

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

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

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

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

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

86 With rapid economic and social development, regional interactions have become more frequent
87 and more tightly linked. The multiregional input–output (MRIO) model is a widely used method to
88 examine the economy and perform the associated environmental assessment among regions and

89 sectors, and many researchers have used it to analyse embodied carbon emissions between regions
90 and the resulting regional inequalities (Li & Li, 2022; Pan et al., 2018; Tian et al., 2020; Tramberend
91 et al., 2019). Generally, previous studies have focused mainly on anthropogenic carbon emissions,
92 and some have also included terrestrial carbon; for example, Chuai et al. (2021) formulated the
93 theory that built-up land expansion in China is significantly affected by economic development and
94 examined external regions' carbon storage loss as embodied in domestic trade. While, these are
95 seldom used in carbon compensation research, if a model considers both regional interior differences
96 and regional carbon interactions, the accuracy of regional inequity will be improved.

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

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

115 **2. Data and methodology**

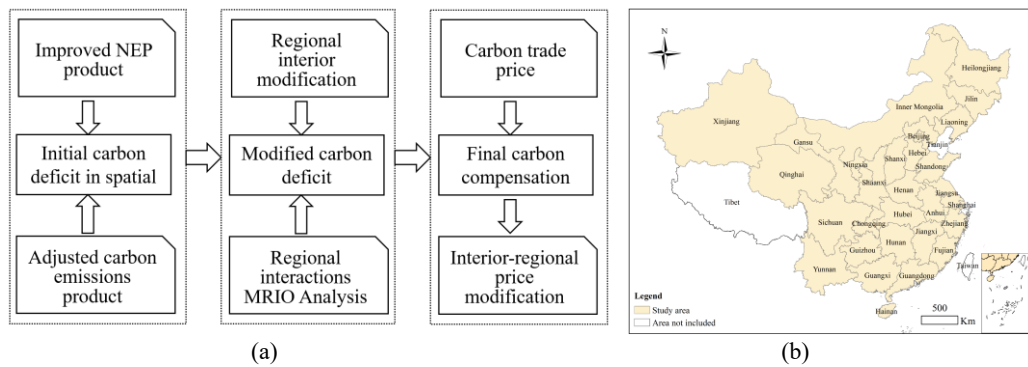
116 **2.1 Data**

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

132 farmland and grassland), built-up land and unused land. Other economic and social data were
133 obtained from the *China Statistical Yearbook*.

134 2.2 Research framework

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



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155
156 Fig. 1 (a) The research framework and (b) the distribution of the provinces

157 2.3 Analysis

158 2.3.1 Calculation of direct anthropogenic carbon emissions

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

162 2.3.2 Carbon emissions embodied in domestic trade

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

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

$$169 \quad AT + F = T \quad (1)$$

$$170 \quad T = (I - A)^{-1}F. \quad (2)$$

171 where A is the direct consumption coefficients matrix, T refers to the total output matrix, and
 172 F is the final use matrix. I is an $n \times n$ identity matrix, and $(I - A)^{-1}$ is the Leontief inverse
 173 matrix. The carbon emissions embodied in domestic trade among provinces were calculated by Eq.
 174 (3):

$$175 \quad C = l(I - A)^{-1}F. \quad (3)$$

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

179 **2.3.3 Modified carbon deficit and compensation**

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

$$182 \quad C_{ei} = C_i + (C_{i-import} - C_{i-export}). \quad (4)$$

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

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

$$189 \quad C_{di} = C_{ei} - C_{si} \quad (5)$$

$$190 \quad ACC_{di} = C_{di} \times P_c \quad (6)$$

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

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

$$198 \quad C_{rdi} = C_{ei} - C_{si} \times \alpha_i \quad (7)$$

$$199 \quad \partial_i = 1 + (ESV_i - \overline{ESV}) / \overline{ESV} \quad (8)$$

200 where C_{rdi} is the first modified carbon deficit of region i , and α_i is the regional modified

201 coefficient carbon sink. The terms ESV_i and \overline{ESV} are the ESV for region i and the mean value
 202 for all regions, respectively. We produced the ESV across China using the method proposed by Xie
 203 et al. (2017).

