Journal of Environmental Management 392 (2025) 126617

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Gridded forest carbon sinks and carbon removal projections from 2020 to 2060 in China

Min Jia [a,1], Shu Ye [b,c,d,1], Li Zhang [e,*], Pengcheng Wu [f], Ni Huang [g], Yanfeng Bai [h], Jianhui Ruan [i], Zhuoming He [j], Mingyu Li [k,**], Shaoyuan Chen [l], Li Wang [g], Bofeng Cai [m,***], Jinnan Wang [m]

[a] School of Economics and Management, North China University of Technology, Beijing, 100144, China
[b] Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, 510650, China
[c] South China National Botanical Garden, Guangzhou, 510650, China
[d] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100049, China
[e] School of the Environment and Safety Engineering, Jiangsu University, Zhenjiang, 212013, China
[f] School of Public Health, Sun Yat-sen University, Guangzhou, 510080, China
[g] State Key Laboratory of Remote Sensing and Digital Earth, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, 100094, China
[h] Research Institute of Forestry, Chinese Academy of Forestry, Beijing, 100091, China
[i] School of Economics and Management, China University of Geosciences, Beijing, 100083, China
[j] School of Economics and Management, University of Chinese Academy of Sciences, Beijing, 100190, China
[k] School of Environment, Tsinghua University, Beijing, 100084, China
[l] Ino-French Institute for Earth System Science, College of Urban and Environmental Sciences, Peking University, Beijing, 100080, China
[m] Center for Carbon Neutrality, Chinese Academy of Environmental Planning, Beijing, 100043, China

ARTICLE INFO

Handling Editor: Dr. Lixiao Zhang

Keywords:
Forest carbon sinks
CO_2 emissions
Emission pathway
Offset effect
Carbon neutrality

ABSTRACT

Clarifying the forest carbon sink in the future and detailing its offsetting effect on CO_2 emissions are of great significance to China's Dual-Carbon strategy. This study has innovatively developed a comprehensive analysis to simultaneously consider grid-specific (10 km × 10 km), yearly, and nationwide forest carbon sink and CO_2 emissions to further explore the carbon offset effects of China's forest resources from 2020 to 2060 under scenario combinations integrated by Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). We find that China is projected to achieve carbon peaks around 2025, 2030, and 2040 and China's forest carbon sink is anticipated to peak around 2025 under their associated scenarios. Especially, there are vast heterogeneities in forest carbon sink and CO_2 emissions across provinces from 2020 to 2060. For instance, Shandong is one of the main CO_2 emission contributors whereas Yunnan contributes to a large proportion of forest carbon sinks. Furthermore, the offsetting ratio of forest carbon sinks to CO_2 emissions exhibits an optimistic overall growth trend, ranging from 4.43 % to 62.87 % between 2020 and 2060. Nevertheless, regional uneven distribution features between the CO_2 emissions and forest carbon sinks pose higher requirements for implementing efficient emission reduction measures in high-emission regions. Our results emphasize the effectiveness of forest carbon sinks on CO_2 emission offsets and the necessity of spatial differentiation policies, thereby facilitating future policymaking.

1. Introduction

Facing the urgency of climate change, the Chinese government has ambitiously proposed the goals of achieving a carbon peak before 2030 and carbon neutrality by 2060 (named the Dual-Carbon goals) (State Council of the People's Republic of China. Opinions on Fully), i.e.,

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: zhangli_1122@outlook.com (L. Zhang), limingyu19@mails.tsinghua.edu.cn (M. Li), caibf@caep.org.cn (B. Cai).
[1] Min Jia and Shu Ye contributed to this work equally and should be considered as co-first authors.

https://doi.org/10.1016/j.jenvman.2025.126617
Received 18 March 2025; Received in revised form 26 June 2025; Accepted 15 July 2025
Available online 21 July 2025
0301-4797/

aiming to achieve net-zero emissions before 2060 by simultaneously balancing carbon emissions from anthropogenic sources and carbon offsets from carbon removal measures. In this way, China has primarily focused on two types of control strategies: controlling carbon emissions from fossil energy combustion (State Council of the People's Republic of China, 2025) and other emission sources and developing carbon removal technologies like ecosystem carbon sinks (State Council of the People's Republic of China, 2025). Particularly, forests significantly dominate terrestrial ecosystem carbon sinks, contributing nearly 70 % of the carbon absorption (Peng et al., 2023). Given that, China has set development targets of achieving forest coverage of 25 % and forest stocks of 19 billion m^3 as of 2030 to ensure the accomplishment of the Dual-Carbon goals (State Council of the People's Republic of China. Opinions on Fully). Therefore, evaluating the future forest carbon sink and detailing its spatiotemporal characteristics in China is of great importance.

Remarkably, as the other core influence element to achieve Dual-Carbon goals, carbon emissions from anthropogenic activities act as primary accelerators of global climate change and should be precisely calculated and predicted. In particular, CO_2 emissions from fossil energy combustion and industrial processes in China continuously increased from 2010 to 2022, with mean yearly increases of 2.35 % (Slotta) and representing approximately 30 % of global CO_2 emissions (Tiseo; International Energy Agency, 1900–2022). To effectively control CO_2 emissions and promote the realization of the Dual-Carbon goals, China has proposed a series of regulations and control measures such as controlling the use of fossil energy and promoting technology upgrades (State Council of the People's Republic of China, 2525). Consequently, CO_2 emission pathways, structure, and patterns would be changed dramatically, and it is of profound significance to quantify and project the CO_2 emission patterns in China. Furthermore, by combining the direct CO_2 emission pathways with the carbon offsets from forests, the development characteristics of carbon peak and neutrality can be effectively depicted, further facilitating associated policy-making.

The spatial heterogeneity of elements in China stresses the importance of performing fine-grained gridded analysis. Due to China's vast land and complicated topography, socioeconomic and geographical elements distribute spatial unevenly, including energy resources, economic development, temperature, etc. These factors are normally influential drivers of carbon sources and sinks (Fernández-Martínez et al., 2019), further resulting in heterogeneous distributions of both. Therefore, high-resolution studies help to anticipate future socio-economic impact, identify reduction hotspots, and promote refined mitigation management (Cheng et al., 2022; Zhang et al., 2023).

Several studies have shown interest in projecting trajectories for forest carbon sinks or CO_2 emissions in China (Shi et al., 2022; Pugh et al., 2019; Ma et al., 2022; Wang et al., 2018; Du et al., 2019; Piao et al., 2007; Cai et al., 2022a, 2022b; Zhang and Deng, 2022; Yu et al., 2021; Ke et al., 2023; Hou and Yin, 2023). However, there is still a lack of dynamic, high-resolution, and nationwide research on the forest carbon sink and its carbon removal effects targeting gridded direct CO_2 emissions. In specific, the existing associated papers were somehow confined to: a certain perspective, such as quantifying carbon sink (Shi et al., 2022; Pugh et al., 2019; Ma et al., 2022; Wang et al., 2018; Du et al., 2019; Piao et al., 2007) (including forest carbon sink (Shi et al., 2022; Pugh et al., 2019; Ma et al., 2022)) or CO_2 emissions (Cai et al., 2022a; Zhang and Deng, 2022; Yu et al., 2021); a low resolution (Zhang and Deng, 2022; Ke et al., 2023; Hou and Yin, 2023; Cai et al., 2022b), such as evaluation at national (Ke et al., 2023; Hou and Yin, 2023), regional (Cai et al., 2022b; Sun et al., 2023), or provincial scale (Lu et al., 2013); and a historical evaluation (Wang et al., 2018; Piao et al., 2007), without long-temporal dynamic estimation simultaneously on both carbon sinks and emissions towards future. Specifically, as for limited studies concerning the forest carbon sinks and their contributions to the absorption of atmospheric CO_2 emissions, only national (Ke et al., 2023; Hou and Yin, 2023) and provincial (Lu et al., 2013) forest carbon sinks and associated mitigation potential analyses were conducted, lacking comprehensive studies with high spatiotemporal resolution. Therefore, this study aims to systematically simulate the national, gridded, and yearly forest carbon sinks and contemporaneous CO_2 emissions from 2020 to 2060 and then further evaluate the carbon offset characteristics of forests and their contribution to the Dual-Carbon goals.

