Response of the Carbon Budget of Global Forest Ecosystems to Future Climate Change

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Abstract

Background At present, global warming is an indisputable fact, and more and more attention has been paid to the impacts of climate warming on global ecological environments. Forests play increasing significant roles in regulating global carbon balance and mitigating climate change. Therefore, to understand the response mechanisms of the carbon budget of global forest ecosystems to future climate change, an improved version of the FORest ecosystem Carbon budget model for CHiNa (FORCCHN) and future Representative Concentration Pathway (RCP) scenario RCP4.5 and RCP8.5 were applied in this study.

Results The global forest ecosystems will play a major role in the carbon sink under the future two climate change scenarios. In particular, the average carbon budget (namely the Net Ecosystem Productivity, NEP) of global forest ecosystems under RCP4.5 scenario was estimated to be 0.017 kg(C)·m^{-2}·yr^{-1} from 2006 to 2100. The future carbon sink areas of global forest ecosystems will increase significantly. Under RCP4.5 and RCP8.5 climate scenarios, the carbon sink areas of global forest ecosystems during 2026–2100 would be significantly higher than those in 2006–2025, with increases of 83.16–87.26% and 23.53–29.70%, respectively. The impacts of future climate change on NEP of global forest ecosystems will significantly vary between different regions. The NEP of forests will be enhanced in the northern hemisphere and significantly weakened in the southern hemisphere under the future two climate change scenarios. The carbon sink regions of global forests will be mainly distributed in the middle and high latitudes of the northern hemisphere. In particular, the forests'NEP in northeastern and central Asia, northern Europe and western North America will increase by 40%~80%. However, the NEP of forests will decrease by 20%~40% in the most regions of the southern hemisphere. In northern South America and central Africa, the forests' NEP will be reduced by more than 40%.

Conclusions The global forest ecosystems will play a major role in the carbon sink under the future two climate change scenarios. However, the NEP of forests will be enhanced in the northern hemisphere and significantly weakened in the southern hemisphere. In the future, in some areas of southern hemisphere, where the forests' NEP was predicted to be reduced, some measures for improving forest carbon sink, such as strengthening forest tending, enforcing prohibiting deforestation laws and scientific forest management, and so on, should be implemented to ensure immediate mitigation and adaptation to climate change.

Highlights

- We quantitatively evaluated the role of global forest in terrestrial carbon cycle.
- We explored the spatial-temporal dynamics of future global forest carbon budget.
- We simulated the responses of global forest carbon budget to future climate change.
- Individual-based carbon budget model FORCCHN and remote sensing outputs were used.

Background

As one of the main manifestations of global change, climate warming effect on global terrestrial carbon cycles, and this effect has important guiding significance for the development of accurate understanding of the carbon cycle process and related policies [3, 6, 14]. The carbon budget, that is the Net Ecosystem Productivity (NEP), was first proposed by Woodwell et al. [28] when analysing the sources and sinks of the terrestrial biosphere. It is used to express the net storage of carbon in large-scale ecosystems, and is the difference between the net primary productivity of vegetation and the heterotrophic respiration of soil. On a global scale, the NEP can indicate the carbon dioxide exchange between the terrestrial ecosystem and atmospheric system. As the main component of terrestrial ecosystems, forests have important roles in the global carbon cycle and are valued globally for the services they provided to society [20, 32], slowing the increases in the contents of CO_2 and other greenhouse gases in the atmosphere, and maintaining the global climate. Photosynthesis and respiration lead to the exchange of substantial amounts of carbon with the atmosphere, and approximately 50% of the global terrestrial carbon is stored in forest ecosystems [21, 27]. Therefore, with global climate change becoming increasingly significant, the NEP of forest ecosystems has also attracted attentions from the scientific and social communities [5, 6, 15, 16, 33].

Methods of assessing the forests' NEP mainly include forest inventory, vorticity related flux observation, isotope tracing, and model simulation [19, 33]. Changes in the forests' NEP span seasons, years, and even decades, and vary spatially, according to the regional, environmental, and climatic conditions and the local vegetation types. Therefore, traditional sampling, fixed-point observations, and other methods of researching dynamic changes in the carbon fluxes of large-scale (regional or global) forest ecosystems are often affected and limited by survey methods, number of observation stations, and findings. With developments of remote sensing, geographic information systems and computer technology, model simulation is being developed rapidly and has become an important and irreplaceable method in the researches of forests' NEP with great prospects.

In recent years, with the occurrence of global change, model simulators in China and overseas have conducted a large amount of meaningful researches on forests’ NEP and their responses to global change and obtained useful conclusions [4, 7, 10, 23, 24, 26, 32, 33, 34]. For example, Wang [26] used three different vegetation models and climate change prediction data to evaluate the impact of increases in temperature and CO_2 on ecosystem productivity in China; and they found that they positively affected vegetation productivity. Devaraju et al. [7] analysed the simulation results from CESM model and found that the effects of CO_2 fertilisation, climatic warming, and nitrogen deposition during 1850–2005 increased the Net Primary Productivity (NPP), with increases of 2.3 $Pg(C)\cdot yr^{-1}$, 0.35 $Pg(C)\cdot yr^{-1}$, and 2.0 $Pg(C)\cdot yr^{-1}$, respectively. However, owing to the poor understanding of various processes in forest ecosystems and the limitations of some methods and technologies used on the global scale, these ecosystem carbon cycle models have many key problems in simulating the carbon cycle of global forest ecosystems, which still need to be solved in model structure, parameters, boundary field and initial field.

For this purpose, an individual tree species FORCCHN model has been established, which can replace the growth table model based on the growth process by the photosynthesis and respiration model based on the physiological mechanism [30]. It can flexibly use the inventory data as the initial field (more accurately), or use the remote sensing information to inverse initial field. Thus, the FORCCHN model can be used to estimate the NEP of global forest ecosystems in the future changing environment, significantly enhancing the estimation ability of future forests' NEP.

In previous study, we have investigated the spatial–temporal dynamics of global forest (vegetation + soil) carbon storage in the future climate change scenario [32]. However, there has been little robust research on the comprehensive impacts of future climate change on the NEP of global forest ecosystems up to now. In this study, we continued to explore the spatial-temporal dynamics of the global forests' NEP under future climate change scenarios based on the improved FORCCHN model and remote sensing, and predict the responses of the NEP of global forest ecosystems to future climate change using long-term datasets based on the results from Zhao et al. [32].

Methods

FORCCHN model

The forest ecosystem carbon budget model FORCCHN with a grid resolution of 0.5°×0.5° was established based on individual tree species and initially only applicable for China [30]; however, it was further improved by Ma et al. [19] and Zhao et al. [33] to allow it to simulate the carbon fluxes of forest ecosystems at a global scale. The FORCCHN model consists of five sub-modules: (1) Initialisation sub-module: the number of trees, species, and tree size are selected randomly according to the leaf area index, evergreen tree proportion, deciduous tree proportion, and forest type, and the random selection is as close to the actual forest as possible; (2) Ecological climate sub-module: this module mainly calculates the daily water and energy budgets, including the soil moisture content and canopy photosynthetic effective radiation, and their quantitative influences on photosynthesis, respiration, decomposition, and other processes; (3) Carbon balance sub-module: this module calculates the photosynthesis, respiration, and withering of each tree daily, and finally obtains the plants' NEP of forest ecosystems; (4) Soil carbon and nitrogen budget sub-module: this module calculates the daily respiration, respiration and transfer of the soil humus layer, and mineralisation of nitrogen, and finally calculates the soil NEP and available nitrogen; and (5) Annual tree growth and carbon balance sub-module: this module calculates the amount of carbon involved in fruit withering and structural growth in a year according to the cumulative daily NEP of each tree, and then the annual increase in the diameter at breast height (DBH) and tree height is obtained. The major processes considered in the model and flow charts are illustrated in Fig. 1, and the main features involved are shown in Table 1 [32]. In the FORCCHN model, the major carbon cycle equations for individual trees and forest stands are as follows:

$$\frac{dx_i}{dt} = GPP_i - t\_resp \times (RM_i + RG_i) - L_i \qquad (1)$$

$$\frac{d\left(\sum x_i\right)}{dt} = \sum GPP_i - t\_resp \times \left(\sum RM_i + \sum RG_i\right) - \sum L_i \qquad (2)$$

where dx_i/d_t denotes the daily carbon budget increment of the *i*th individual tree (i = 1, 2, …,n, t = 0, 1, 2, …, n; kg C·d^{-1});

$$\frac{d\left(\sum x_i\right)}{dt}$$

is the daily carbon budget increment of a forest stand (kg C·d^{-1}); GPP_i is the daily gross primary productivity of the *i*th individual tree (kg C·d^{-1}); RM_i is the daily maintenance respiration of the *i*th individual tree (kg C·d^{-1}); RG_i is the daily growth respiration of the *i*th individual tree (kg C·d^{-1}); L_i is the daily litter am ount from the *i*th individual tree (kg C·d^{-1}), and *t_resp* is the effect of air temperature on plant respiration, which ranges from 0 to 1.

In this study, global forests were categorized into five ecological types according to their habitats and generic characteristics: (1) deciduous coniferous forests, (2) evergreen coniferous forests, (3) evergreen coniferous deciduous broad-leaved mixed forests, (4) deciduous broad-leaved forests, and (5) evergreen broad-leaved forests. Descriptions of the features, structure, mathematical representation, basic parameters, building strategy, relevant computations, and validation of the FORCCHN model were presented in Yan and Zhao [30], Ma et al. [19] and Zhao et al. [33]. The spatial–temporal dynamics of global forest (vegetation + soil) carbon storage in the future climate change scenario had been investigated by Zhao et al. [32]. This study describes our first test of the improved FORCCHN model and our application of it to explore the responses of the NEP of global forest ecosystems to future climate change based on the original results from Zhao et al. [32].

Data source and processing

The data for driving the FORCCHN model mainly included meteorology, soil, and forest data. Because the meteorological conditions in each grid were the same, according to the principle of ecology and the climate single top principle of vegetation, the vegetation in FORCCHN model in each grid was considered to the same. In addition, compared with the dynamic change of forests, the change in soil type was much slower, so the soil in FORCCHN model was considered to unrelated to whether the forests were mature or young.

Meteorological data

The global daily meteorological datasets for future RCP4.5 and RCP8.5 scenarios were used in this study, including the daily maximum and minimum air temperatures (°C), precipitation (mm), wind speed (m·s^{-1}), relative humidity (%), atmospheric pressure (hPa), and total solar radiation (W·m^{-2}). These data were

obtained from the simulation results of Community Climate System Model version 4 (CCSM4) from 2006 to 2100, with a grid resolution of 1.25 × 0.9°. The data from 2006 to 2025 were used to reach the equilibrium state of the model, and the data from 2026 to 2100 were used to predict the NEP. The above data were obtained from the Earth System Grid (https://www.earthsystemgrid.org/home.html).

All global meteorological data were resampled to match the resolution of the FORCCHN model using the bilinear interpolation method, which was widely used in the interpolations of meteorological elements in model simulations [35, 36]. All the climate data bias was corrected based on CRU-JRA data sets.

Soil data

The soil data used in this study were obtained from two sources. The first was the Global Gridded Surfaces of Selected Soil Characteristics (Global Soil Data Task Group 2000), which had a spatial resolution of approximately 10 km × 10 km and soil depth of 0–100 cm, and included the soil carbon density (kg C·m^{-2}), nitrogen density (kg N·m^{-2}), field capacity (cm), bulk density (kg C·m^{-3}), and water content (cm). The other source was from the Harmonised World Soil Database [37], which provided the soil sand, silt, and clay contents (%) and had a spatial resolution of approximately 1 km × 1 km and soil depth of 0–100 cm. The litter pool decomposition parameters were obtained from the results of Zhao et al. [32] and Ma et al. [19]. All soil data were resampled to a resolution of 0.5 × 0.5° to match the resolution of the FORCCHN model.

