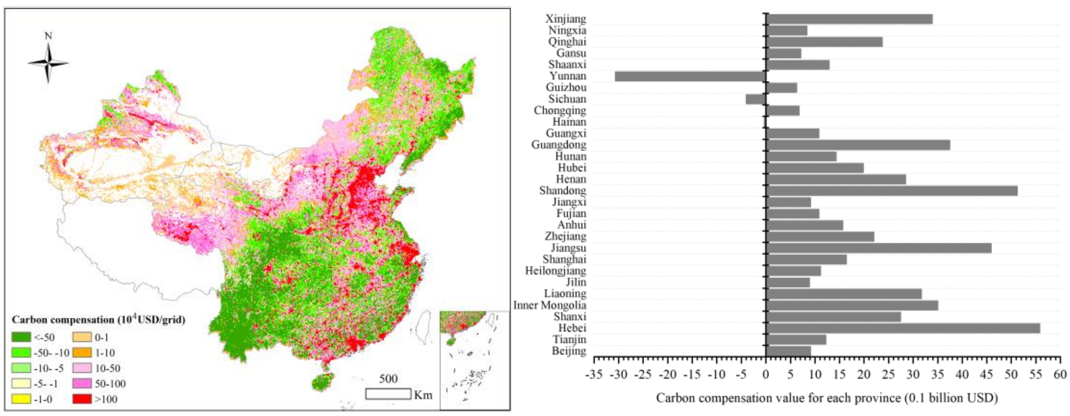
(a) (b)

Fig. 3 (a) The modified carbon deficit and (b) the changes compared with the initial carbon deficit

3.2 Initial carbon compensation without modification

The initial carbon compensation reached 537 × 10^8 USD. Fig. 4(a) shows the differences in carbon compensation within a 0.1° × 0.1° grid. The negative-value area indicates the areas that should receive carbon compensation. They are intensively distributed in the southwest, with large areas showing carbon compensation values higher than 50 × 10^4 USD/grid. Additionally, the coastline region and a large area in the northeast should receive a considerable amount of carbon compensation. A total of 60.14% of the entire area (mainly located in Northern, Central and Eastern China) should pay for net carbon emissions. The positive carbon compensation values are much higher than the negatives, with a large area showing values higher than 50 × 10^4 USD/grid, especially in certain national economic regions, including the Circum Bohai Sea economic sphere and the Yangtze River/Pearl River economic zones.

Fig. 4(b) shows the carbon compensation differences among provinces. The three provinces of Yunnan, Sichuan and Hainan should receive carbon compensation, and Yunnan's should be almost eight times higher than Sichuan's. Hebei Province should pay for the highest carbon compensation of 27.4 × 10^8 USD, followed by Shandong, Jiangsu, Guangdong, Inner Mongolia, Xinjiang, Liaoning, Henan, Shanxi, Qinghai and Zhejiang, with compensation values ranging from 51.21 × 10^8 to 21.98 × 10^8 USD. Eight provinces have carbon compensation values higher than 10 × 10^8 but lower than 20 × 10^8 USD. The remaining provinces all have carbon compensation values below 10 × 10^8 USD.

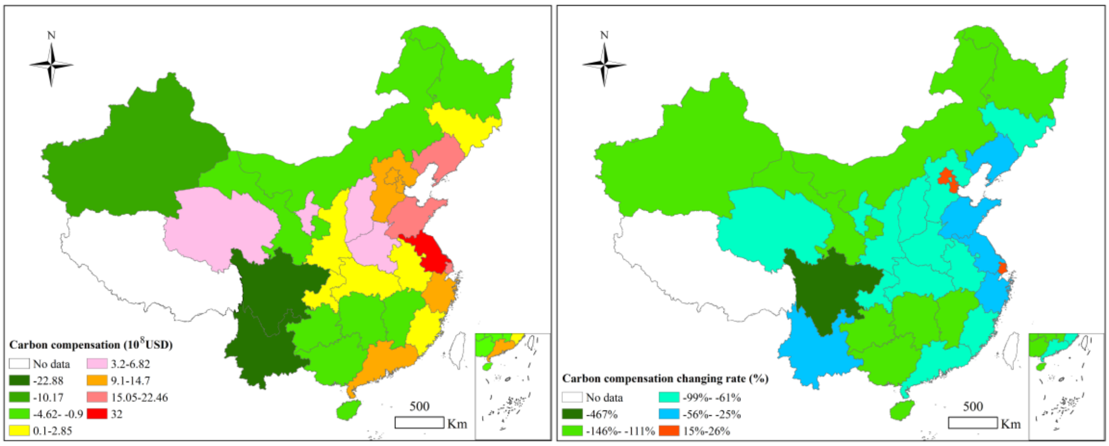


(a) (b)