Overall, this study fills in the gap by systematically assessing and projecting the pathways of the grid-specific, yearly, and nationwide forest carbon sinks and CO_2 emissions and the offset effects of forest carbon sinks in China from 2020 to 2060. To the best of our knowledge, the primary contributions of this study can be organized into the following three points: (1) it is an innovative and comprehensive analysis that simultaneously considers gridded forest carbon sink and CO_2 emissions, further exploring the carbon offsetting effects of China's forest resources; (2) this study is conducted on a 10 km × 10 km grid level in China, whereas the other studies were usually performed at the national (Ke et al., 2023; Hou and Yin, 2023), regional (e.g., the Yellow River Basin (Sun et al., 2023)) or provincial scale (Lu et al., 2013); (3) compared to the existing studies, this study explores the long temporal dynamic development paths for both forest carbon sinks and CO_2 emissions in China from 2020 to 2060, which can effectively depict and reflect the realization path of the Dual-Carbon goals (Cai et al., 2022a). Particularly, the spatiotemporal carbon offsetting effects of forests are analyzed.

The remainder of this paper is organized as follows: Section 2 details the projection model for CO_2 emissions and forest carbon sinks, the data sources, and the scenario settings in this work. Section 3 details the spatiotemporal characteristics of CO_2 emissions, forest carbon sinks, and the associated offsetting effects from 2020 to 2060 under various scenarios. Lastly, section 4 concludes the research and highlights the potential directions for future research.

2. Methods

2.1. Prediction of gridded carbon emissions

We apply a calculation approach to obtain gridded carbon source projections by downscaling the national CO_2 emissions for China. The downscaling procedure is a hybrid of two schemes: Contraction and Convergence (C&C) and Carbon Intensity Convergence (CIC). In this way, we manage to reflect both the current emission status quo and future trends toward a more equal emission distribution.

2.1.1. Contraction and convergence (C&C)

The C&C scheme reflects a future leading to equal per capita emissions. Requiring all economies to immediately achieve equal per capita emissions will result in a sudden shift in emissions pathways, posing practical implementation difficulties. Considering that, we follow the design of Bows et al. (2008) (Bows and Anderson, 2008), compromising between the status quo and the ideal of an equitable future. At the target year (t_e), the per capita emission of each grid will be the same, that is, the carbon emission share (χ^P_{i,t_e}) of grid i will be equal to its population share of the national total. Before the target year, the carbon emission share of each grid takes the current level (χ_{i,t_s}) as the starting point (t_s) and the target level (χ^P_{i,t_e}) as the endpoint (t_e) and convergent in a linear form. The carbon emission share provided by the C&C scheme is calculated as follows:

$$\chi^P_{i,t} = \chi_{i,t_s} + \frac{\chi^P_{i,t_e} - \chi_{i,t_s}}{t^P_e - t_s}(t - t_s) \tag{1}$$

$$\chi_{i,t_s} = \frac{E_{i,t_s}}{\sum_{i=1}^{n} E_{i,t_s}} \tag{2}$$

$$\chi_{i,t_e}^{P} = \frac{P(i,t_e)}{\sum_{i=1}^{n} P(i,t_e)} \tag{3}$$

where $\chi_{i,t}^{P}$ refers to the CO_2 emission proportion under C&C scheme for the *i*th grid in year *t*. χ_{i,t_s} is the CO_2 emission proportion for the *i*th grid in current year t_s, calculated from emission E_{i,t_s}.

2.1.2. Carbon intensity convergence (CIC)

The C&C scheme outlines a future reduction trajectory guided by equal emission intensity. At the target year (t_e), the carbon emission intensity of each grid will be the same, that is, the carbon emission share (χ_{i,t_e}^{GDP}) of grid *i* will be equal to its GDP share of the national total. Before the target year, the carbon emission share of each grid takes the current level (χ_{i,t_s}) as the starting point (t_s) and the target level (χ_{i,t_e}^{GDP}) as the end point (t_e), and convergent in a linear form. The carbon emission share provided by the CIC scheme is calculated as follows:

$$\chi_{i,t}^{GDP} = \chi_{i,t_s} + \frac{\chi_{i,t_e}^{GDP} - \chi_{i,t_s}}{t_e - t_s}(t - t_s) \tag{4}$$

$$\chi_{i,t_e}^{GDP} = \frac{GDP(i,t_e)}{\sum_{i=1}^{n} GDP(i,t_e)} \tag{5}$$

where $\chi_{i,t}^{GDP}$ refers to CO_2 emission share under the CIC scheme for *i*th grid in year *t*. χ_{i,t_s} is the CO_2 emission proportion for the *i*th grid in current year t_s, calculated from emission E_{i,t_s}.

The above two schemes result in grid carbon emissions converging towards equal per capita emissions and equal emission intensity, respectively. These two trends cannot be simultaneously achieved and represent two conflicting value tendencies. Former influential allocation studies (Robiou du Pont and Meinshausen, 2018; Pan et al., 2017) include multiple decomposition schemes to reconcile the contradictions. For example, Muller (Müller, 1998) proposed a preference scoring method between the grandfathering scheme and the equal per capita scheme, intuitively combining preferences for the two. Following this idea, we include and weigh the allocation results of the C&C and CIC schemes to balance the two possible futures.

$$E_{i,t} = Q_t \times \left(\alpha \times \chi_{i,t}^{P} + \beta \times \chi_{i,t}^{GDP}\right) \tag{6}$$

where α and β refer to the weight of C&C and CIC schemes in the final results, respectively, and $\alpha + \beta = 1$, which are both set as 0.5 according to related research (Müller, 1998). $E_{i,t}$ refers to the final downscaling results for the grid *i* in year *t*. Q_t is the national CO_2 emissions total for China in year *t*.

2.2. Prediction of gridded carbon sinks

Forests, as the main component of terrestrial ecosystems, not only constitute the largest carbon reservoir in the system but also play a crucial role in mitigating climate change. In this study, the Miami model is employed to simulate the distribution of future forest net primary production (NPP) in China, mainly considering the carbon sinks from above- and belowground biomass, without the changes in soil. Carbon sink (C_{sink}) is calculated by land use type and terrestrial ecosystem carbon allocation patterns.

Miami model is the first global-scale empirical model of terrestrial net primary productivity (NPP, g biomass/m^2), and its simplicity and relative accuracy have led to its wide use (Zaks et al., 2007). NPP is limited by either temperature (T) or precipitation (P). Therefore, the model estimates NPP as a function of mean annual temperature (MAT, °C) and mean annual precipitation (MAP, mm), using Eqs. (7)–(9):

$$NPP = \min(NPP_T, NPP_P) \tag{7}$$

$$NPP_T = \frac{3000}{1 + e^{1.315 - 0.119MAT}} \tag{8}$$

$$NPP_P = \frac{3000}{1 - e^{-0.000664MAP}} \tag{9}$$

where NPP_T is net primary productivity calculated by temperature (g biomass/m^2), NPP_P is net primary productivity calculated by precipitation (g biomass/m^2), which are derived from *the WorldClim data* website (https://www.worldclim.org/data/index.html).

According to ecosystem carbon allocation patterns, the CS_{sink} is calculated as Eq. 10

$$CS_{sink} = NPP \times R \times C \times \frac{44}{12} \tag{10}$$

where *NPP* is the forest net primary productivity (g biomass/m^2); *R* is the ratio of net ecosystem productivity to the net primary productivity, which is mainly from the latest studies (Wang et al., 2015) with the value of 0.5; *C* is carbon content ratio in biomass (g C/g biomass) equaling to 0.58; $\frac{44}{12}$ is the conversion coefficient that transforms carbon (g C) into carbon dioxide equivalents (g CO_2-e).

Due to the monotonous character of the model, extreme temperatures and precipitation were not taken into account. A saturation threshold was defined with an upper year limit informed by stand age, implicitly capturing long-term age dynamics (Ji et al., 2008; Xu et al., 2023; He et al., 2017). Moreover, considering the influence of China's afforestation activities, we have extended the forest land use coverage by transferring the potential forest land (such as swampland), therefore implementing the related forest carbon sinks for the future years.