Forest data

In this study, the global forest types and forest coverage rates of the forest and non-forest grids were obtained from the International Geosphere-Biosphere Program-Data and Information Service (IGBP-DIS) *DISCover* land cover classification system, with a spatial resolution of 0.5°×0.5°. Additionally, the eight-day 5 km leaf area index (LAI) from the Global LAnd Surface Satellite (GLASS) was used [17]. After assessing any quality control flags in the LAI, the eight-day GLASS data were composited into yearly maximum and minimum values. The satellite datasets were then resampled to match the geographic projection and spatial resolution of the FORCCHN model.

Currently, many institutions have used different satellite observation data to release global leaf area index products, such as Moderate Resolution Imaging Spectroradiometer (MODIS), GLOBal land products for CARBON model assimilation (GLOBCARBON), and Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites (CYCLOPES). However, Fang et al. [9] stated that the errors of the existing LAI products were within ± 1.0, which did not meet the accuracy requirements of global climate observation system for LAI products (± 0.5). The GLASS LAI product developed by Beijing Normal University was based on satellite observation data [17]. Xiang et al. [29] conducted comparative verification and found that the determination coefficient (R^2) of the GLASS LAI product was 0.76 when compared with LAI ground measurement data (17 stations worldwide, 20 samples in total), which was significantly higher than that of MODIS (0.46) and CYCLOPES (0.59). According to the relative root mean

square error (RMSE), GLASS (0.51) and CYCLOPES (0.41) were more accurate than MODIS (1.11). Therefore, the global GLASS LAI products were used for FORCCHN model initialisation in this study.

Selection of future climate change scenario

To assess the future climate, the Intergovernmental Panel on Climate Change (IPCC) proposed RCPs for its fifth Assessment Report (AR5) in 2014 that included four different greenhouse gas concentration trajectories: RCP2.6, RCP4.5, RCP6, and RCP8.5 [14]. RCP2.6 assumes that the global annual greenhouse gas emissions (measured in CO_2-equivalent concentration levels (ppm)) will peak at 490 ppm before 2100, with emissions declining substantially thereafter. In RCP4.5, the emissions will peak at 650 ppm, and then stabilise after 2100. In RCP6, the emissions will peak at 850 ppm and then stabilise after 2100. In RCP8.5, the emissions will continuously rise, and peak at 1370 ppm by 2100 [32]. In this study, the RCP4.5 and RCP8.5 scenarios were selected, and the results were used as the input data for predicting the NEP of global forest ecosystems from 2006 to 2100.

Results

Temporal evolution of the NEP in global forest ecosystems under future climate change scenarios

The simulation results based on FORCCHN demonstrated that, owing to future climate change, the global forest ecosystems will mainly serve as a carbon sink from 2006 to 2100. In particular, the NEP per unit area of global forest ecosystems from 2006 to 2100 will be 0.017 kg(C)·m^{-2}·yr^{-1} under the RCP4.5 climate scenario. The results show that, under the future RCP4.5 scenario, the NEP per unit area of the global forest ecosystems in 2026–2045, 2046–2065, 2066–2085, and 2086–2100 will be 0.191, 0.213, 0.214, and 0.199 kg(C)·m^{-2}·yr^{-1}, respectively, which will be greater than those in the period of 2006–2025. Additionally, under the future RCP8.5 scenario, the NEP per unit area of global forest ecosystems in 2026–2045, 2046–2065, 2066–2085, and 2086–2100 will be 0.187, 0.203, 0.193, and 0.163 kg(C)·m^{-2}·yr^{-1}, respectively, which will be higher than those in 2006–2025.

Response of the NEP in global forest ecosystems to future RCP4.5 climate scenario

The results show that climate change will significantly impact the NEP of global forest ecosystems under the future RCP4.5 scenario. Furthermore, future climate change will be generally conducive to carbon sequestration in the global forest ecosystems. For example, in 2026–2045, 2046–2065, 2066–2085, and 2086–2100, the carbon sink areas of global forest ecosystems will significantly increase by 83.16%, 84.19%, 87.26%, and 87.17% compared in 2006–2025, respectively; the increased proportions in the areas of forests' NEP with the value of 0.01–0.30 kg(C)·m^{-2}·yr^{-1} during these periods will be 57.47%, 55.28%, 55.85%, and 52.42% respectively; and the increased proportions in the areas of forests' NEP with the

value of 0.31–0.60 kg(C)·m^{-2}·yr^{-1} during these periods will be 15.21%, 15.86%, 17.07%, and 19.68%, respectively.

The impacts of future climate change on the NEP of global forest ecosystems will vary significantly with different regions. Under the future moderate emissions RCP4.5 scenario, the forest ecosystems in the northern hemisphere will mainly serve as a carbon sink. The carbon sink regions of global forests will be mainly distributed in the middle and high latitudes of the northern hemisphere. In particular, the forests' NEP in Northeast Asia, Western Europe, and western North America will increase by 0.01–0.30 kg(C)·m^{-2}·yr^{-1} in 2026–2085. During 2086–2100, the forests' NEP in the Northern and Southeast Asia, and Southeast North America will increase by 0.31–0.60 kg(C)·m^{-2}·yr^{-1}. In addition, the NEP in northeastern and central Asia, Western Europe and western North America will increase by 40%~80% during 2026–2100 (Fig. 2–5). However, the forest ecosystems in the southern hemisphere will mainly serve as a carbon source. The forests' NEP will decrease by 20%~40% in the most regions of the southern hemisphere. In northern South America and central Africa, the forests' NEP will be reduced by more than 40% (Fig. 2–5).

Response of the NEP in global forest ecosystems to future RCP8.5 climate scenario

Climate warming will still promote the carbon sequestration of global forest ecosystems under future RCP8.5 climate scenario. The proportions of carbon sink area of global forests will increase. Especially, during 2026–2045, 2046–2065, 2066–2085, and 2086–2100, the proportions of the carbon sink area of the global forest ecosystems under future scenario RCP8.5 increased by 27.64%, 29.62%, 29.13%, and 23.53%, respectively, compared to in 2006–2025 (Fig. 6). Moreover, in 2086–2100, the carbon sink areas with NEP values between 0.21–0.40 kg(C)·m^{-2}·yr^{-1} and 0.41–0.60 kg(C)·m^{-2}·yr^{-1} will increase by 25.88% and 75.16% compared to in 2006–2025, respectively. However, the carbon sink areas with NEP values between 0.01 kg(C)·m^{-2}·yr^{-1} and 0.20 kg(C)·m^{-2}·yr^{-1} in global forest ecosystems will decrease by 13.96% compared to in 2006–2025.

Discussion

Carbon sink effects of global forest ecosystems

As the dominant biomes in the biosphere, forest ecosystems have the richest species composition and the most complex hierarchical structure, and serves as an important "buffer" in the biogeochemical processes of the biosphere and in adjusting the global carbon balance by reducing greenhouse gas concentrations and maintaining the global climate [1, 33]. Research indicated that the CO_2 in the atmosphere was exchanged with the terrestrial biosphere through photosynthesis every seven years, 70% of which occurs in forests [25]. Interactions between forest ecosystems and climate systems are carried out through the energy balance, water vapour exchange, and biogeochemical cycle. The climate provides necessary environmental resources for forest growth and physiological metabolism, as well as energy

and material resources which determine the composition, distribution, productivity, and intensity of the biogeochemical cycle of the ecosystem [18]. In turn, changes in the composition, distribution, and function of forest ecosystems affect climatic factors, such as the contents of greenhouse gases and bio-aerosols in the atmosphere [13, 22].

According to the IPCC, the global average surface temperature has increased by approximately 0.8 °C since the late 1800s [14]. Consequently, the increased air temperature had a significant, positive impact on the NEP of forests by influencing the high winter and early spring temperatures, favouring forest precocious assimilation [2]. On a global scale, we found that the forest ecosystems mainly served as carbon sinks, and the impacts of climate change on the NEP per unit area of forest ecosystems per year during 2006 – 2100 would be generally positive. Under future moderate emission RCP4.5 scenario, the average absorbed carbon by global forest ecosystems from 2006 to 2100 will be 0.017 $kg(C)\cdot m^{-2}\cdot yr^{-1}$. This further demonstrates that future climate change will overall increase the carbon sequestration of global forest ecosystems. Our results are similar to those of previous studies [2, 19, 20, 33]. For example, Pan et al. [20] stated that the global total annual forest carbon sink from 1990 to 2007 was 2.4 ± 0.4 $Pg(C)\ a^{-1}$, according to the forest resources inventory data and long-term ecosystem carbon research data. Zhao et al. [33] demonstrated that global forest ecosystems represented a large carbon sink from 1982 to 2011, and that the total NEP by evergreen broad-leaved forests, evergreen coniferous forests, deciduous broad-leaved forests, deciduous coniferous forests, and evergreen coniferous deciduous broad-leaved mixed forests was 0.388, 0.116, 0.082, 0.048, and 0.044 $kgC\cdot m^{-2}\cdot yr^{-1}$, respectively. Our future global forecasts about NEP of global forest ecosystems were also roughly the same as the global results from Yu et al. [31] who showed that future climate scenarios (whether RCP 2.6, 4.5, or 8.5) were estimated to increase the mean global terrestrial NPP for all ecoregion types, when comparing values for 2071–2100 to the baseline (1971–2000) period.

Spatial variability in the NEP of global forest ecosystems and adaptation strategy

On the regional or global scale, there are spatial differences in the forests' NEP due to differences in climate change, land use, soil vegetation change, forest management, regeneration of deforestation, fire, insect disaster, and other disturbances. Some studies have suggested the high northern latitudes (> 55° N) are one of the largest carbon sink regions and have become warmer and drier in recent decades due to the rising temperatures [11]. Dixon et al. [8] summarised the NEP of global forest ecosystems based on a large number of documents and found that the forests in low-latitude areas (0–25°) mainly served as carbon sources, particularly those in Africa. In this study, we found the forest ecosystems in the northern hemisphere mainly served as carbon sinks, while the forest ecosystems in the southern hemisphere mainly served as carbon sources. In particular, the forests'NEP in northeastern and central Asia, northern Europe and western North America from 2026 to 2100 will increase by 40%~80% compared in 2006–2025. However, the NEP of forests will decrease by 20%~40% in the most regions of the southern hemisphere. Our results are basically consistent with the previous conclusions from Dixon et al. [8] and Forkel et al. [11]. In order to ensure immediate mitigation and adaptation to future climate change, some

measures should be implemented for improving forest carbon sink in these areas where the NEPs were predicted to be reduced, such as strengthening forest tending, enforcing prohibiting deforestation laws and scientific forest management, and so on [32].

Uncertainties and prospects

There are still some uncertainties in forecasting the future NEP of forest ecosystems on a global scale, thereby possibly amplifying the simulation results. In this study, the individual tree-based carbon budget FORCCHN model based on the basic principles of plant physiology, forest ecology, and soil environment was adopted, which could explain the dynamics of the NEP of forest ecosystems under future climate change [19, 30, 33]. However, the influences of other important factors affecting the growth and development of forests were not considered in the FORCCHN model, such as fires, pests, extreme weather events, and other biogeochemical factors. The limitations presented here potentially impacted the accuracy of the final simulation results. These effects will be considered in the next version of the FORCCHN model in the future, greatly reducing the uncertainty of the final simulation results. Additionally, the FORCCHN model could only simulate the carbon flux on a unit scale and assume that the land cover type was constant. The forest areas' reduction through tree death could be simulated, but it could not simulate forest areas' expansion. In recent decades, the increased carbon sink areas of global forest ecosystems were mainly caused by the growth of trees. Finally, the global daily meteorological datasets with a grid resolution of 1.25°× 0.9° in the future climate scenarios from the simulation results of Community Climate System Model version 4 (CCSM4) were applied in this study. All the future meteorological data corrected based on CRU-JRA data sets were finally resampled to the resolution of 0.5°×0.5°. Nevertheless, there might be some spatial variabilities that led to low levels of uncertainty in determining forests' NEP.