Fig. 4 (a) Initial carbon compensation values and (b) total compensation values for different provinces in2015

3.3 **Final modified carbon compensation**

After the comprehensive modification, which considered both regional interactions and regional interior differences, the resulting carbon compensation is shown in Fig. 5. The results reveal that the total carbon compensation is approximately 20% of the initial compensation. Fig. 5(a) shows 11 provinces with negative compensation values, who should all receive compensation. Sichuan and Yunnan should receive the highest amount (both -22.88×10^8 USD), and Xinjiang should receive the third-highest amount (-10.16×10^8 USD). Heilongjiang, Inner Mongolia, Hunan and Guangxi should follow, with values varying between -4.63×10^8 and -2.49×10^8 USD. The other four provinces (Guizhou, Jiangxi, Gansu, and Hainan) have carbon compensation values close to 1×10^8 USD. Spatially, the provinces that should receive final modified carbon compensation are mainly located in the south and north of China; the remaining 19 provinces that should pay for compensation are typically concentrated in East and Central China. Jiangsu should pay the highest amount of carbon compensation at 31.99×10^8 USD. Shandong and Shanghai exhibit the second- and third-highest compensation amounts of 22.46×10^8 and 18.93×10^8 USD, respectively. Liaoning, Hebei, Tianjin, Beijing, and Zhejiang also have high compensation values above 10×10^8 USD.



(a) (b)

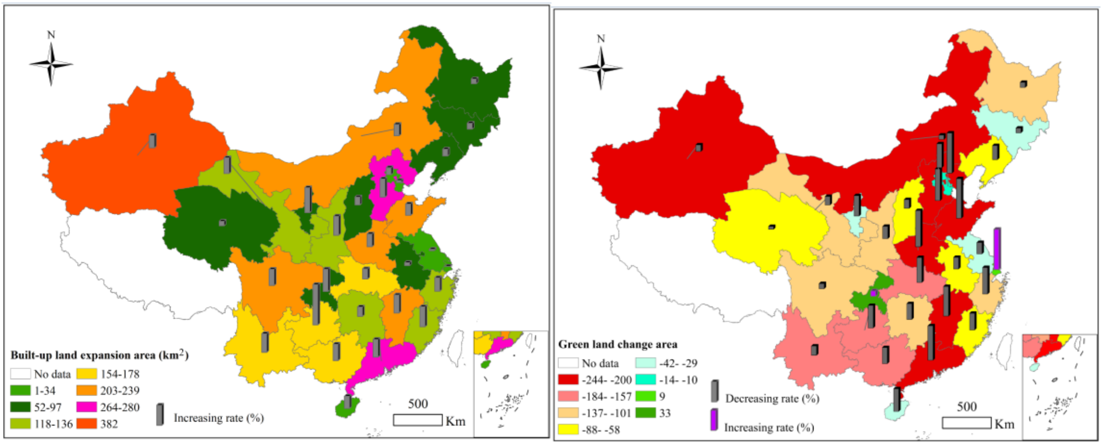
Fig. 5 (a) Final modified carbon compensation for different provinces (10^8 USD) and (b) the percentage change compared with the initial carbon compensation (%)

Fig. 5(b) shows the percentage change compared with the initial carbon compensation as shown in Fig. 4(b). The three provinces of Beijing, Tianjin and Shanghai have had their carbon compensation increased, but the percentages are not high, with Beijing at 26.06% and Tianjin and Shanghai at 19.37% and 15.29%, respectively. The other provinces all exhibited a decrease with much higher percentage values. Sichuan had the highest decrease rate of −467%. Nine provinces, which are located mainly in the south and north, had decrease rates of between −146% and −111%. The remaining provinces had decrease rates of between −99% and −25%.