2.3. Data sources, scenario settings and sensitivity analysis

Regarding the calculation of CO_2 emissions, gridded datasets contain present CO_2 emissions data and future socioeconomic data. Gridded CO_2 emissions for China in 2020 are provided by China High Resolution Emission Database (CHRED) (Cai et al., 2018). Global future gridded GDP datasets with spatial resolutions of 30 arc-seconds and 0.25 arc-degrees are provided by associated research (Wang and Sun, 2022), consistent with the shared socioeconomic pathways. Chen et al. (2020) (Chen et al., 2020) provide gridded population projection at 30 arc-seconds resolution for China under shared socioeconomic pathways. Moreover, national data contain future CO_2 emission trajectories of China, which are derived from AR6 databases. We select trajectories corresponding to various shared socioeconomic pathways and representative concentration pathways (SSP-RCPs), including SSP1-2.6, SSP2-4.5, and SSP5-baseline scenarios as an approximate substitute for SSP5-8.5, which represent sustainable development scenario, middle of the road scenario and high reference scenario with no additional climate policy, respectively.

As for the projection of forest carbon sinks, climate data in three future climate scenarios, i.e., Representative Concentration Pathways (RCPs; RCP 2.6, RCP 6.0, and RCP 8.5), were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (https://doi.org/10.48364/ISIMIP.208515). The three scenarios are characterized as having very low greenhouse gas concentration levels, stabilized emissions with the application of a range of technologies, and the highest greenhouse gas concentration levels, respectively. The mean annual temperature (MAT) and mean annual precipitation (MAP) were calculated from daily temperature and precipitation at a spatial resolution of 0.5°.

By integrating the scenarios for CO_2 emissions and forest carbon sinks, we encompass 9 scenario combinations to comprehensively analyze the offsetting effect of forest carbon sinks on CO_2 emissions, as listed in Table 1.

We have conducted a sensitivity analysis for gridded carbon emission

Table 1
Scenario settings for offsetting effect analyses.

		Scenarios for forest carbon sinks		
		RCP 2.6	RCP 6.0	RCP 8.5
Scenarios for CO_2 emissions	SSP1-2.6	S1R2	S1R6	S1R8
	SSP2-4.5	S2R2	S2R6	S2R8
	SSP5-8.5	S5R2	S5R6	S5R8

estimation, targeting weighting parameters of the models, i.e., α, which is an important input in the proposed model. Therefore, a sensitivity analysis of this parameter is conducted to test the robustness of the model. Typically, two additional scenarios are designed and simulated under the SSP2-4.5 scenario in 2030, with parameters equal to 0 and 1, which presents the estimation of pure C&C and pure CIC schemes, for comparison.

3. Results

Generally, we investigate projected carbon emissions and carbon sinks and further evaluate the estimated offsets under SSP-RCP scenario combinations. The estimation results for carbon emissions and forest carbon sinks are presented in Sections 3.1 and 3.2, respectively. Section 3.3 discusses the offsetting effects of forest carbon sinks on CO_2 emissions.

3.1. Carbon emission estimation

As illustrated in Fig. 1a, CO_2 emission in China would reach a peak after 2020, as estimated by the three scenarios (i.e., SSP1-2.6, SSP2-4.5, SSP5-8.5). Nevertheless, a heterogeneous trajectory in CO_2 emission dynamics across different scenarios is identified, pointing to an interesting conclusion that China's peak year would be further advanced and perform much lower emissions under an optimistic climate policy. China will achieve a carbon peak in around 2025, 2030, and 2040 at 12.28, 12.41, and 17.75 billion tons under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. Afterward, it projected that the emissions reflect a steadily decreasing trend, with mean annual decreases of 5.42 %, 1.93 %, and 1.83 %, respectively, especially a higher decreasing rate under scenario SSP1-2.6. This trend appears more plausible in light of the Chinese government's commitment to achieve carbon neutrality by 2060 and peak carbon emissions by 2030. Our results further validate that the implementation of a sustainable development strategy will be more conducive to achieving the dual carbon goals.

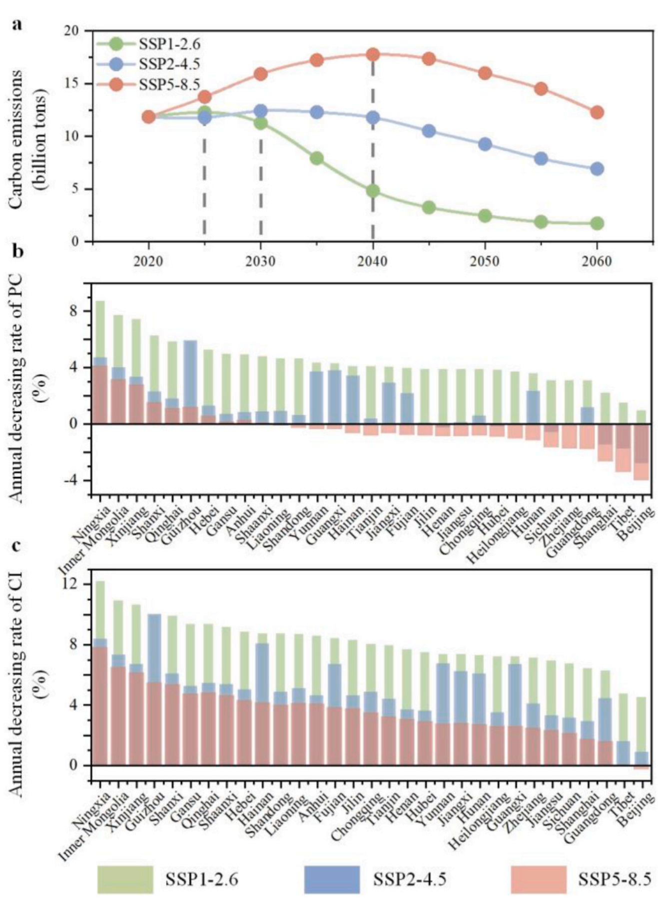

Fig. 1. National CO_2 emissions (**a**), province-specific yearly decreasing rate of per-capita carbon emissions (PC) (**b**), and carbon intensities (CI) (**c**) under scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 from 2020 to 2060.

Concerning the spatial distribution characteristic (as depicted in Figs. 2 and 3), we find that the CO_2 emissions during 2020–2060 under the three scenarios are expected to be concentrated in specific provinces. Shandong greatly contributes to the country's total CO_2 emissions (accounting for 8.01–9.14 % under the three scenarios) from 2020 to 2060, closely followed by Guangdong (5.34–7.64 %) and Jiangsu (6.92–7.59 %). On the contrary, Tibet contributes the smallest proportion of CO_2 emissions, accounting for only 0.12–0.13 %, and a characteristic similarly is observed in Hainan and Qinghai. This phenomenon primarily arises from the fact that eastern regions like Shandong mainly serve as key industrial clusters accompanied by significant energy consumption and carbon emissions. Furthermore, we find vast disparities across provinces in the decreasing rate of carbon emissions. Ningxia, Inner Mongolia, and Xinjiang exhibit the most significant downward trends between 2020 and 2060, with average annual decline rates of 3.85–8.44 %, 3.58–8.16 %, and 2.01–6.70 %, respectively, under the three scenarios, compared with the provinces such as Tibet and Beijing, which present a relative slowly declining (1.65 % and 1.54 % under scenario SSP1-2.6, respectively) or even increasing trend (1.60–3.30 % and 2.20–3.40 % under the other two scenarios, respectively). In the meantime, a consistent trend among almost all provinces that CO_2 emission in each province performs a much steeper downtrend under scenario SSP1-2.6 (Fig. 2b and c) relative to the other two scenarios has been discovered, manifesting the prominent mitigation effect of renewable policies.

We further include another two parameters, i.e., per-capita CO_2 emissions (PC) and carbon intensities (CI, that is, carbon emissions per unit of GDP), as shown in Fig. 1b and c. Continuous declines in per-capita CO_2 emissions and carbon intensities of each province, with average annual reductions of 0.38–4.39 % from 2020 to 2060 under three scenarios, are observed. Yet, there are provincial heterogeneities for these declines and a dramatic transition of emission hotspots in terms of these two indexes. Inner Mongolia and Ningxia feature the highest level of 40.23 and 37.37 t CO_2 per capita for PC and 5.60 and 6.81 t CO_2 10^{-4} RMB for CI, respectively in 2020 and the largest decreasing rates of 3.15–7.74 % and 4.13–8.71 % for PC and 6.48–10.92 % and 7.81–12.22 % for CI between 2020 and 2060 in the three scenarios. Reversely, these two provinces are projected to perform at a relatively low level in 2060 and Shanghai will gradually present the highest level of 3.02–21.41 t CO_2 per capita for PC, and Heilongjiang will feature the largest value of 0.11–0.74 t CO_2 10^{-4} RMB for CI amongst the three scenarios in 2060. Considering the discrepancies among scenarios, the values under the sustainable scenario, i.e., SSP1-2.6, are notably lower than those under the other two scenarios (that is, SSP2-4.5 and SSP5-8.5), exhibiting reductions of 45.28 % and 63.10 %, respectively.