Despite above restrictions, the results of this work offered a more comprehensive understanding of the response of the NEP of global forest ecosystems to future climate change at a global scale. Generally, the NEP of forest ecosystems is not only limited by climate factors, but also closely related to the cycles of nitrogen, phosphorus, sulfur, and other geochemical elements, which have certain constraints and influences on plant photosynthesis, litter formation, structure and decomposition, and soil respiration [33]. Future research should consider the synergistic effects of other chemical elements and climate factors.

Conclusions

This study demonstrated the responses of the NEP of global forest ecosystems to future climate change based on the individual tree species forest ecosystem carbon budget model FORCCHN and future climate scenario dataset. The global forest ecosystems will mainly serve as carbon sinks from 2006 to 2100 under the future RCP4.5 and RCP8.5 climate scenarios. In the future, impacts of climate change on the NEP of global forest ecosystems exhibited significant regional differences. Overall, the forest ecosystems in the northern hemisphere mainly served as carbon sinks. The carbon sink regions of global forests will be mainly distributed in the middle and high latitudes of the northern hemisphere. The NEP in

northeastern and central Asia, Western Europe and western North America in the northern hemisphere will increase by 40%~80% during 2026–2100. However, the forest ecosystems in the southern hemisphere will mainly serve as a carbon source. The forests' NEP will decrease by 20%~40% in the most regions of the southern hemisphere. In northern South America and central Africa, the forests' NEP will be reduced by more than 40%

In summary, our findings can offer important information support for the realization of global sustainable development goals, and provide scientific basis for correctly evaluating the role of forests in ecological environment construction and global climate change research. However, the carbon budget process and its evolution in the forest ecosystems are complex. To objectively and accurately resolve these issues, it is necessary to deeply understand the carbon cycle process and mechanism in forest ecosystems and their responses to the greenhouse effect, and connect it with the biogeochemical cycle of other circles. Future studies should consider additional factors affecting the global forests' NEP based on observations and modelling. Furthermore, efforts should be devoted to simultaneously modifying the biogeochemical cycle module of the FORCCHN to allow it to be more accurately applied to global conditions.

Declarations

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Authors' contributions

HX and JM led the data collection and calculation. HX, JZ and WY did the data analyses and led the writing of the manuscript. All authors contributed to the drafts and gave final approval for publication. All authors read and approved the final manuscript.

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Availability of data and materials

All the data are available upon request to corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1

Main characteristics of the FORCCHN model

Characteristic	Detailed description
Initial conditions	Field water holding capacity, soil carbon storage, soil nitrogen storage, and remote sensing LAI data.
Boundary variables	Daily maximum temperature, minimum temperature, average temperature, precipitation, relative air humidity, total radiation, average wind speed, average air pressure, and atmospheric CO2 concentration.
Material balance scheme	Complete carbon balance, and nitrogen and water in the atmospheric-soil-forest ecosystem
Time step and scheme	Daily carbon and nitrogen uptake, litter flux and respiration flux per tree; Daily soil carbon, nitrogen, and water are imported and exported; Daily forest carbon and nitrogen uptake and litter flux in patches; Calculations of carbon accumulation per tree, flower, and fruit litter flux, and tree DBH; and growth, tree height growth, and subbranch height growth year by year.
Carbon and nitrogen budget module per tree per day	Considering total photosynthesis, maintenance respiration, growth respiration, distribution, and the litter of photosynthate, the photosynthate buffer pool scheme was adopted to enhance resistance to extreme climatic conditions.
Daily soil carbon and nitrogen budget module	An improved CENTURY model suitable for forest soils is adopted so that the decomposition and respiration of forest soils can be temporarily considered as valid in the absence of validation data.
Annual tree growth	Calculations of annual photosynthate distribution, flower and fruit litter, tree DBH, tree height, under-branch height, and potential maximum leaf volume in the buffer pool.

Figures

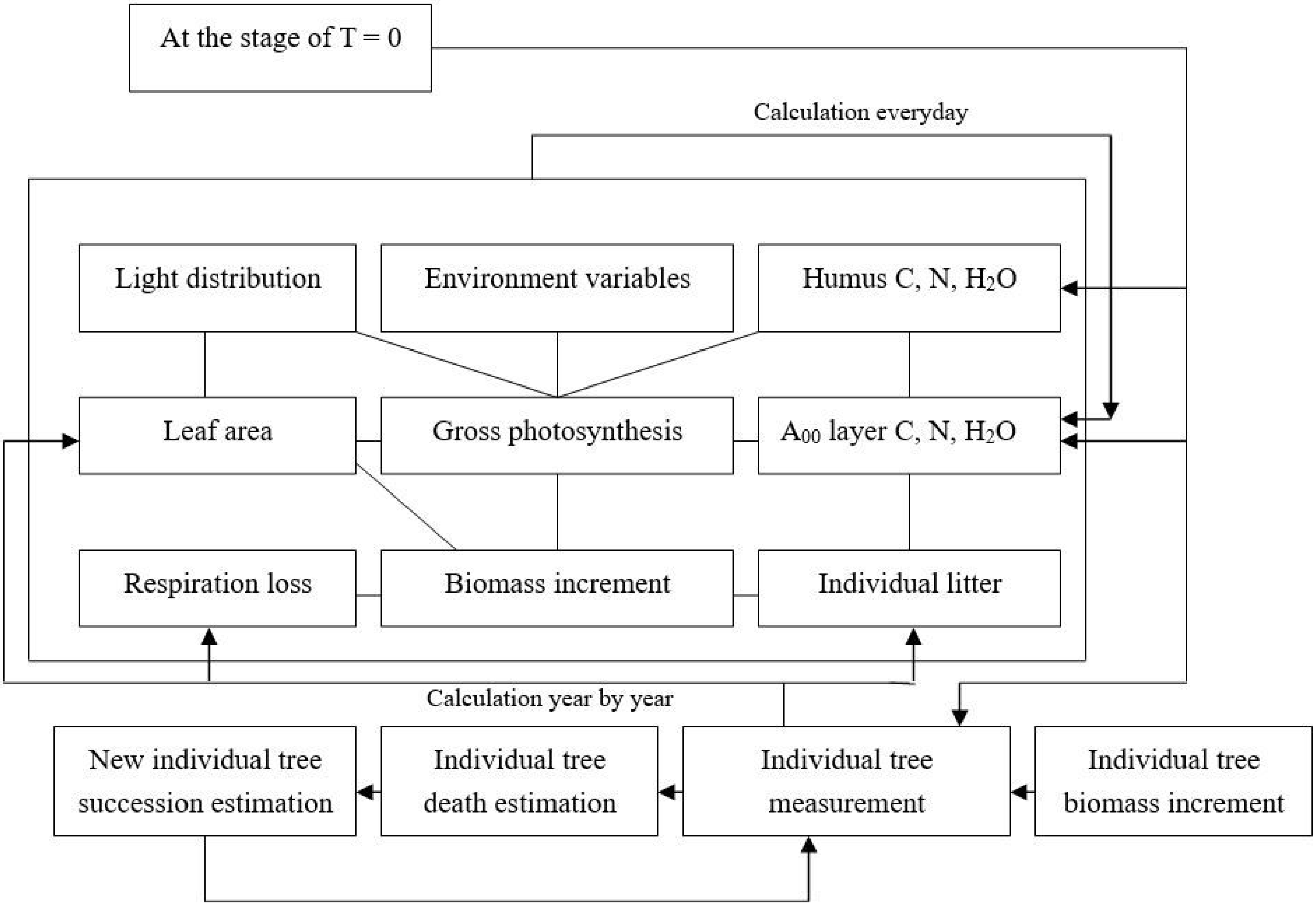
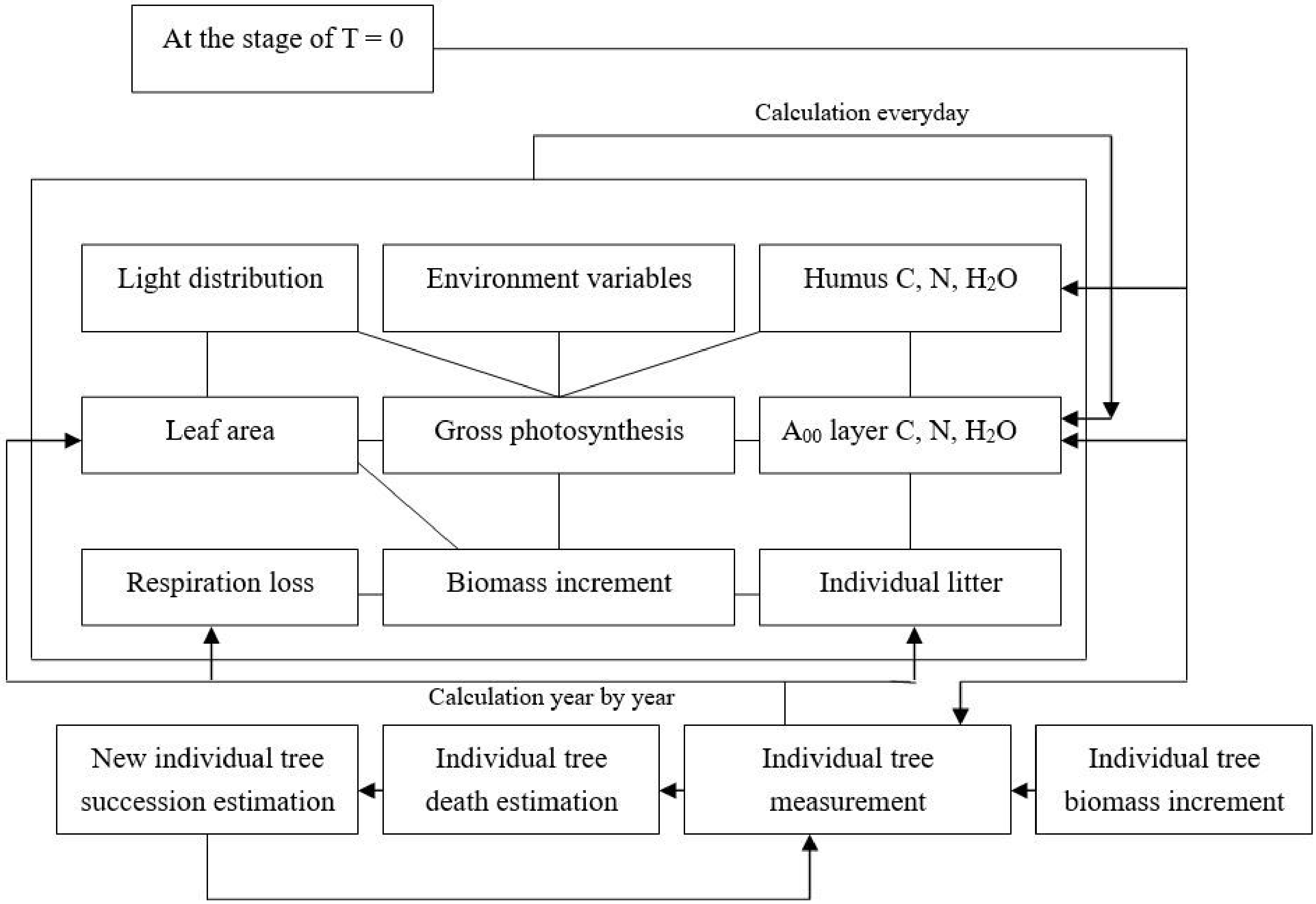