3.4 **The influence of land-use changes on carbon compensation**

In 2015, all the provinces had their built-up land area increased, with the increased area reaching 3,960 km^2 for China a whole (Fig. 6 (a)). Xinjiang had the highest increase of 382 km^2. For the other provinces, the increases were all below 300 km^2. Guangdong, Hebei, Shandong, Sichuan, Henan, Inner Mongolia and Jiangxi followed, with areas decreased from 280 to 203 km^2. The increase in built-up land is affected significantly by regional areas; for example, Beijing, Tianjin and Shanghai have the lowest area increases. In terms of increase rates, Guizhou, Ningxia and

Chongqing are the only three provinces with rates higher than 1%. Guizhou was particularly high at 1.88%. Fujian, Shaanxi, Yunnan, Hebei, Jiangxi and Guangdong also had high increase rates above 0.8%. Shanghai and Jiangsu had the lowest values of 0.01% and 0.06%, respectively. The decrease in vegetated land corresponds well with the increase in built-up land (Fig. 6(b)). Guangdong, Hebei, Henan, Xinjiang, Jiangxi, Shandong and Inner Mongolia all exhibited decreases in vegetated land area of more than 200 km^2. Beijing and Tianjin had the lowest decreases in vegetated land area of 14 and 11km^2, respectively. Additionally, Shanghai and Chongqing exhibited an increase in vegetated land area. Regarding the decrease rate, the values were higher for provinces in the east, especially for coastal regions, while the provinces in the west had lower values.



(a) (b)

Fig. 6 (a) Built-up land expansion (km^2) and (b) the changes in vegetated land area (km^2) for different provinces in 2015

Table 1 shows that the change in land-use type in all provinces led to increased carbon emissions. Land-use change in Shanghai generated the highest carbon emissions increase per unit area (10500 t/km^2), while Beijing, Shanxi, Tianjin and Hebei also exhibited high increases (between 7828 and 6559 t/km^2), indicating the high intensity of carbon emissions in these regions. Qinghai exhibited the lowest increase of just 432 t/km^2. Generally, increases have been higher in big cities and provinces in Central and East China, while lower values are found in the northwest and Yunnan. In 2015, the land-use type change caused a 3.74 × 10^8 USD increase in initial carbon compensation, which is approximately 0.7% of the total initial carbon compensation. Hebei had the highest increase of 0.47×10^8 USD, followed by Guangdong, Shandong, Guizhou and Sichuan, with increases of between 0.36 × 10^8 and 0.2 × 10^8 USD. Shanghai, Qinghai, and Yunnan had the lowest increases. Regarding the modified carbon compensation, land use-type change in 2015 caused the total compensation amount to increase by 0.13 × 10^8 USD. The top two provinces that should pay for carbon compensation are Hebei and Guangdong (0.14 × 10^8 and 0.1 × 10^8 USD, respectively). Zhejiang, Fujian and Shandong should also pay for high carbon compensation (between 0.09 × 10^8 and 0.08 × 10^8 USD). In total, 13 provinces should receive compensation, with Inner Mongolia and Sichuan having the highest levels (0.14 × 10^8 and 0.13 × 10^8 USD, respectively).

Table 1 Carbon emissions density changes, initial carbon compensation and modified carbon compensation variations (10^4 USD) caused by land-use type changes

Provinces	Carbon density	Initial compensation	Modified compensation	Provinces	Carbon density	Initial compensation	Modified compensation

	changes (t/km²)	(10^4 USD)	(10^4 USD)		changes (t/km²)	(10^4 USD)	(10^4 USD)
Beijing	7828	298	296	Hubei	2574	1200	-20
Tianjin	6841	124	121	Hunan	2520	932	-326
Hebei	6559	4710	1368	Guangdong	4715	3591	1010
Shanxi	6857	982	126	Guangxi	3110	1303	5
Inner Mongolia	2498	1441	-1411	Hainan	2338	208	76
Liaoning	5180	1174	318	Chongqing	4607	1220	533
Jilin	2529	358	-134	Sichuan	3432	2041	-987
Heilongjiang	1642	396	-675	Guizhou	5557	2701	647
Shanghai	10500	19	-3	Yunnan	1051	86	-620
Jiangsu	3692	341	-572	Shaanxi	4572	1476	305
Zhejiang	5069	1756	934	Gansu	2287	788	-116
Anhui	2078	317	-259	Qinghai	432	80	-179
Fujian	4983	1717	873	Ningxia	5404	862	379
Jiangxi	2233	1235	149	Xinjiang	1215	1262	-1352
Shandong	4406	2869	775	China	3119	37350	1298
Henan	3171	1863	34				

4. Discussion

Carbon compensation values are determined by carbon sinks, carbon emissions and the per-unit carbon price. For the use of carbon sinks in carbon compensation, previous studies have typically used the mean carbon sink values of different land-use types in certain regions or empirical data from other studies as the basic data. However, they have ignored the graphical and time-point matching between the quoted carbon sink values and the applicability for the study area; since there always exists obvious spatial heterogeneity for carbon sink/source capacities even within areas of the same land-use type. Additionally, the concept of carbon sink capacity has been used inconsistently, for example, using NEP as the carbon sink capacity for woodland and grassland but vegetation carbon storage as the carbon sink for agricultural land (Wan et al., 2020; Yang et al., 2019). Thus, such an evaluation is unrefined and may cause some bias in carbon compensation. In this study, NEP is used as the terrestrial carbon sink/source capacity, which will help reduce the bias and can support the carbon deficit check on the grid scale.