3.2. Projected forest carbon sinks

The forecasts of China's forest carbon sink under three scenarios (i.e., RCP2.6, RCP6, and RCP8.5) are summarized in Fig. 4. Generally, China's forest carbon sink is expected to exhibit an initial rise, succeeded

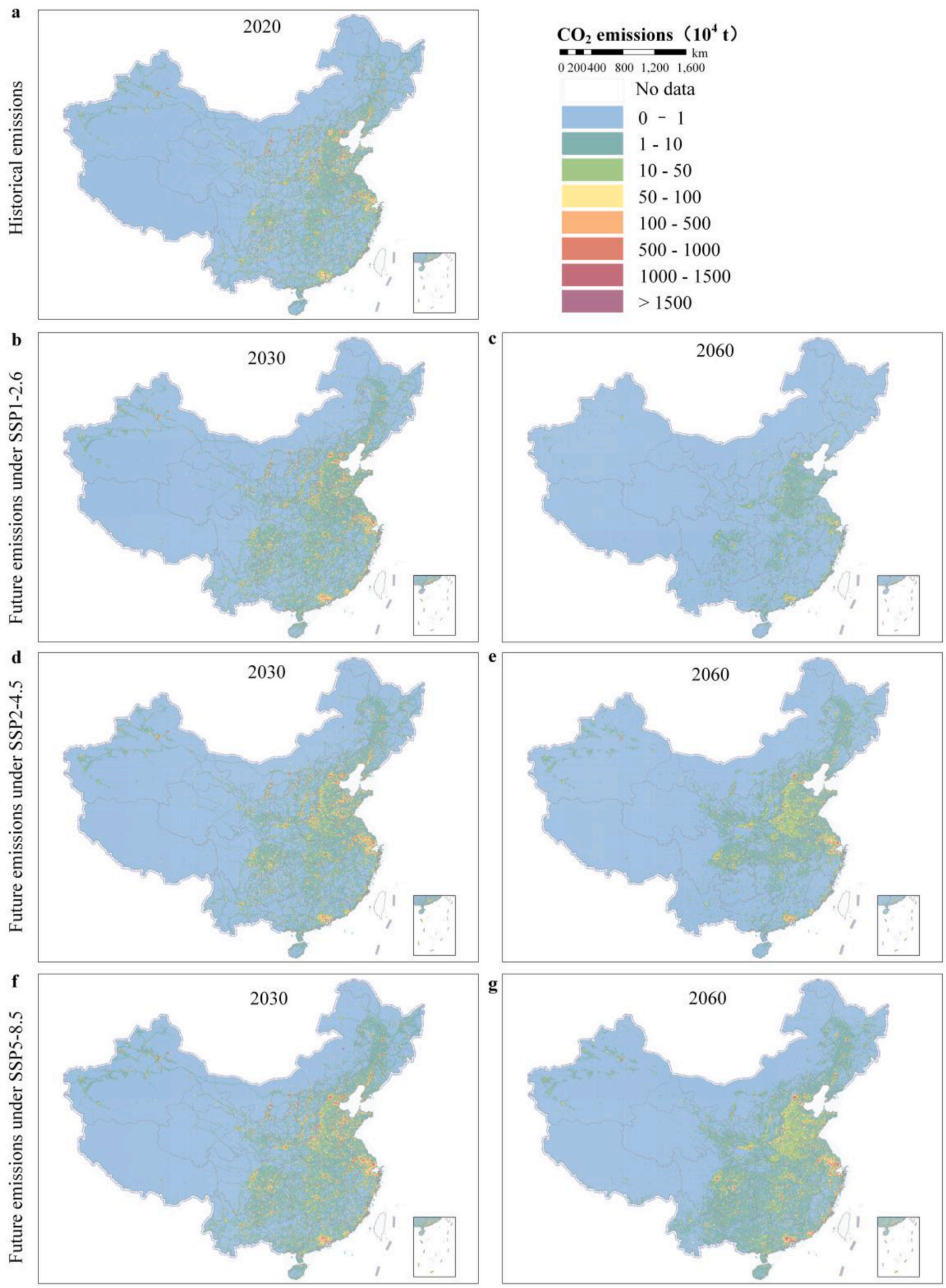

Fig. 2. Geographic distributions of CO_2 emissions at present (**a**) and under future scenarios SSP1-2.6 (**b, c**), SSP2-4.5 (**d, e**), and SSP5-8.5 (**f, g**) from 2020 to 2060.

by a decline with minor fluctuations under all three scenarios, and is anticipated to peak around 2025. Our findings further indicate that by 2025, forest carbon sinks in China will reach 1.35, 1.47, and 1.35 billion tons under the three scenarios, respectively, signifying substantial increases of 39.32 %, 52.59 %, and 39.35 % compared to the historical levels in 2020, respectively. Moreover, by comparing the projections under different scenarios, distinct phased heterogeneity characteristics are observed in the forest carbon sinks. Between 2020 and 2030, the forest carbon sink in scenario RCP6 significantly surpasses that in RCP2.6 by 6.46 % and in RCP8.5 by 6.98 %, respectively. Similarly, the highest estimations are observed under scenario RCP 8.5 between 2030 and 2060, exhibiting a 5.96 % and 10.14 % increase compared to RCP2.6 and RCP6, respectively. Consequently, China's forest carbon sink under scenario RCP2.6 basically remains at a lower level, mainly due to the lower temperatures and precipitation that may have the opposite effects on plant growth.

From the spatial characteristic perspective, as shown in Figs. 5 and 6, forest carbon sinks vary considerably nationwide, with the major carbon sinks predominantly concentrated in southern provinces. Specifically, Yunnan makes a substantial contribution to the country's future forest