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

$$205 \quad \eta_i = \frac{P_i \times L_i}{\sum P_i \times L} \quad (9)$$

$$206 \quad C_i = C_{rdi} - \eta_i \sum C_{rdi} \quad (10)$$

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

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

$$212 \quad ACC_i = C_i \times P_c \times \theta_i \quad (11)$$

$$213 \quad \theta_i = G_i / G_T (1 + ae^{-bt}) \quad (12)$$

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

218 **2.3.4 Carbon compensation variations from land-use change**

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

$$221 \quad C_{i-change} = \sum_{j=1}^n L_{j-begin} \times D_j - \sum_{j=1}^n L_{j-end} \times D_j \quad (13)$$

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

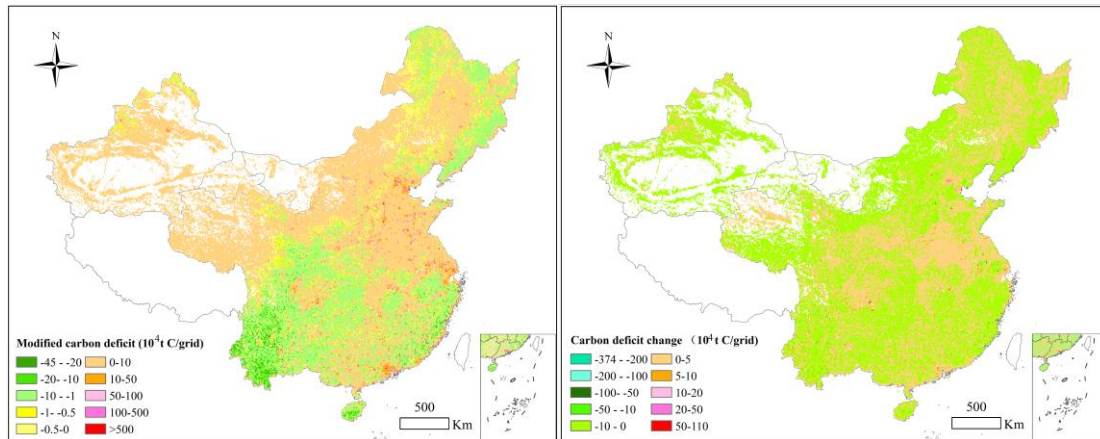
225 Then, $C_{i-change}$ can be used to replace C_{di} , the initial carbon compensation without modification
 226 can be calculated by Eq. (6), and $C_{i-change}$ can be used to replace C_{rdi} . The final carbon
 227 compensation after modification can be calculated by Eqs. (10)–(12).

228 **3. Results**

229 **3.1 Modified carbon deficit and changes**

230 The modified carbon deficit was calculated using Eq. (10). Fig. 2(a) shows that, after the
 231 modification, the entire carbon deficit reached 17.34×10^8 t C in the year 2015, representing a

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



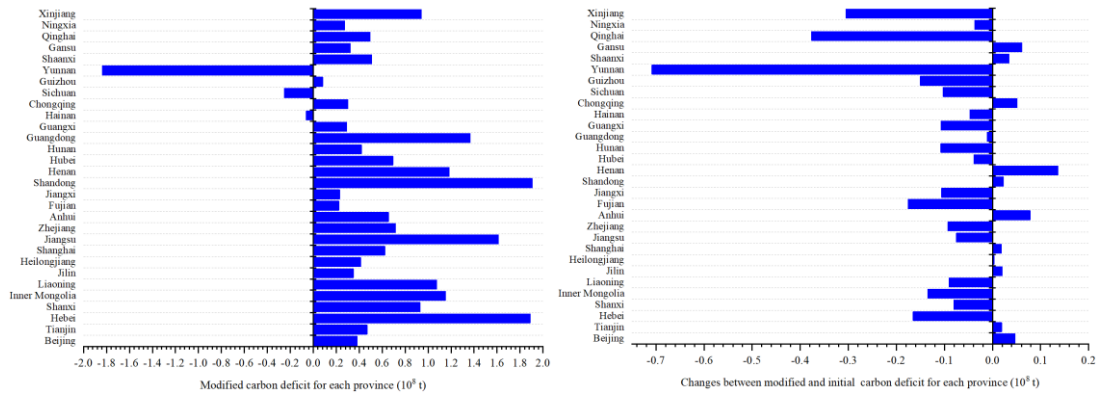
(a)