Figure 1

Primary processes and flow chart of the FORCCHN model



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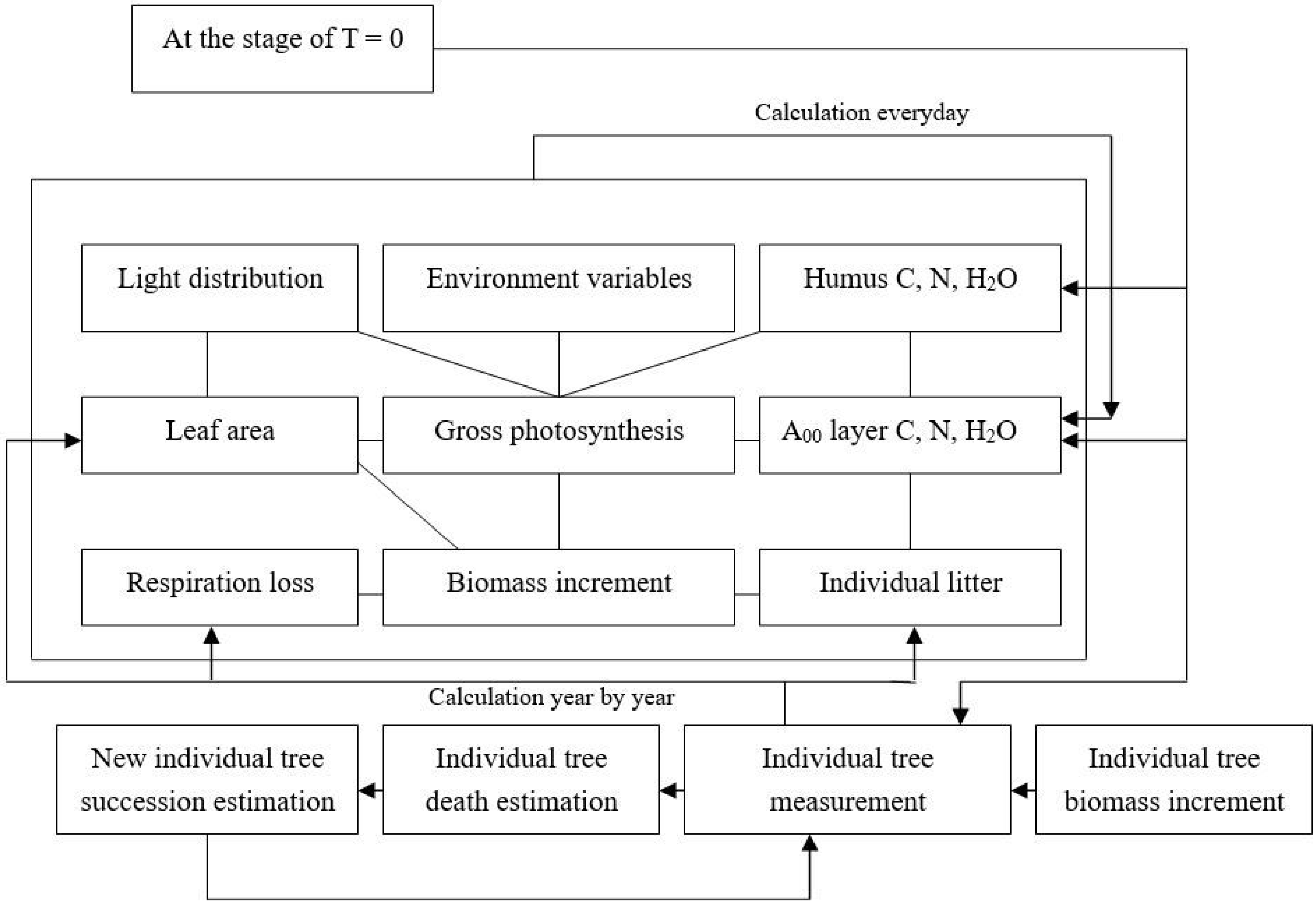

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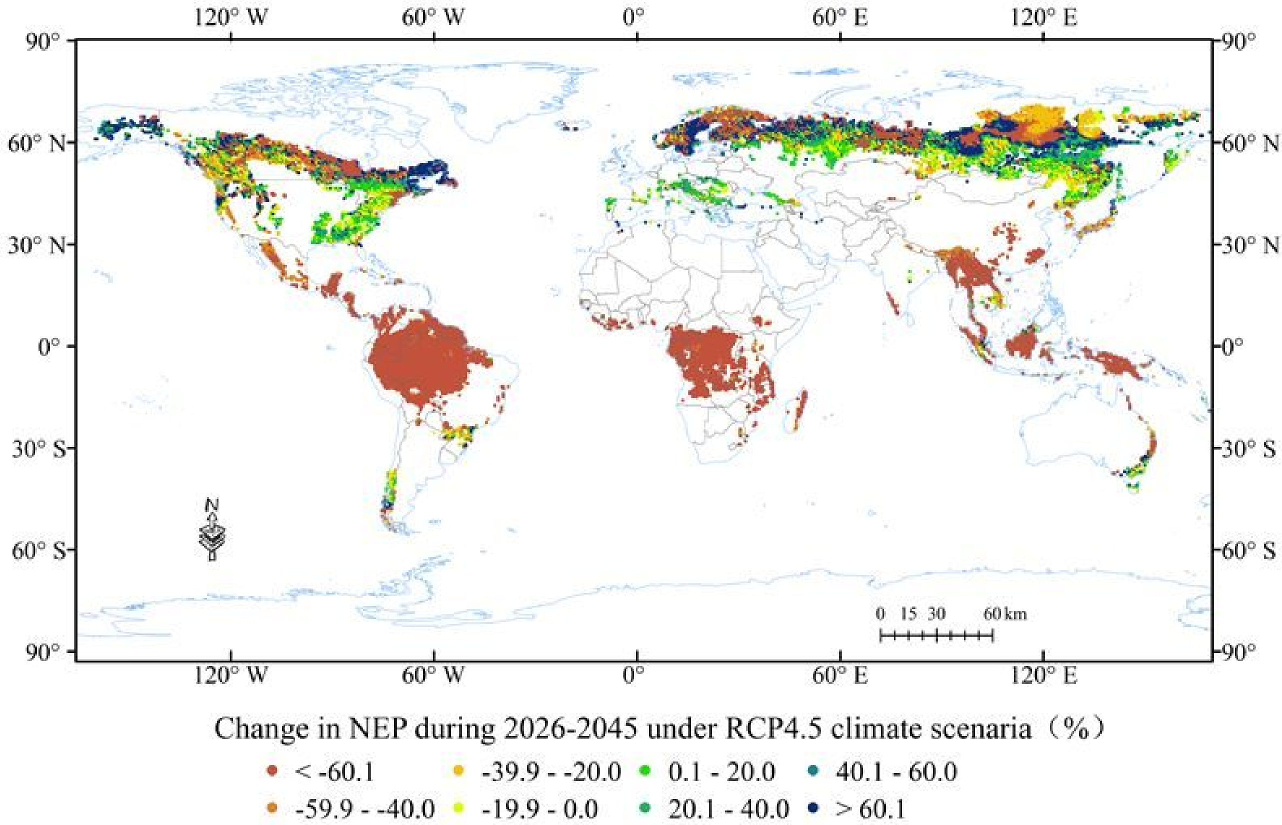
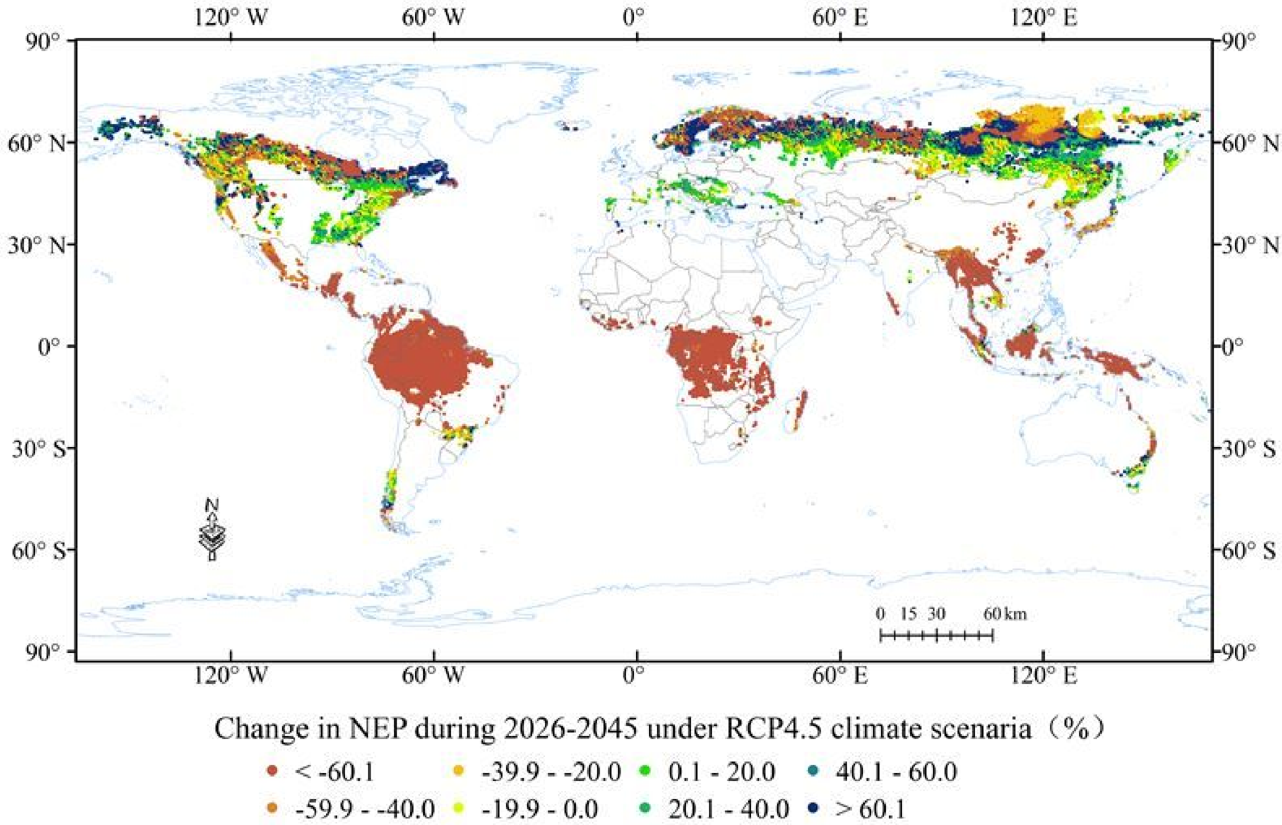


Figure 2

Change in NEP of global forest ecosystems under future RCP4.5 climate scenario during 2026–2045 compared than in 2006–2025 (%) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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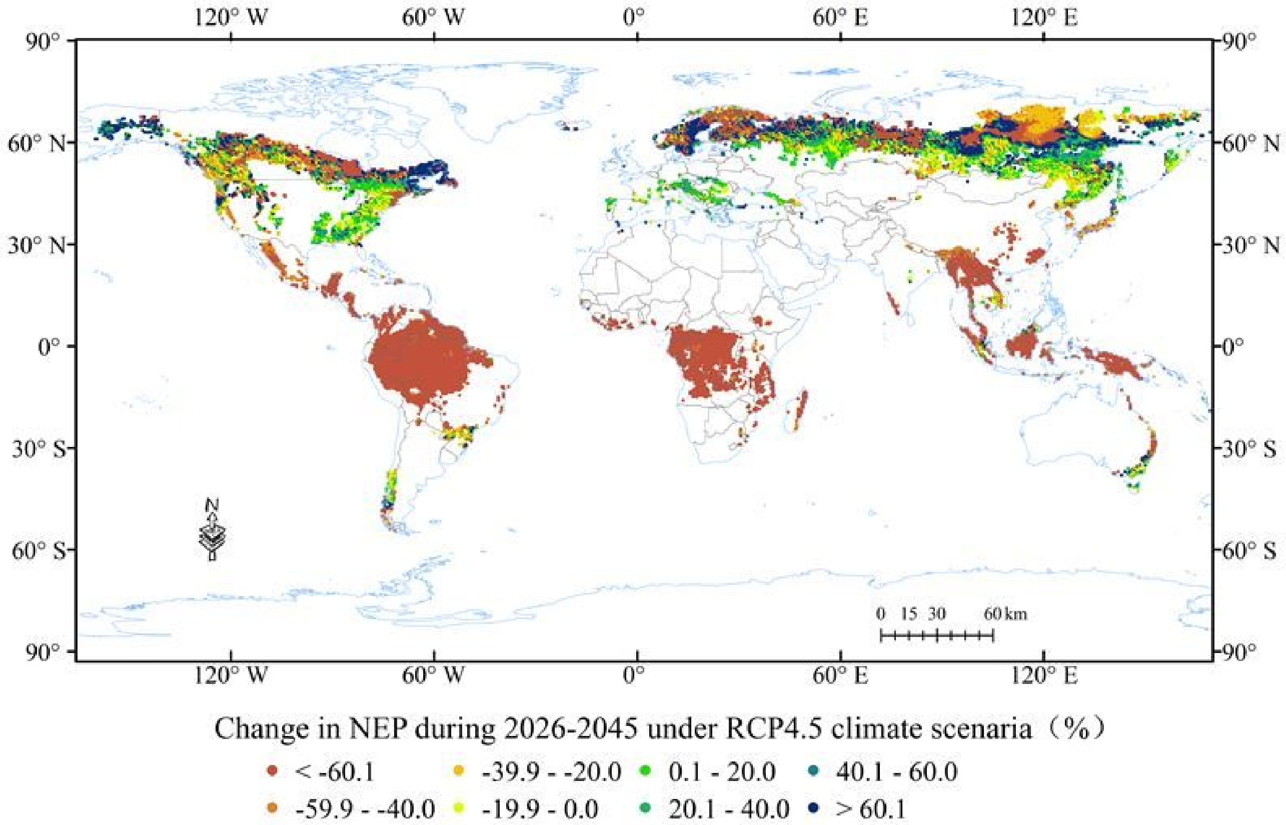