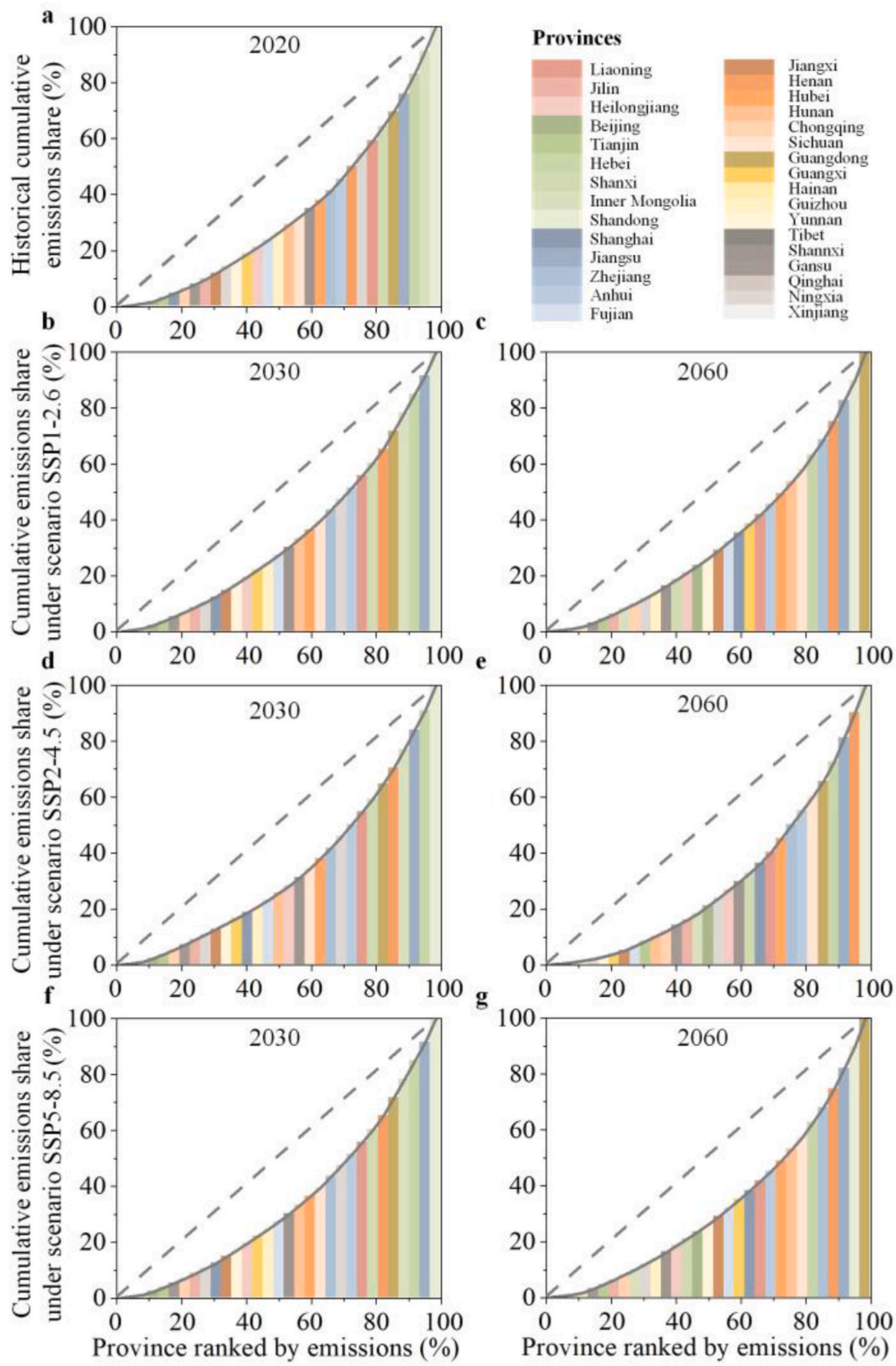

Fig. 3. Lorenz curve of province-level emissions from 2020 to 2060 at present (**a**) and under future scenarios SSP1-2.6 (**b, c**), SSP2-4.5 (**d, e**), and SSP5-8.5 (**f, g**). The colour shows the province; the gray solid curves denote the cumulative emission shares (%).

sinks (accounting for 14.65 %, 14.72 %, and 14.60 % under the three scenarios, respectively) from 2020 to 2060, closely followed by Guangxi (11.21 %, 11.15 %, and 11.11 %, respectively) and Guangdong (8.77 %, 8.83 % and 8.80 %, respectively). Conversely, Shanghai contributes the lowest shares of the total forest carbon sinks (only representing 0.01 % of total values), which is similarly performed in Ningxia and Tianjin. The disparity in carbon sinks can primarily be attributed to the suitable climatic and land conditions in central-southern regions, significantly facilitating the carbon sequestration level. Interestingly, our results also indicate the largest yearly increases of 7.51–7.92 % forest carbon sinks from 2020 to 2060 in Shanghai, compared to the relatively low level (−0.26 %–0.12 %) in Yunnan, mainly attributed to the thorough exploitation of woodland and relatively low development potential (with an already high proportion of natural forests (Leng et al., 2024) and older forest age classes (Li et al., 2022)) in the future.

Furthermore, based on the prediction of China's carbon sinks, another two indicators are further calculated, i.e., per-capita carbon sinks (PS) and carbon sink per unit area (SA), as depicted in Fig. 4b and c. As for PS, there are huge spatial heterogeneities among provinces. Considerably, Tibet exhibits the largest level of 13.95–15.19 t CO_2 per capita from 2020 to 2060 under the three scenarios, which are mainly attributed to the vast land resources and sparse distribution of residents in this province, compared to the provinces in eastern and northern regions, such as Shanghai (0.0029–0.0030 t CO_2 per capita) with

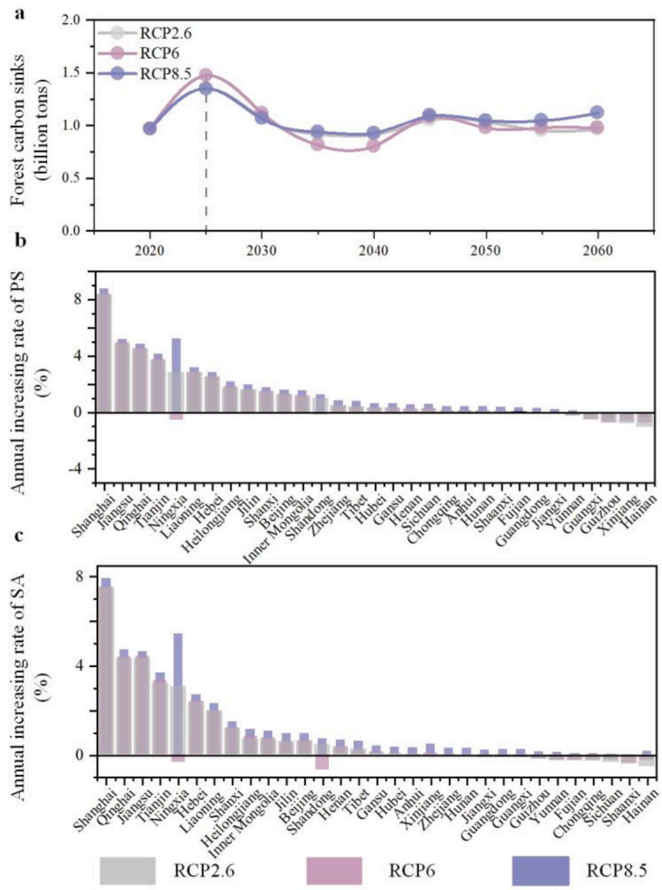

Fig. 4. National forest carbon sinks (**a**), province-specific yearly decreasing rate of per-capita carbon sinks (PS) (**b**) and carbon sink per unit area (SA) (**c**) in scenarios RCP2.6, RCP6, and RCP8.5 from 2020 to 2060.

opposite attribute characteristics. Remarkably, this structural feature undergoes a dramatic reversal when considering annual increases in PS. From 2020 to 2060, Shanghai has the highest annual increasing rate of 8.36–8.77 %, whereas Tibet performs at a relatively low level (0.31–0.78 %). As for SA, Hainan, Fujian, and Guangdong perform the largest values of 589.36–628.03 t CO_2 km^{-2}, 483.32–504.98 t CO_2 km^{-2}, and 497.72–518.94 t CO_2 km^{-2}, in sharp contrast to Ningxia, Xinjiang, and Shandong. Similar to PS, Shanghai is anticipated to demonstrate the highest annual growth rate of 7.51–7.92 %, contrasting with −0.54-0.15 % in Hainan. Furthermore, taking the disparities among scenarios into account, both two indicators under scenario RCP 8.5 are greater than those in scenario RCP 2.6 (by 4.49 %) and RCP 6 (by 4.42 %), which coincides with the results of China's total forest carbon sinks**.**

3.3. Contribution to carbon emission reduction

Overall, this study encompasses 9 scenario combinations by integrating three scenarios for CO_2 emissions and three scenarios for carbon sinks, as listed in Table 1. Concerning the temporal characteristics, the offset ratio of carbon sinks to total CO_2 emissions demonstrate an overall pattern characterized by an initial increase, subsequent decrease, and subsequent increase, ranging from 4.43 % to 62.87 % under the 9 scenarios between 2020 and 2060, as showed in Fig. 7a. Moreover, we find that scenarios directed by SSP5-8.5 exhibit the most modest and the procrastinating growth of offset ratio (with the annual increases of 2.16–2.88 % under the associated three scenarios from 2040 to 2060), compared to the scenarios led by SSP1-2.6 (5.98–6.59 % from 2030 to 2060) and SSP2-4.5 (2.55–3.05 % from 2035 to 2060). In addition, we tallied the number of provinces achieving complete offsetting of forest carbon sinks to carbon emissions across various scenarios and years. Accordingly, in 2020, only one province had completely offset emissions through carbon sinks, whereas the value at most significantly is expected to reach to nine in 2060 under a set of scenarios. These findings highlight that the forest carbon sinks are expected to gradually play a significant role in China's endeavors to achieve carbon neutrality, especially under renewable development scenarios.