(b)

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

244 Fig. 3 shows that the three provinces of Yunnan, Sichuan and Hainan have negative carbon
 245 deficits. This means they have more carbon sinks than carbon sources, especially Yunnan ($-1.8 \times$
 246 10^8 t C). Yunnan also had the highest carbon deficit decrease compared with its initial carbon deficit
 247 (-0.78×10^8 t C). For provinces with positive carbon deficits, Shandong has the highest ($1.91 \times$
 248 10^8 t C), followed by Hebei, Jiangsu, Guangdong, Henan, Inner Mongolia and Liaoning, with values
 249 varying between 1.9×10^8 and 1.08×10^8 t C. The other provinces have positive carbon deficits
 250 lower than 1×10^8 t C. After modification, 19 provinces exhibited a decreases in their carbon
 251 deficits. After Yunnan, the provinces of Qinghai and Xinjiang had the second- and third-highest
 252 decreases. Fujian, Hebei, Guizhou and Inner Mongolia had similar decrease values ranging from
 253 -0.18×10^8 to -0.13×10^8 t C. For the 11 provinces with carbon deficit increases, the increases
 254 were much lower. Henan had the highest increase at 0.14×10^8 t C, while the others were all lower
 255 than 0.1×10^8 t C.

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

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3.2 Initial carbon compensation without modification

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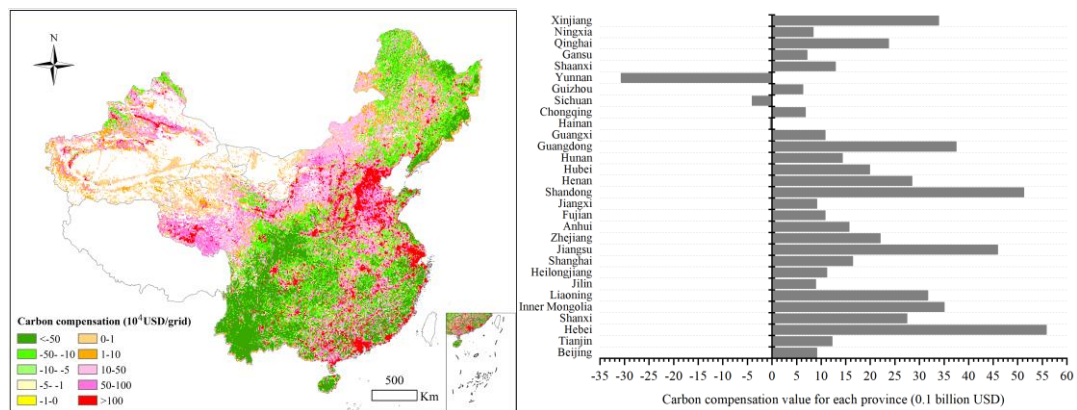
The initial carbon compensation reached 537×10^8 USD. Fig. 4(a) shows the differences in carbon compensation within a $0.1^\circ \times 0.1^\circ$ grid. The negative-value area indicates the areas that should receive carbon compensation. They are intensively distributed in the southwest, with large areas 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.