Our examination of the carbon deficit at the grid scale is the first attempt to show carbon compensation spatially in high resolution. The calculation of anthropogenic carbon emissions has a mature accounting system and method, and the total amounts derived from DEGAR and our domestic calculation results are very close. In addition, we performed a modification for each province for the EDGAR grid product based on our calculation, which further improved the accuracy. Accordingly, the accuracy of the basic data for carbon compensation is higher than that in previous studies. We used the market price method for calculating carbon compensation values. The mean carbon emission exchange price in China from 2013 to 2017 was approximately 16.1 USD/t C (Wang et al., 2020), and more recently, it was approximately 24.21 USD/t C, indicating a rapid increase in the mean carbon trade price. However, this is still lower than in the EU, and the economic cost of extra carbon emissions is still relatively low. The carbon price can be affected by many factors, including energy and financial markets, consumption preferences and meteorological and political factors. With policy changes, carbon compensation providers may pay much higher prices in future (Brink et al., 2016; Ji et al., 2018; Pradhan et al., 2017). Based on the abovementioned data, carbon compensation can be achieved at the prefectural level, e.g. the county, township and village level. Overall, carbon compensation can be made more precise in terms of both data accuracy and resolution.

In China, spatial heterogeneity is obvious regarding both natural conditions and the level of socioeconomic development. As the precipitation decreases from the southwest to the northeast, the amount of biomass shows a similar pattern, determining the capacity of terrestrial ecosystem carbon sinks/sources and providing higher-capacity carbon sinks in the south and lower-capacity carbon sinks or even terrestrial ecosystem carbon sources in the northwest (He et al., 2022). Furthermore, the different natural conditions determine population distribution, anthropogenic activities and regional development. The east and south have relatively better natural conditions – they feed a large population and produce a high GDP – although they also generate high carbon emissions. Thus, compensation needs to seriously consider interior-regional differences to provide a sufficiently equitable compensation mechanism. Some studies have considered the difference in carbon efficiencies and believe carbon emissions with high efficiency should be associated with less responsibility for compensation (Wan et al., 2020). However, we think that there may be certain other problems; for example, the carbon efficiency in Beijing is higher than that in other provinces (Zhan, 2021), and besides technological improvements, the structure of industries may play a key role. In addition, a large number of energy-intensive industries have been relocated to other regions, especially in Hebei Province. In this respect, we do not agree with the findings of previous studies. In this study, we used land area, population and economic conditions to modify carbon emissions and compensation values, which we consider to be a more reasonable approach (Yang et al., 2019; Wang et al., 2020). The regional carbon sink is modified by the *ESV* based on the consideration that terrestrial ecosystems can provide other ecological services. By this assumption, regional carbon payments should be increased, and this modification will further improve regional inequity (Chen & Jiang, 2018). Surely, there is still room to consider additional factors and develop more scientific models to provide equitable carbon compensation. At this stage, our study attempts to provide inspiration for future studies.

Another factor that can affect regional inequity but is not considered in carbon compensation studies is regional interaction. Through trade, considerable carbon emissions are transferred between regions and countries (Tan & Lin, 2022; Wang & Yang, 2020), and in China, a regular pattern of developed regions transferring carbon emissions to undeveloped regions exists (Chuai et al., 2021). The current domestic pattern is determined by various factors, such as the physical conditions and development strategies. For example, since the economic reform began in 1978, the central government has given national investments and preferential policies to support the development of some coastal regions, which have also benefited from richness in local physical resources and convenient transportation; these regions were thus prioritised regarding development and achieved a high economic level. Meanwhile, to obtain economic profits, the less-developed inland regions began to provide a considerable amount of resources or certain industrial products for the developed regions. In this way, indirect carbon emissions were generated. To alleviate this inequity, this study integrated the MRIO model with the carbon compensation modification model to help create more equitable lateral compensation.