In terms of spatial distribution, as depicted in Fig. 8a,b-h, there exist regional uneven distribution features between CO_2 emissions and forest carbon sinks across China. Notably, eastern provinces such as Shandong, Hebei, and Jiangsu exhibit relatively higher total CO_2 emissions but relatively lower forest carbon sinks. Conversely, southwestern provinces such as Yunnan and Guangxi display higher forest carbon sinks but relatively lower total CO_2 emissions, as mentioned above. This uneven distribution primarily resulted from the critical industrial layouts in the eastern region and rich forestry resources in the southwestern region. Therefore, provinces in the eastern region perform higher net emissions, and the offset ratios of forest carbon sinks to CO_2 emissions vary widely, traversing various provinces across the country. Generally, the forest carbon sinks in Tibet, Yunnan, and Hainan contribute the largest shares to associated CO_2 emissions, giving offset ratios of 170.75–1671.24 %, 26.72–357.32 %, and 15.69–188.46 % between 2020 and 2060 under different scenarios. In contrast, Shanghai, Tianjin, and Jiangsu perform the lowest offsetting ratio of 0.00–0.14 %, 0.02–0.55 %, and 0.02–0.68 %, which further illustrates that implementing other carbon removal technologies (such as bio-energy with carbon capture and storage) beyond forest carbon sinks in these provinces is imperative from the long-term perspective.

Considering the differences among scenarios, our results reveal that the magnitude of total carbon emissions predominantly drive the offsetting effects. Specifically, as shown in Fig. 7b–e and Fig. 8d, scenarios following SSP1-2.6 (i.e., S1R2, S1R6, and S1R8) yield the highest offsetting effects of 25.86–27.74 % from 2020 to 2060, compared to 9.85–10.31 % and 6.76–7.02 % in other scenarios driven by SSP2-4.5 and SSP5-8.5. Similarly, there are only at most one and five provinces that give the offsetting ratio over 100 % and achieve complete offsets of forest carbon sinks under the latter two series of scenarios, whereas the value can dramatically reach nine under the former scenarios. Furthermore, as for the comparison of scenarios targeting forest carbon sinks, the higher offset ratio with an average of 27.74 %, 10.31 %, and 7.02 % occurs in the RCP8.5 related scenarios (i.e., S1R8, S2R8, and S5R8), respectively, compared to the values in RCP2.6 (i.e., S1R2, S2R2, and S5R2, with the offset ratio of 25.97 %, 9.85 %, and 6.76 %, respectively) and RCP6 related scenarios (i.e., S1R6, S2R6, and S5R6, with the offset ratio of 25.86 %, 9.85 %, and 6.77 %, respectively). The findings underscore that substantial mitigations of emission sources are pivotal for achieving the dual carbon development goals.

4. Conclusions

To effectively depict and reflect the realization path of the Dual-Carbon goals, we comprehensively explore the grid-specific, yearly, and nationwide forest carbon sinks and CO_2 emissions in China from 2020 to 2060. In addition, based on the projections of high-resolution China's forest carbon sinks and CO_2 emissions, we further investigate the spatiotemporal carbon offsetting effects of China's forest carbon sinks, which can offer insightful policy references and guidelines on future forest layouts.

Our results reveal large spatiotemporal heterogeneities in CO_2 emissions. On the one hand, we find that CO_2 emissions in China would reach a peak after 2020 and China's peak year would be further advanced and perform much lower emissions under an optimistic climate policy, which is in line with previous studies (Xu et al., 2024). On the other hand, our results highlight the regional heterogeneities in the CO_2 emissions, per-capita emissions and carbon intensities, during

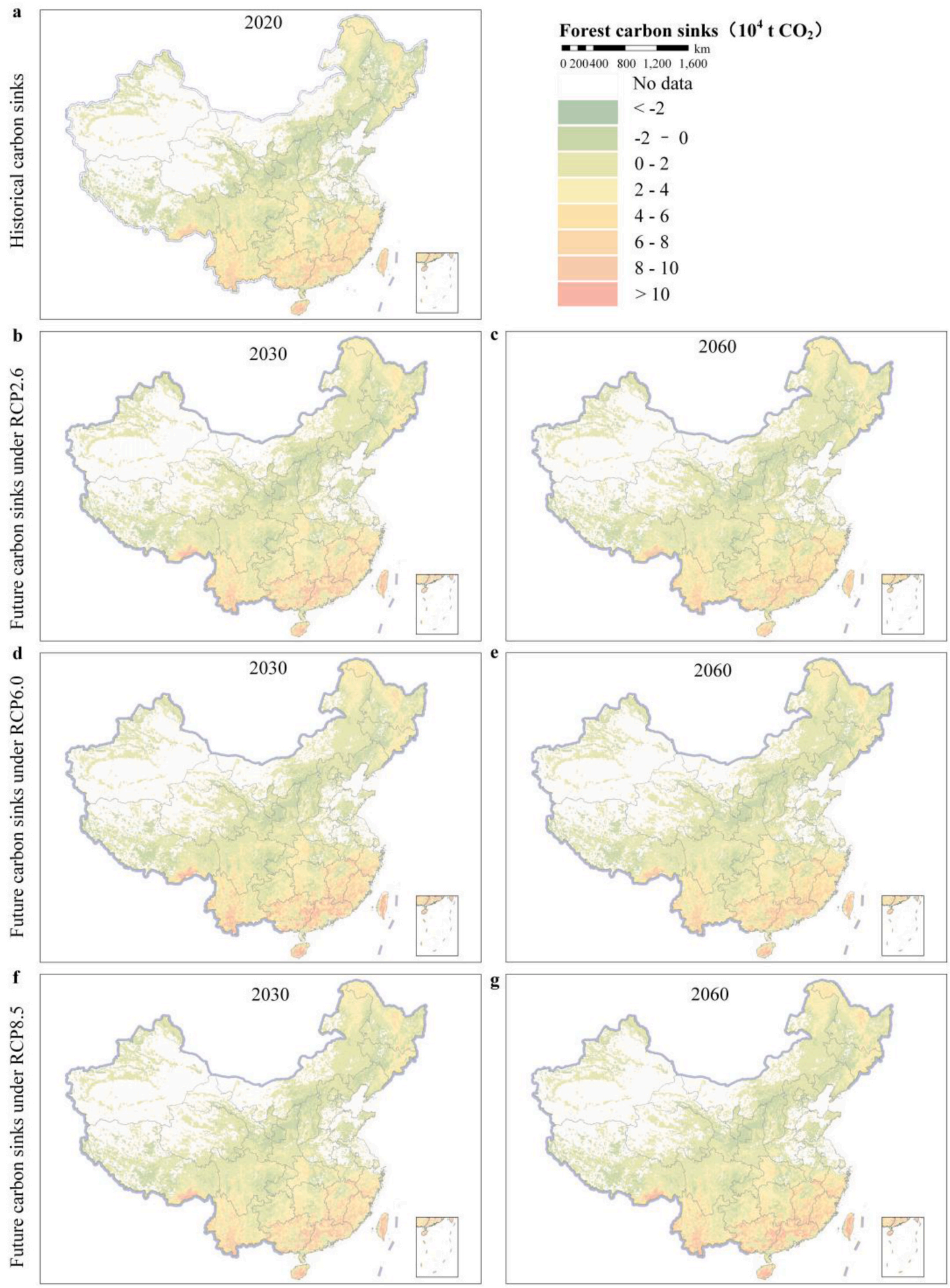

Fig. 5. Geographic distributions of forest carbon sinks in the present (**a**) and future scenarios RCP2.6 (**b, c**), RCP6 (**d, e**), and RCP8.5 (**f, g**) from 2020 to 2060.

2020–2060 under the three scenarios. In particular, our results indicate that China's CO_2 emissions are primarily located in specific provinces, such as Shandong, Guangdong, and Jiangsu. Whereas, the yearly decreases of emissions in these provinces are in the middle of the range amongst all provinces, which suggests that there is a need to institute stricter control measures (for example, phasing out outdated facilities and developing clean energy (State Council of the People's Republic of China. Opinions on Fully)) in the future. Additionally, the values under the sustainable scenario, i.e., SSP1-2.6, are significantly lower than those under the other two scenarios. This provides messages that there is a necessity to promote associated renewable development policies (such as the Emissions Trading Scheme) in China to substantially reduce CO_2 emissions in the future.