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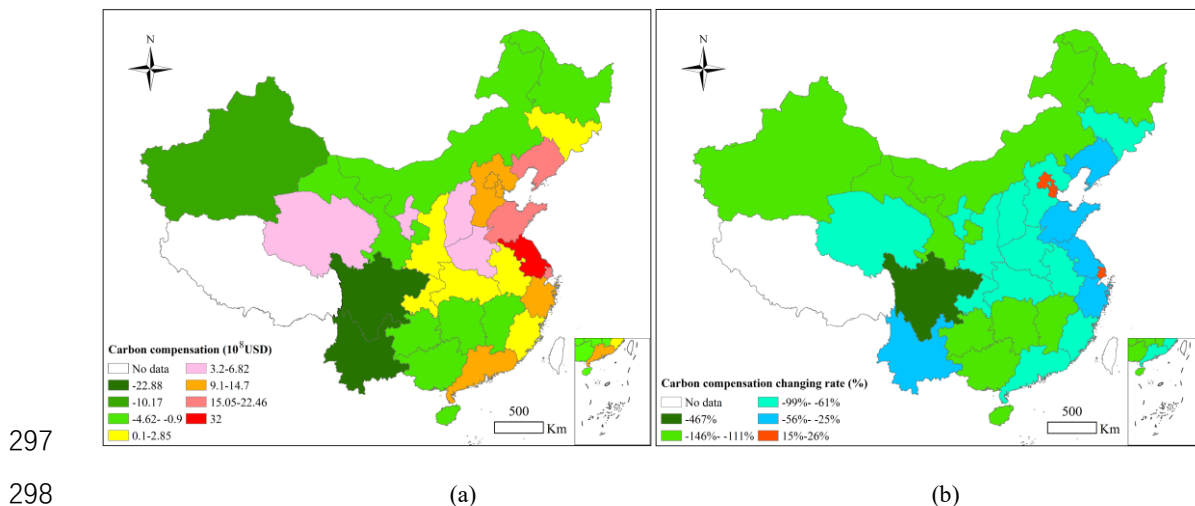
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(a) (b)
Fig. 4 (a) Initial carbon compensation values and (b) total compensation values for different provinces in 2015

282 **3.3 Final modified carbon compensation**

283 After the comprehensive modification, which considered both regional interactions and regional
284 interior differences, the resulting carbon compensation is shown in Fig. 5. The results reveal that the
285 total carbon compensation is approximately 20% of the initial compensation. Fig. 5(a) shows 11
286 provinces with negative compensation values, who should all receive compensation. Sichuan and
287 Yunnan should receive the highest amount (both -22.88×10^8 USD), and Xinjiang should receive
288 the third-highest amount (-10.16×10^8 USD). Heilongjiang, Inner Mongolia, Hunan and Guangxi
289 should follow, with values varying between -4.63×10^8 and -2.49×10^8 USD. The other four
290 provinces (Guizhou, Jiangxi, Gansu, and Hainan) have carbon compensation values close to $1 \times$
291 10^8 USD. Spatially, the provinces that should receive final modified carbon compensation are
292 mainly located in the south and north of China; the remaining 19 provinces that should pay for
293 compensation are typically concentrated in East and Central China. Jiangsu should pay the highest
294 amount of carbon compensation at 31.99×10^8 USD. Shandong and Shanghai exhibit the second-
295 and third-highest compensation amounts of 22.46×10^8 and 18.93×10^8 USD, respectively. Liaoning,
296 Hebei, Tianjin, Beijing, and Zhejiang also have high compensation values above 10×10^8 USD.



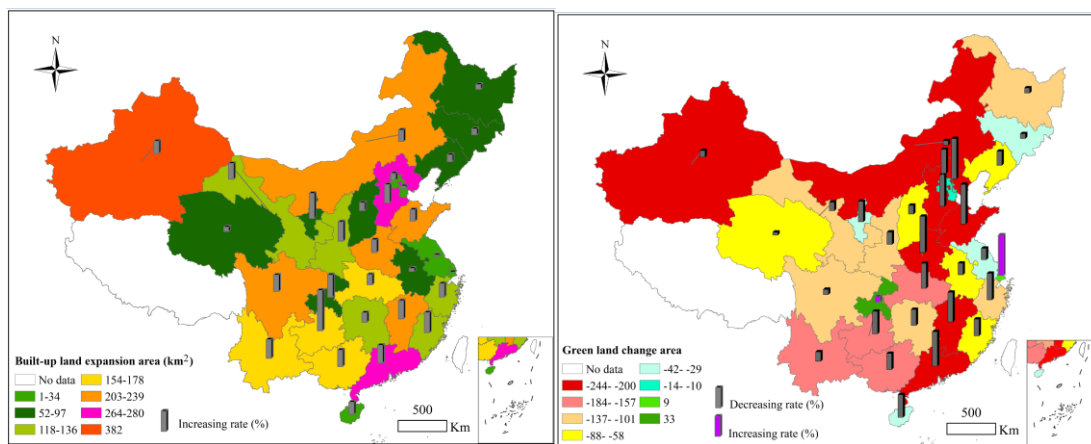
299 Fig. 5 (a) Final modified carbon compensation for different provinces (10^8 USD) and (b) the percentage change
300 compared with the initial carbon compensation (%)