The final lateral compensation determined in our study is consistent with previous studies in that it suggests that the provinces that should receive carbon compensation are located mainly in underdeveloped regions, particularly in the northwest and southwest, while those that should pay carbon compensation costs are concentrated mainly in developed regions in Central and East China (Miao et al., 2019; Yang et al., 2019). There is also some bias. For example, in a previous study, the results showed that certain developed regions, such as Guangdong (Wan et al., 2020), should also receive carbon compensation. However, because our study considers interregional interactions, we think our results may be more reasonable. These results are conducive to both carbon reduction and harmonious development. Since developed regions usually have high carbon emission levels, the proposed economic payment will force them to control their carbon emissions. Payments to undeveloped regions can, to some extent, help to eliminate economic difficulties, and the compensation may also help to strengthen fragile ecological environmental protection or carbon emissions reduction.

Land-use changes, especially for built-up areas occupying vegetated land, are more frequent in developed regions in the east (Deng & Li, 2016). In our study, this regularity may not be obvious since a change of only one year is considered. Due to high land capacity, the per-unit land-use transfer in the east will cause much higher carbon emissions. This is determined not only by the high carbon emissions intensity of built-up land but also by the loss of vegetated land, which will result in the loss of a considerable amount of carbon from the terrestrial ecosystem (Zhang et al., 2015); thus, strict land-use control is needed. In the western part of China, since ecological environment is very fragile, and land degradation frequently occurs (Kang et al., 2021), the protection of vegetated land and ecological restoration is needed and should be strengthened as this can not only increase carbon sinks but also improve the ecological environment.

This study has some limitations. First, for data limitation and matching, we selected the year 2015 for our case study, which may not accurately reflect the most recent situation. If all data become available, this could be updated. Second, we used the average carbon emissions trade value of China, which may not be entirely appropriate for every province, and the price of carbon sinks also may not be appropriate in terms of carbon emissions. Third, we made grid-scale carbon compensations for the initial carbon deficit but not for the final modification. One reason for this is the accessibility limitations of the grid data, while another is the applicability of the model at the grid scale. This may be a valuable direction for guiding innovative studies in the future. Fourth, due to the source (survey) data, the MRIO model's sector detail, the regional coverage and the number of environmental extensions, the MRIO analysis also contained some uncertainties (Lin et al., 2014).

4. Policy implications

Some policy implications are here proposed according to the findings. First, the government should keep increasing the establishment of field observations to reduce the uncertainties in terrestrial ecosystem carbon sink/source capacity evaluation. Second, strategies should be devised to support the research on anthropogenic carbon emissions checks in high resolution, addressing both spatial and time intervals, which will assist in providing more accurate carbon compensation. Third, the central government should strengthen its macro-control, create and improve laws and regulations to coordinate interregional carbon compensation (e.g. the compensation mechanism), institutionalise and standardise carbon compensation, establish pilot studies, and make gradual improvements to and disseminate carbon compensation to the whole country. Fourth, diversified forms of compensation should be encouraged, for example, allowing carbon compensation payers to also provide technological or strategic support to compensation receivers to help improve carbon efficiency and decouple local economic development from carbon emissions. Aside from government-charged compensation, other forms should also be encouraged, such as individual carbon compensation in the form of tree planting, household carbon reduction encouragement and extra emissions punishment, carbon compensation through the integration of land trade, and land carbon level evaluation and management. Finally, auxiliary measures should be formulated, for example, financial regulations should be implemented via carbon funds, carbon taxes, and low-carbon loans.

5. Conclusions

According to the analysis performed in this study, the following conclusions can be drawn. Currently, China faces a great gap in its journey to achieve carbon neutrality. Lateral carbon compensation is an effective way to achieve both carbon emissions reduction and harmonious regional development. Wide regional inequities exist across China, and carbon compensation needs to seriously consider the inequity caused by both regional interactions and interior differences. The developed regions, which are mainly located in China's eastern and coastal areas, usually benefit from economic profits but also have a high carbon deficit, so they should pay for carbon compensation. The areas that should receive carbon compensation are usually the less-developed regions, which are mainly located in the south and north of China. Built-up land occupying ecological land is the main type of land-use change in China and can increase carbon compensation. The protection of ecological land and control of the expansion of built-up land are the main land-use management tasks. The central government should strengthen its macro-control and make and improve related laws and regulations to coordinate interregional carbon compensation, while diversified forms of compensation should also be encouraged to promote the reduction of carbon emissions and help reduce the inequity in regional development.

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