Furthermore, our analysis indicates that China's forest carbon sink is expected to exhibit an initial rise, followed by a decline with minor fluctuations under all three scenarios, and is anticipated to peak around 2025. These findings also coincide with existing related research (Xu et al., 2024). Concerning the spatial patterns, our results show that provinces with higher forest carbon sinks, per-capita carbon sinks and carbon sink per unit area in 2020, are expected to perform relatively low annual increases in the future, primarily due to the already high share of natural forests (Leng et al., 2024) and older forest age classes (Li et al.,

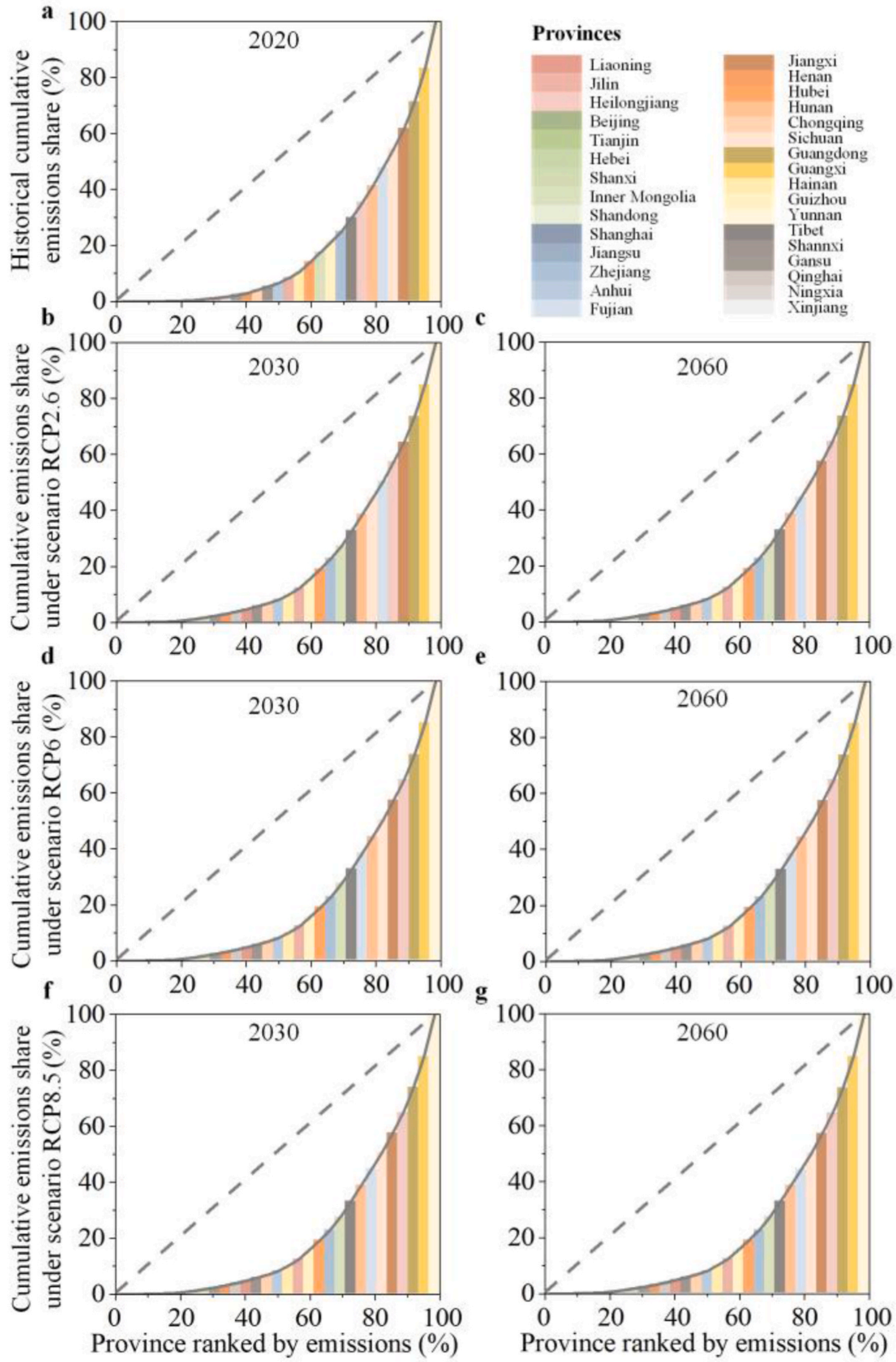

Fig. 6. Lorenz curve of province-level forest carbon sinks from 2020 to 2060 in present (**a**) and future scenarios RCP2.6 (**b, c**), RCP6 (**d, e**), and RCP8.5 (**f, g**). The colour shows the province; the gray solid curves denote the cumulative emission shares (%).

2022) in these regions. These findings suggest that appropriately expanding forest land coverage in the future, particularly in environmentally suitable but undeveloped regions like Jiangsu and Shandong, would be advisable (United Nations, 2017–2030).

Significantly, we develop 9 scenarios to analyze the offset of China's forest carbon sinks to CO_2 emissions. Our evaluations demonstrate that the offsetting ratio of carbon sinks to total carbon emissions follows an overall pattern characterized by an initial increase, subsequent decrease, and subsequent increase, ranging from 4.43 % to 62.87 % between 2020 and 2060. This result shows that forest carbon sinks are gradually more exploited in achieving the Dual-Carbon targets (Ke et al., 2023). Yet, an unfavorable pattern that regional heterogeneity distribution features between the carbon emissions and forest carbon sinks across China is discovered, which offers a significant insight that developing forest carbon sinks, especially in high-emitting areas, makes great sense for achieving climate goals (Central People' et al.). Furthermore, by comparing individual scenarios, our findings suggest that the amount of total carbon emissions primarily influences the offsetting effects. This suggests that the foremost priority to achieve the goal of carbon neutrality remains the promotion of significant reductions from emission sources.

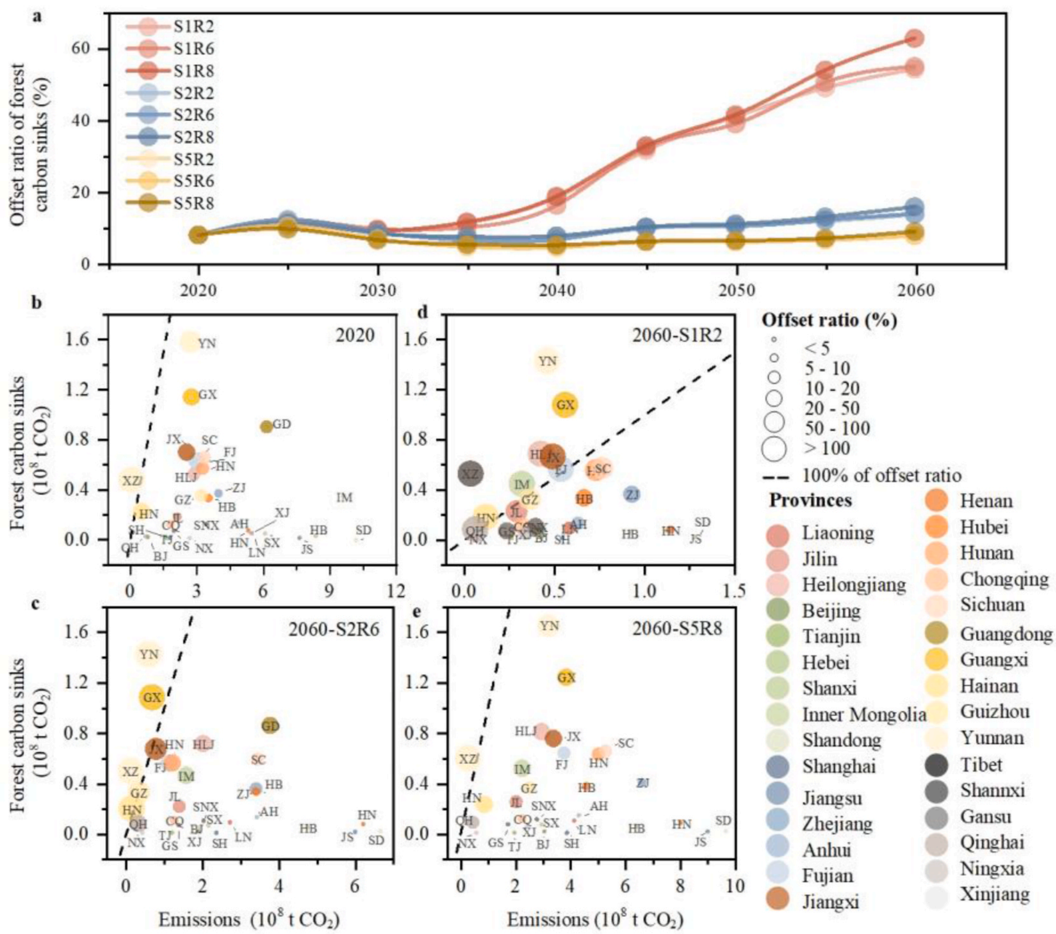

Fig. 7. **a,** Offset ratio of forest carbon sinks to national CO_2 emissions under nine scenarios from 2020 to 2060. **b-e**, Provinces with each plotted according to the forest carbon sinks (*y*-axis) and CO_2 emissions (*x*-axis) from 2020 to 2060.