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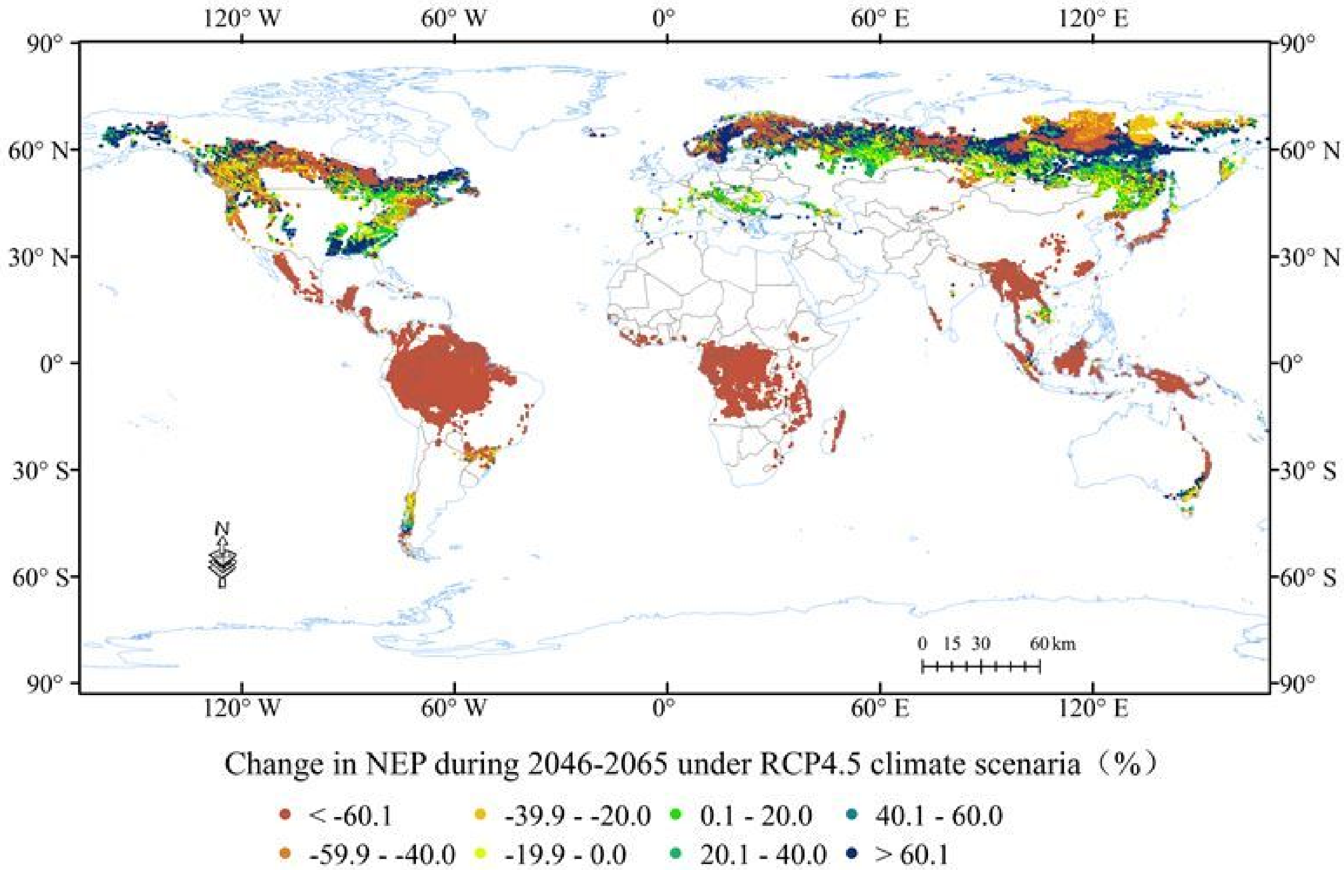

Figure 3

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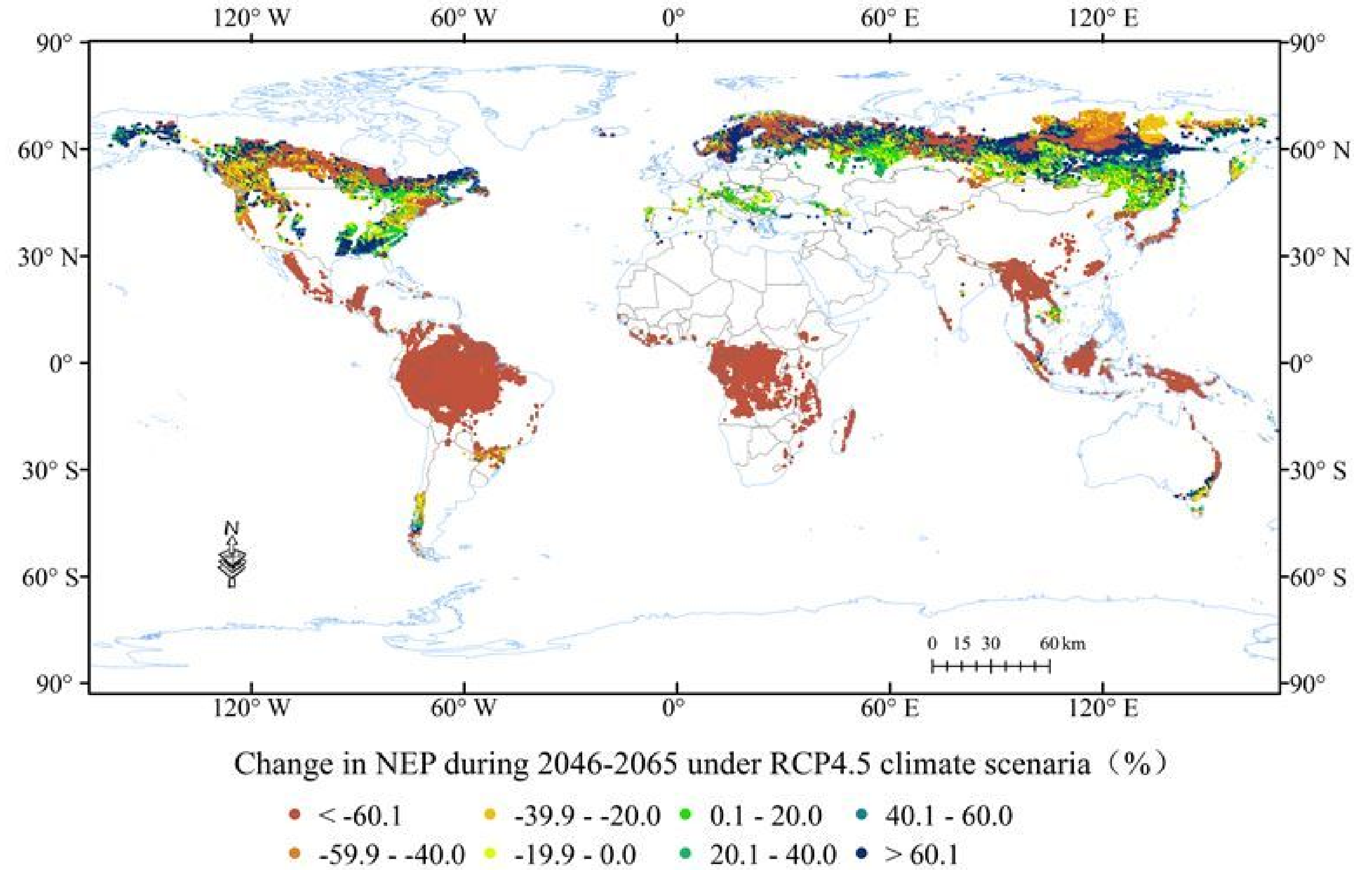

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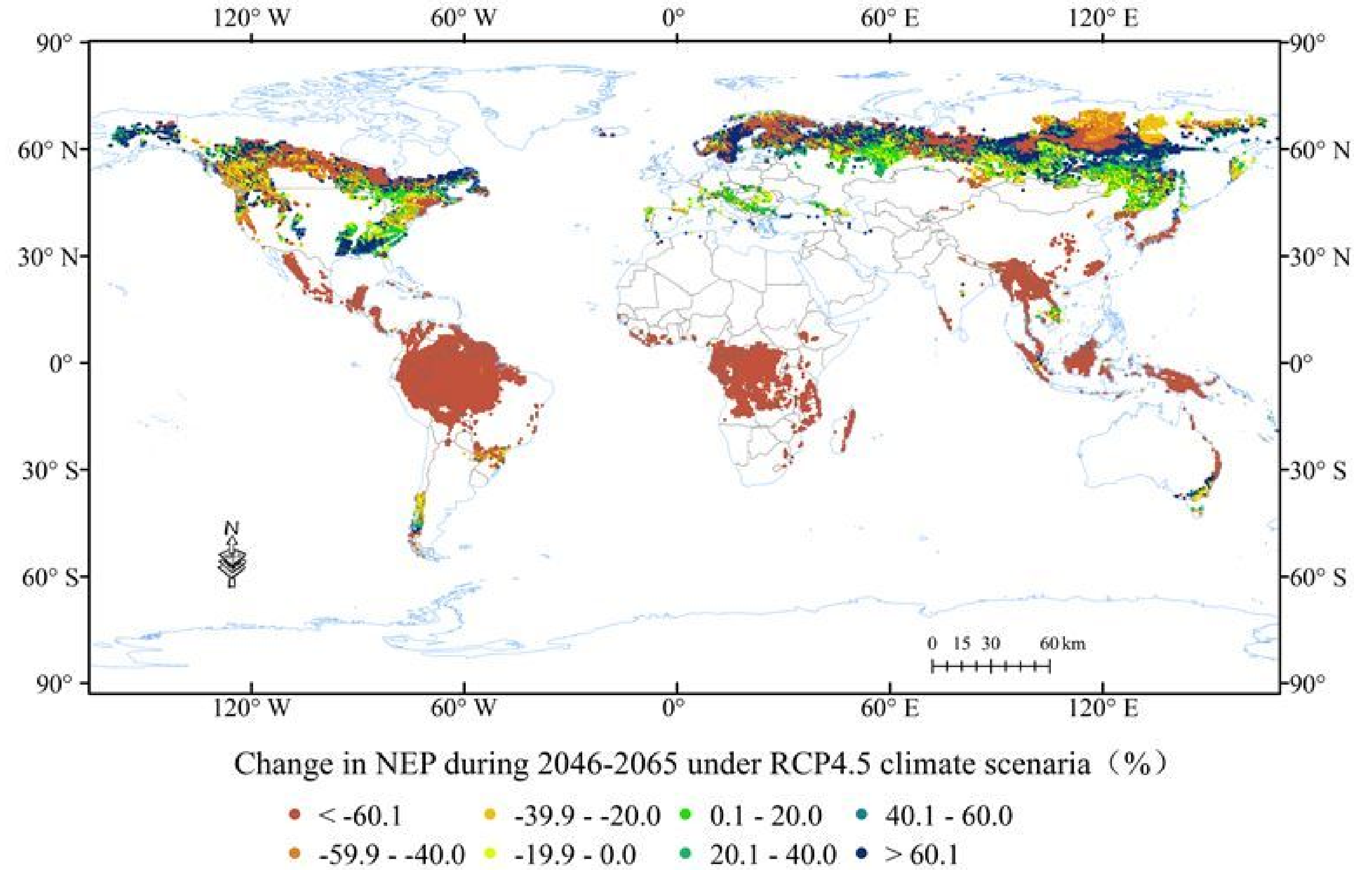