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

308 **3.4 The influence of land-use changes on carbon compensation**

309 In 2015, all the provinces had their built-up land area increased, with the increased area reaching
310 $3,960 \text{ km}^2$ for China a whole (Fig. 6 (a)). Xinjiang had the highest increase of 382 km^2 . For the
311 other provinces, the increases were all below 300 km^2 . Guangdong, Hebei, Shandong, Sichuan,
312 Henan, Inner Mongolia and Jiangxi followed, with areas decreased from 280 to 203 km^2 . The
313 increase in built-up land is affected significantly by regional areas; for example, Beijing, Tianjin
314 and Shanghai have the lowest area increases. In terms of increase rates, Guizhou, Ningxia and

315 Chongqing are the only three provinces with rates higher than 1%. Guizhou was particularly high
 316 at 1.88%. Fujian, Shaanxi, Yunnan, Hebei, Jiangxi and Guangdong also had high increase rates
 317 above 0.8%. Shanghai and Jiangsu had the lowest values of 0.01% and 0.06%, respectively. The
 318 decrease in vegetated land corresponds well with the increase in built-up land (Fig. 6(b)).
 319 Guangdong, Hebei, Henan, Xinjiang, Jiangxi, Shandong and Inner Mongolia all exhibited decreases
 320 in vegetated land area of more than 200 km². Beijing and Tianjin had the lowest decreases in
 321 vegetated land area of 14 and 11km², respectively. Additionally, Shanghai and Chongqing exhibited
 322 an increase in vegetated land area. Regarding the decrease rate, the values were higher for provinces
 323 in the east, especially for coastal regions, while the provinces in the west had lower values.



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(a)

(b)

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Fig. 6 (a) Built-up land expansion (km²) and (b) the changes in vegetated land area (km²) for different provinces in 2015

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328 Table 1 shows that the change in land-use type in all provinces led to increased carbon emissions.
 329 Land-use change in Shanghai generated the highest carbon emissions increase per unit area (10500
 330 t/km²), while Beijing, Shanxi, Tianjin and Hebei also exhibited high increases (between 7828 and
 331 6559 t/km²), indicating the high intensity of carbon emissions in these regions. Qinghai exhibited
 332 the lowest increase of just 432 t/km². Generally, increases have been higher in big cities and
 333 provinces in Central and East China, while lower values are found in the northwest and Yunnan. In
 334 2015, the land-use type change caused a 3.74×10^8 USD increase in initial carbon compensation,
 335 which is approximately 0.7% of the total initial carbon compensation. Hebei had the highest increase
 336 of 0.47×10^8 USD, followed by Guangdong, Shandong, Guizhou and Sichuan, with increases of
 337 between 0.36×10^8 and 0.2×10^8 USD. Shanghai, Qinghai, and Yunnan had the lowest increases.
 338 Regarding the modified carbon compensation, land use-type change in 2015 caused the total
 339 compensation amount to increase by 0.13×10^8 USD. The top two provinces that should pay for
 340 carbon compensation are Hebei and Guangdong (0.14×10^8 and 0.1×10^8 USD, respectively).
 341 Zhejiang, Fujian and Shandong should also pay for high carbon compensation (between 0.09×10^8
 342 and 0.08×10^8 USD). In total, 13 provinces should receive compensation, with Inner Mongolia
 343 and Sichuan having the highest levels (0.14×10^8 and 0.13×10^8 USD, respectively).

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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
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	changes (t/km ²)	(10 ⁴ USD)	(10 ⁴ USD)		changes (t/km ²)	(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				

346 **4. Discussion**

347 Carbon compensation values are determined by carbon sinks, carbon emissions and the per-unit
348 carbon price. For the use of carbon sinks in carbon compensation, previous studies have typically
349 used the mean carbon sink values of different land-use types in certain regions or empirical data
350 from other studies as the basic data. However, they have ignored the graphical and time-point
351 matching between the quoted carbon sink values and the applicability for the study area; since there
352 always exists obvious spatial heterogeneity for carbon sink/source capacities even within areas of
353 the same land-use type. Additionally, the concept of carbon sink capacity has been used
354 inconsistently, for example, using NEP as the carbon sink capacity for woodland and grassland but
355 vegetation carbon storage as the carbon sink for agricultural land (Wan et al., 2020; Yang et al.,
356 2019). Thus, such an evaluation is unrefined and may cause some bias in carbon compensation. In
357 this study, NEP is used as the terrestrial carbon sink/source capacity, which will help reduce the bias
358 and can support the carbon deficit check on the grid scale.