5. Discussion

Our study is constrained by several limitations. First, our estimation of China's carbon sinks is primarily conducted by applying the Miami model, the first global-scale empirical model. Nowadays, many other models have emerged, such as the ecosystem process model like CASA (Xu et al., 2023) and a comprehensive comparison among these models can be systematically developed. In addition, our estimation mainly considers the carbon sinks from above- and belowground biomass, without the changes in soil, which constitute a substantial and long-term component of NPP. Future works may extend our estimation by integrating soil carbon dynamics to provide a more comprehensive assessment if the associated data are available. There also exist differences between plantation forests and natural forests in their carbon sinks or amongst different age groups, while our model does not currently distinguish these forest types or age groups due to data limitations. Thus, future work can further incorporate forest-type-specific or age-based NPP parameters to greatly enhance the accuracy of the estimation. Moreover, our study mainly focuses on the offsetting effects of forest carbon sinks without considering carbon-removal technologies (such as bio-energy with carbon capture and storage (Jiang and Ashworth, 2021)). This can be included in the future, thus enabling a much more comprehensive assessment of carbon neutrality pathways.

A sensitivity analysis is performed to test the robustness of our model for gridded carbon estimation. In particular, the differences stemming from changes in the weighting parameters could be finely controlled within a relatively small range (±16.47 %), which indicates the robustness of the proposed model. Moreover, to evaluate the accuracy of our results on forest carbon sinks, we have compared our estimation with those of existing studies. Generally, our projections are in the middle of the existing estimation, with −216.47–48.33 % lower than the available studies (Ke et al., 2023; Hou and Yin, 2023; Xu et al., 2010, 2024; Lu et al., 2022; Zhu et al., 2023; Cai et al., 2022c; Jiang and Huang, 2016).

Notwithstanding these limitations, our study has provided significant contributions. Our study is a comprehensive analysis to simultaneously consider the gridded forest carbon sink and CO_2 emissions, providing a deeper understanding of the carbon offsetting effects of China's forest resources. This represents a major advance in achievement evaluations of the Dual-Carbon goals in China (Jia et al., 2024). Furthermore, our study also holds great significance in the study of the development pathways of CO_2 emissions (Zhang et al., 2024a, 2024b, 2025) and forest carbon sinks. Specifically, the spatial matching of carbon emissions and forest carbon sink has great significance in identifying key areas and supporting regional policies in the future (Francesconi et al., 2022). As a result, our results offer valuable insights for policymakers in China and elsewhere aiming to explore forest layouts.

CRediT authorship contribution statement

Min Jia: Writing – original draft, Software, Methodology, Conceptualization. **Shu Ye:** Writing – original draft, Software, Methodology. **Li Zhang:** Writing – review & editing, Supervision. **Pengcheng Wu:** Validation. **Ni Huang:** Methodology. **Yanfeng Bai:** Methodology. **Jianhui Ruan:** Methodology. **Zhuoming He:** Visualization. **Mingyu Li:**

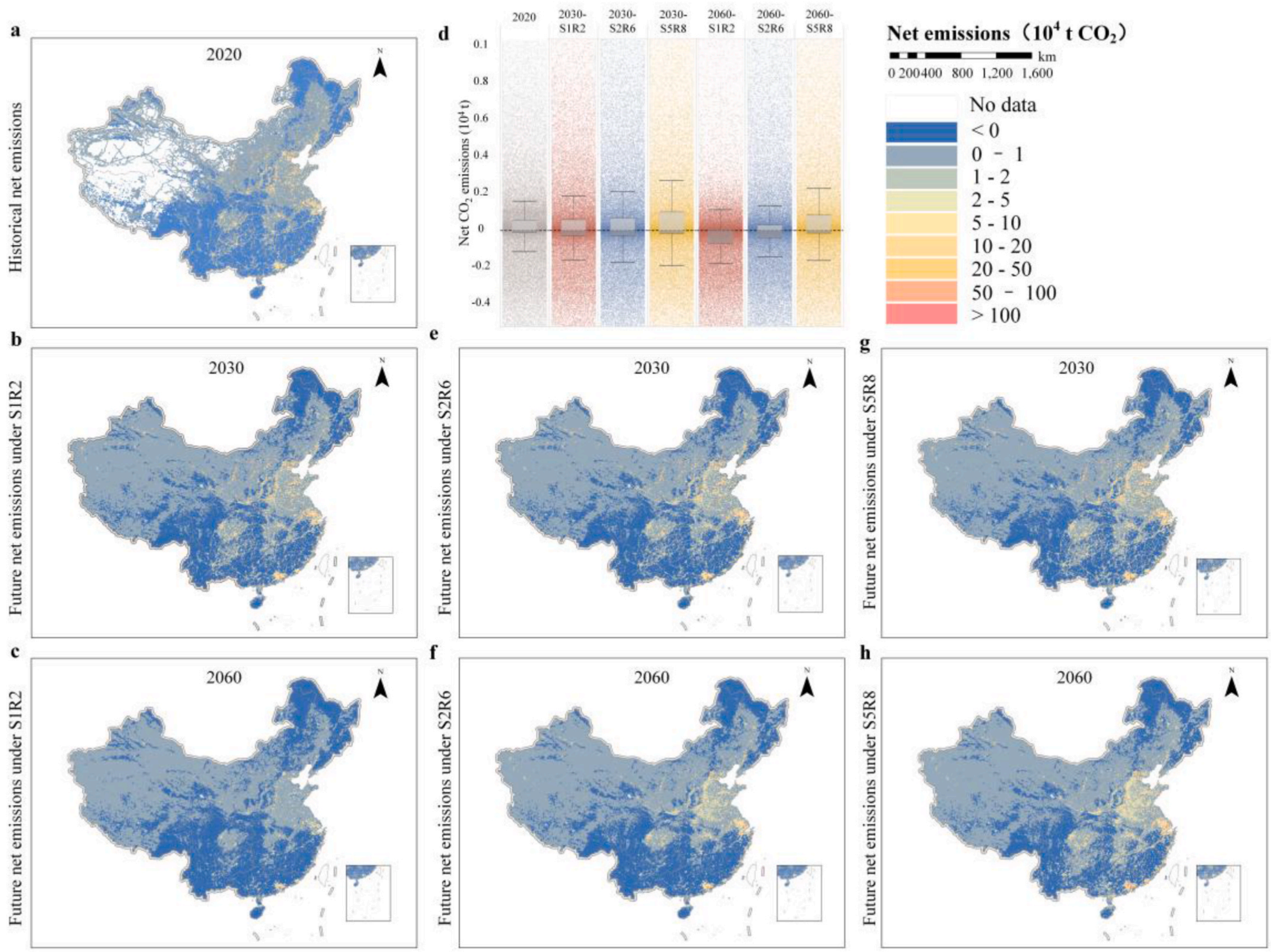

Fig. 8. a, b-c, e-h, Geographic distributions of net CO_2 emissions at present and under scenarios S1R2, S2R6, and S5R8 from 2020 to 2060. **d,** Distribution of provincial net CO_2 emissions under different scenarios between 2020 and 2060.

Writing – original draft, Software, Methodology. **Shaoyuan Chen:** Methodology. **Li Wang:** Methodology. **Bofeng Cai:** Supervision, Conceptualization. **Jinnan Wang:** Supervision.

Declaration of competing interest

There is no known conflict of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 72140004 and 72074154), the Chinese Academy of Engineering (Grant No. 2022-PP-01), and the National Key Research and Development Program of China (Grant No. 2023YFC3807700).

Data availability

Data will be made available on request.

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