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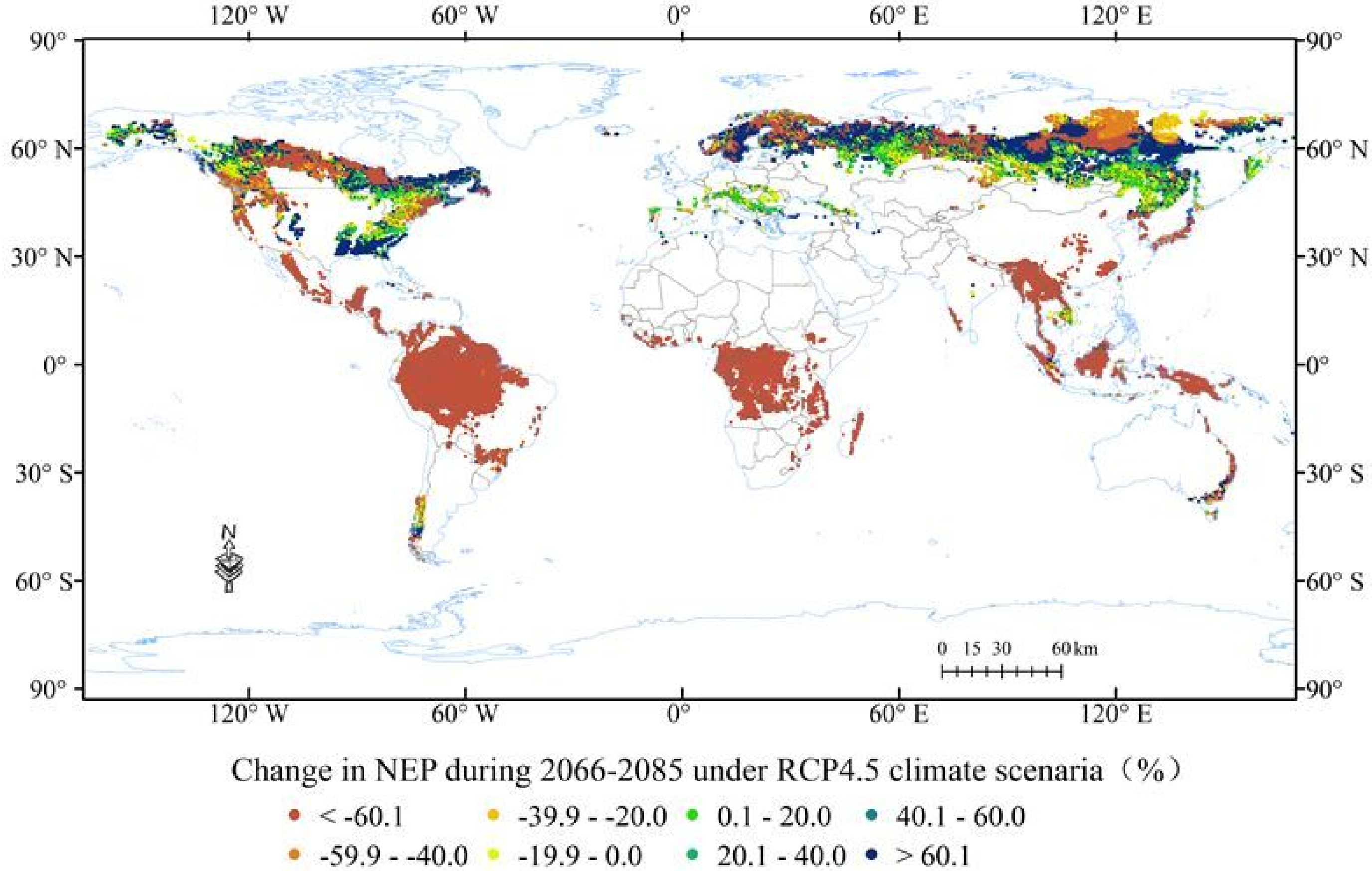
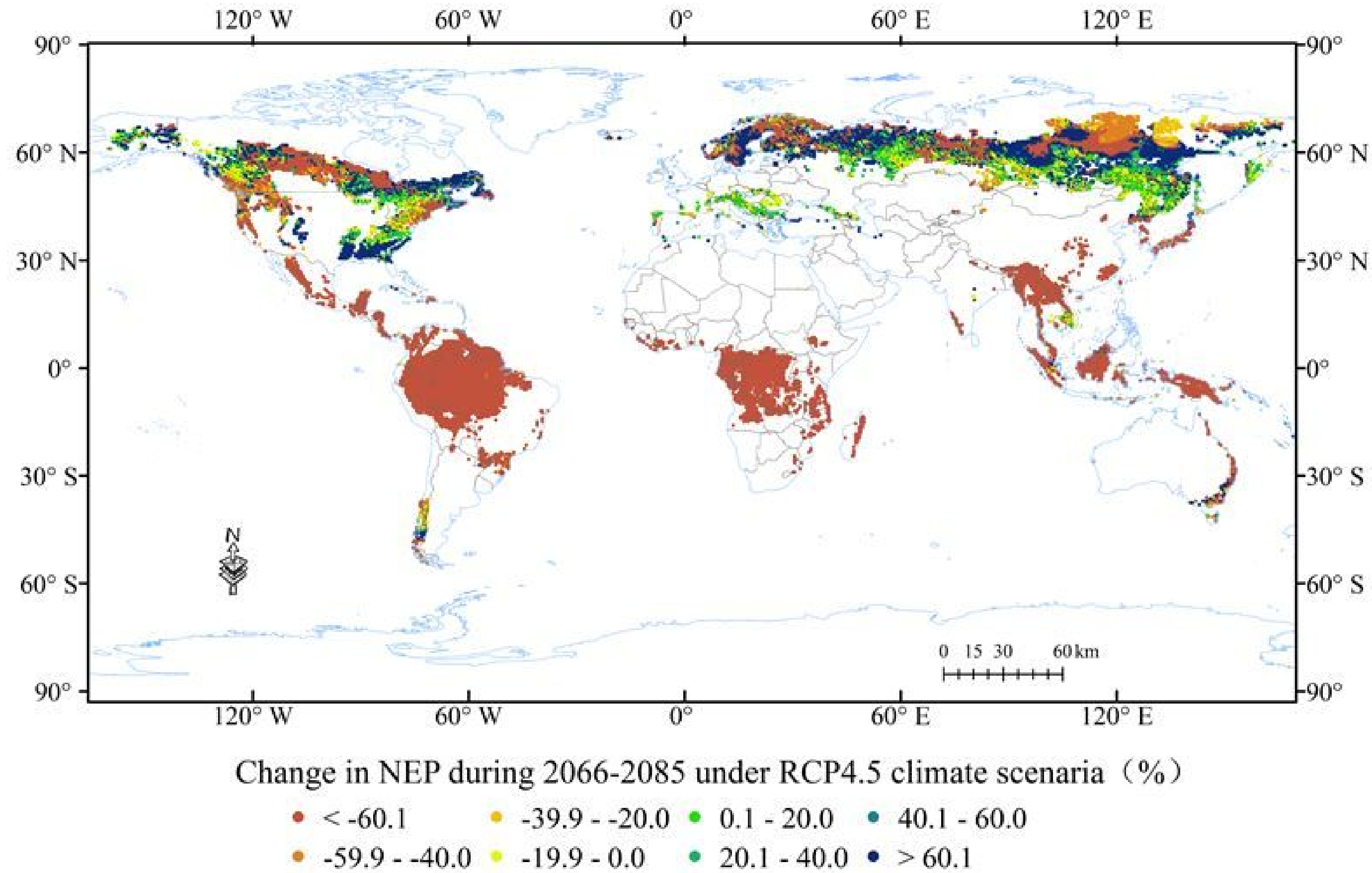


Figure 4

Change in NEP of global forest ecosystems under future RCP4.5 climate scenario during 2066–2085 compared than in 2006–2025 (%) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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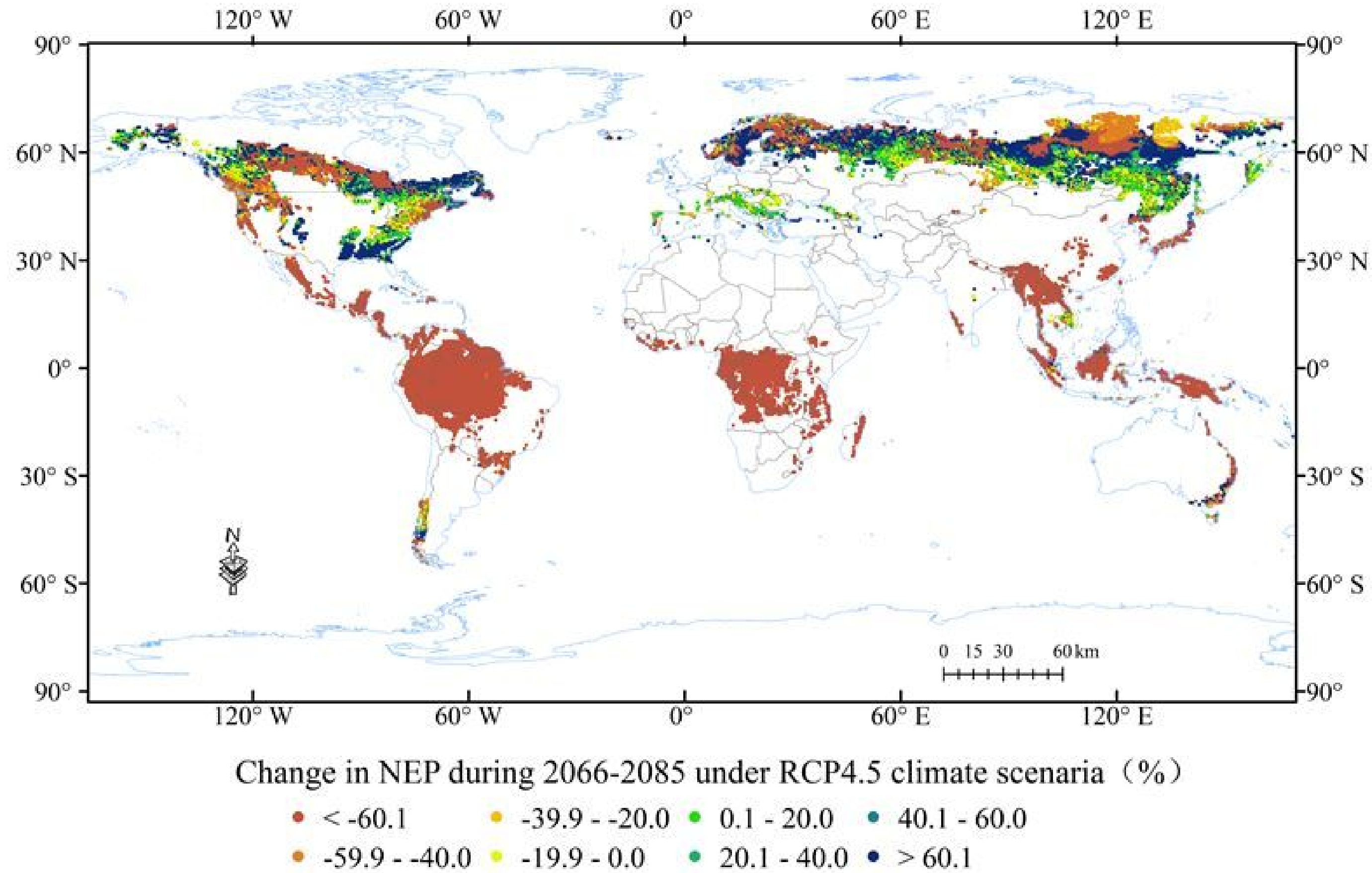