359 Our examination of the carbon deficit at the grid scale is the first attempt to show carbon
360 compensation spatially in high resolution. The calculation of anthropogenic carbon emissions has a
361 mature accounting system and method, and the total amounts derived from DEGAR and our
362 domestic calculation results are very close. In addition, we performed a modification for each
363 province for the EDGAR grid product based on our calculation, which further improved the
364 accuracy. Accordingly, the accuracy of the basic data for carbon compensation is higher than that in
365 previous studies. We used the market price method for calculating carbon compensation values. The
366 mean carbon emission exchange price in China from 2013 to 2017 was approximately 16.1 USD/t
367 C (Wang et al., 2020), and more recently, it was approximately 24.21 USD/t C, indicating a rapid
368 increase in the mean carbon trade price. However, this is still lower than in the EU, and the economic
369 cost of extra carbon emissions is still relatively low. The carbon price can be affected by many
370 factors, including energy and financial markets, consumption preferences and meteorological and

371 political factors. With policy changes, carbon compensation providers may pay much higher prices
372 in future (Brink et al., 2016; Ji et al., 2018; Pradhan et al., 2017). Based on the abovementioned data,
373 carbon compensation can be achieved at the prefectural level, e.g. the county, township and village
374 level. Overall, carbon compensation can be made more precise in terms of both data accuracy and
375 resolution.

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

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

414 The final lateral compensation determined in our study is consistent with previous studies in that

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

427 Land-use changes, especially for built-up areas occupying vegetated land, are more frequent in
428 developed regions in the east (Deng & Li, 2016). In our study, this regularity may not be obvious
429 since a change of only one year is considered. Due to high land capacity, the per-unit land-use
430 transfer in the east will cause much higher carbon emissions. This is determined not only by the
431 high carbon emissions intensity of built-up land but also by the loss of vegetated land, which will
432 result in the loss of a considerable amount of carbon from the terrestrial ecosystem (Zhang et al.,
433 2015); thus, strict land-use control is needed. In the western part of China, since ecological
434 environment is very fragile, and land degradation frequently occurs (Kang et al., 2021), the
435 protection of vegetated land and ecological restoration is needed and should be strengthened as this
436 can not only increase carbon sinks but also improve the ecological environment.

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

447 **4. Policy implications**

448 Some policy implications are here proposed according to the findings. First, the government should
449 keep increasing the establishment of field observations to reduce the uncertainties in terrestrial
450 ecosystem carbon sink/source capacity evaluation. Second, strategies should be devised to support
451 the research on anthropogenic carbon emissions checks in high resolution, addressing both spatial
452 and time intervals, which will assist in providing more accurate carbon compensation. Third, the
453 central government should strengthen its macro-control, create and improve laws and regulations to
454 coordinate interregional carbon compensation (e.g. the compensation mechanism), institutionalise
455 and standardise carbon compensation, establish pilot studies, and make gradual improvements to
456 and disseminate carbon compensation to the whole country. Fourth, diversified forms of
457 compensation should be encouraged, for example, allowing carbon compensation payers to also

458 provide technological or strategic support to compensation receivers to help improve carbon
459 efficiency and decouple local economic development from carbon emissions. Aside from
460 government-charged compensation, other forms should also be encouraged, such as individual
461 carbon compensation in the form of tree planting, household carbon reduction encouragement and
462 extra emissions punishment, carbon compensation through the integration of land trade, and land
463 carbon level evaluation and management. Finally, auxiliary measures should be formulated, for
464 example, financial regulations should be implemented via carbon funds, carbon taxes, and low-
465 carbon loans.

466 **5. Conclusions**

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

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