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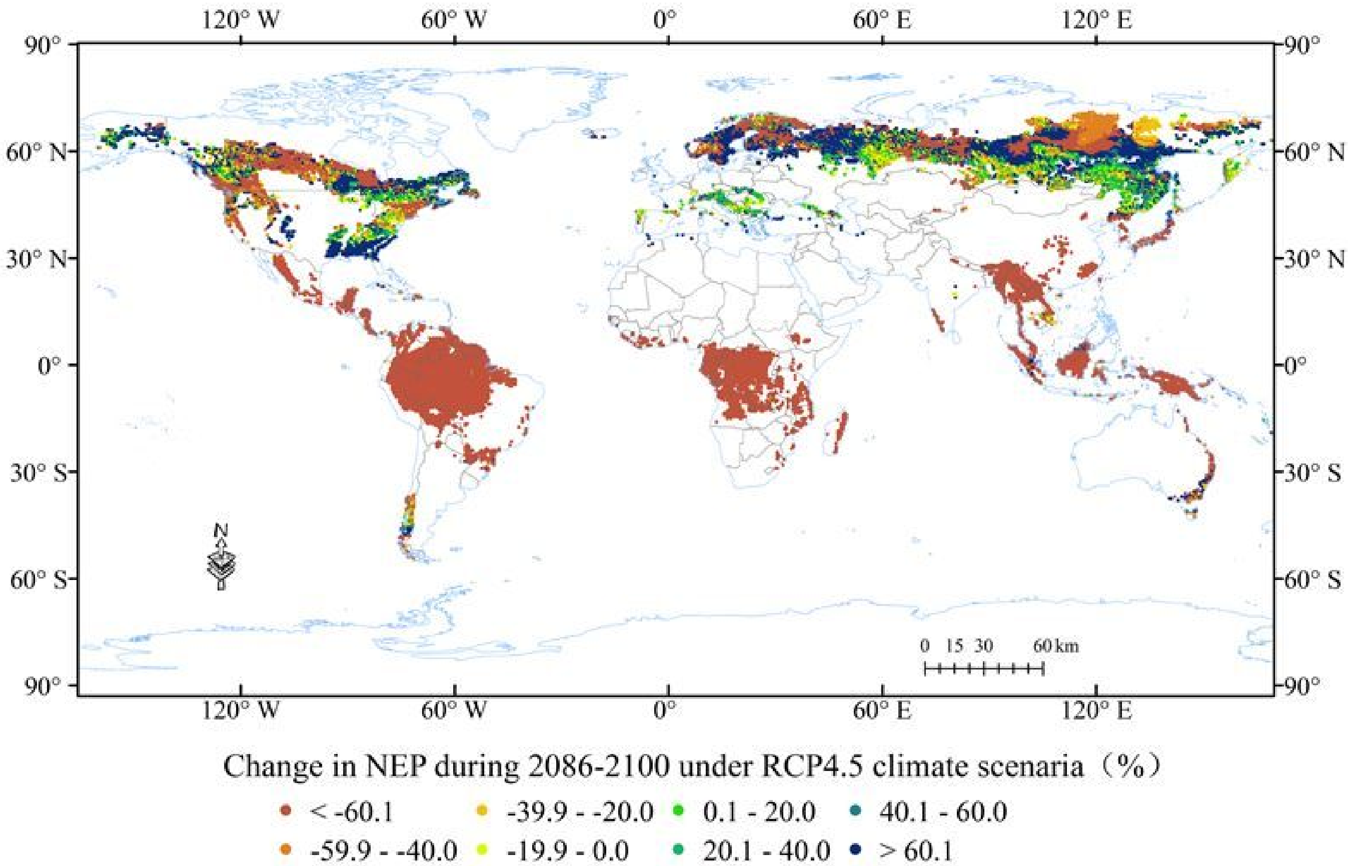
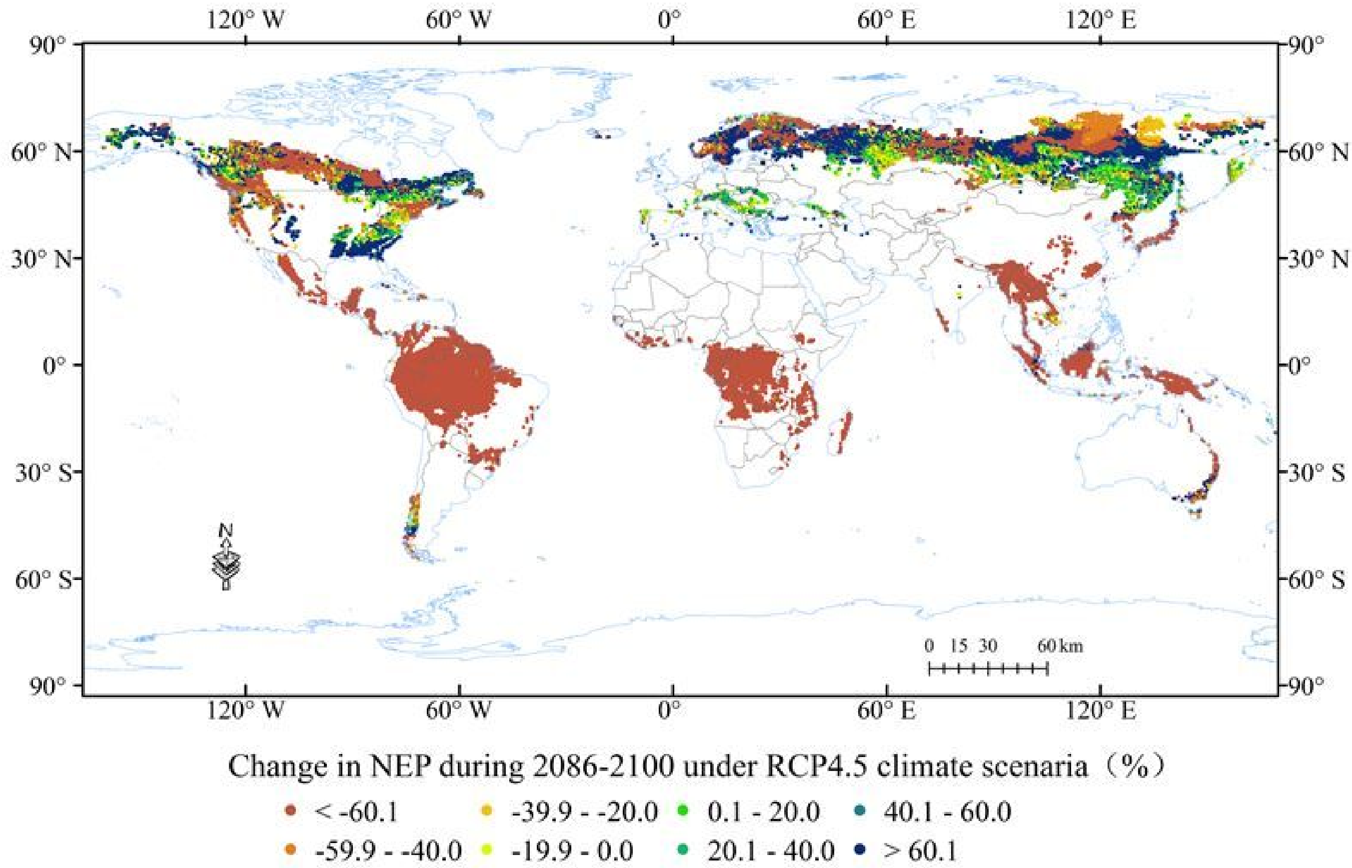


Figure 5

Change in NEP of global forest ecosystems under future RCP4.5 climate scenario during 2086–2100 compared than in 2006–2025 (%) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



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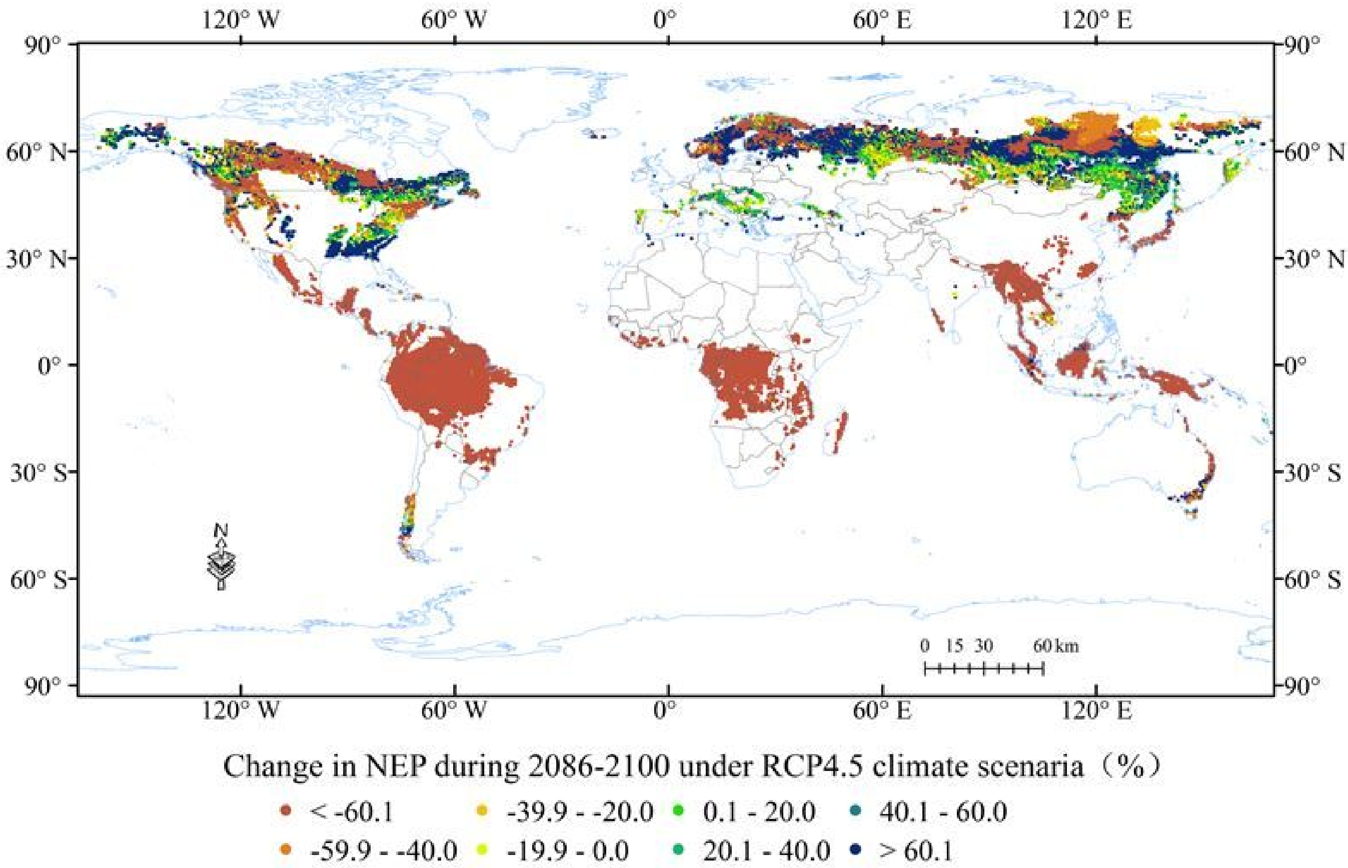

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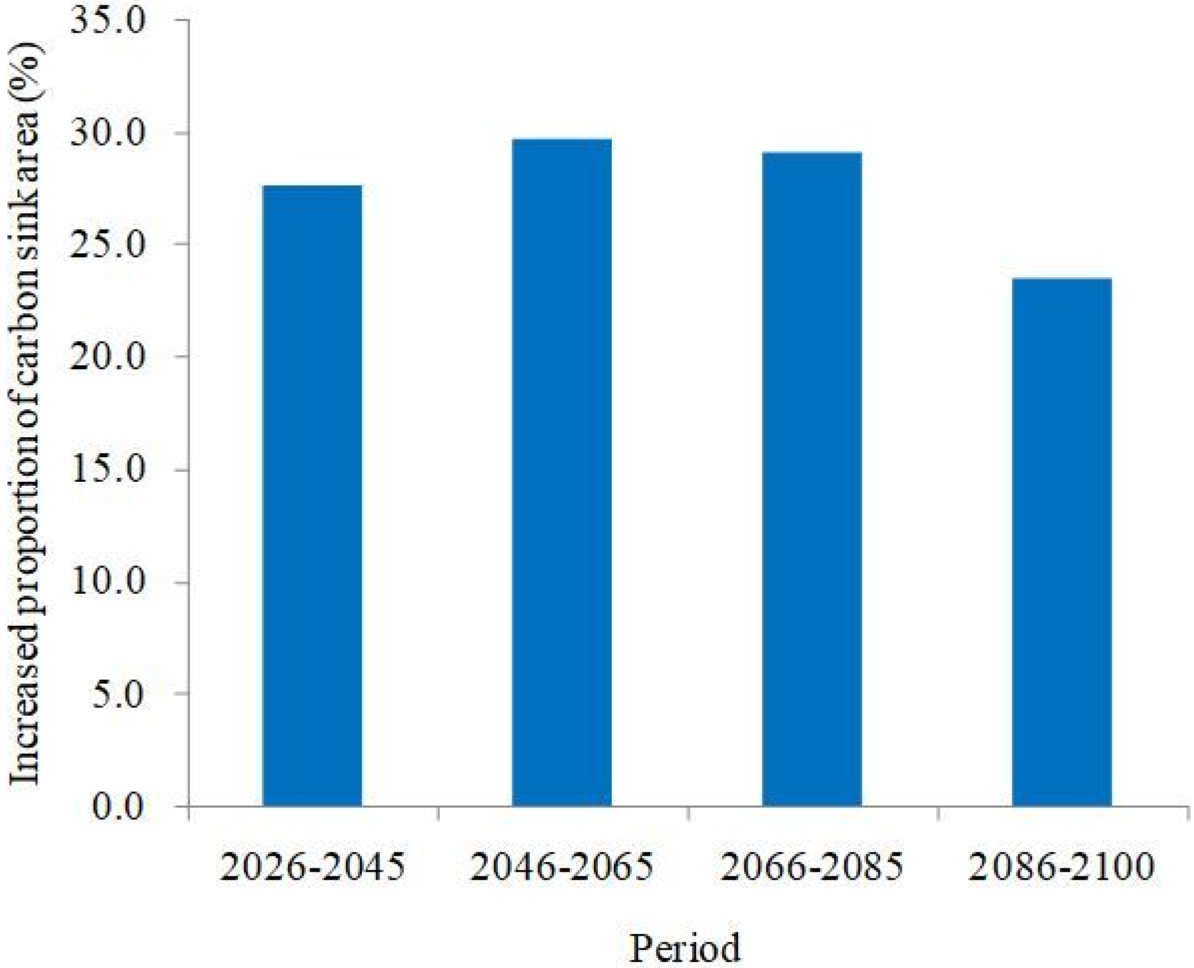
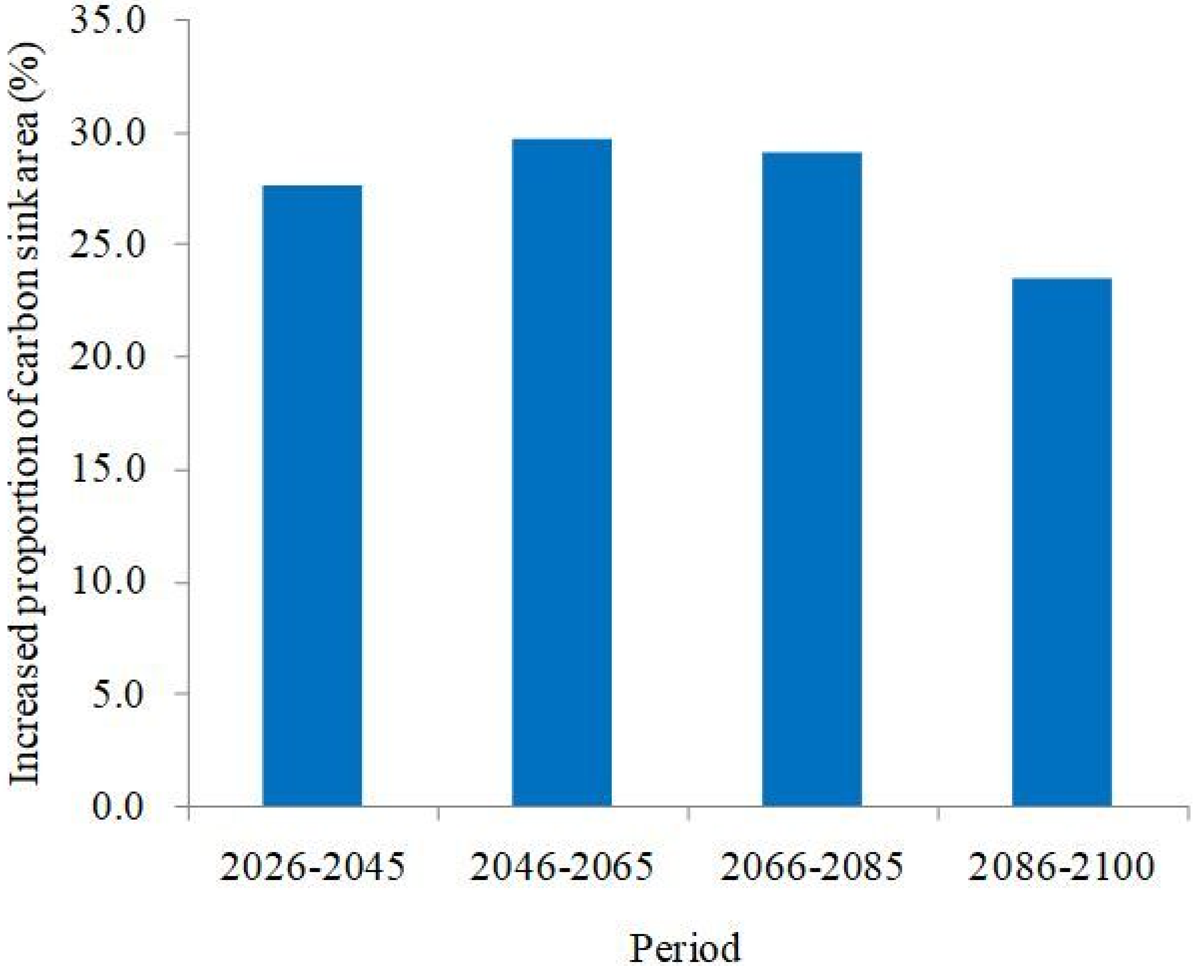


Figure 6

Increased proportion of the carbon sink area of global forest ecosystems under future scenario RCP8.5 compared to the period of 2006-2025



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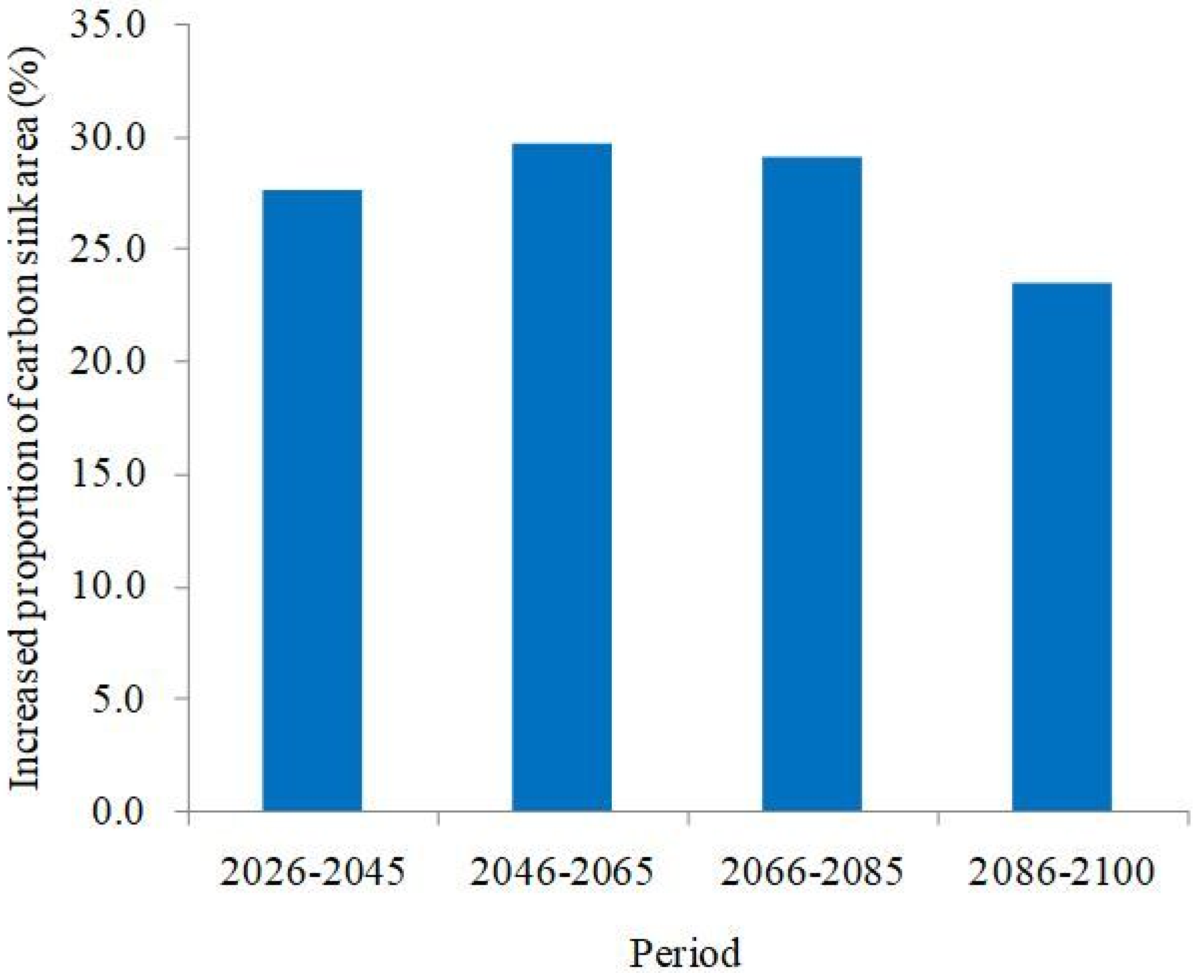

Figure 6

Increased proportion of the carbon sink area of global forest ecosystems under future scenario RCP8.5 compared to the period of 2006-2025

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