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Forest Change and Population Redistribution Reshaped China's Human–Forest Nexus over Three Decades: Contrasting Natural and Planted Forests

Ze Meng [1], Fangyu Ding [2,3,*], Mengmeng Hao [2,3], Shuai Chen [2,3], Jun Zhuo [2,3], Jiping Dong [2,3], Zhichao Li [2,3], Haochen Yu [2,3], Jiaqi Li [2,3] and Hua Wu [1]

[1] School of Engineering, Xizang University, Lhasa 850000, China; mengze@igsnrr.ac.cn (Z.M.); xzwhua@163.com (H.W.)
[2] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; haomm@igsnrr.ac.cn (M.H.); chenshuai@igsnrr.ac.cn (S.C.); zhuojun6545@igsnrr.ac.cn (J.Z.); dongjiping2017@igsnrr.ac.cn (J.D.); lizc@igsnrr.ac.cn (Z.L.); yu.haochen.hc@gmail.com (H.Y.); lijiaqi241@mails.ucas.ac.cn (J.L.)
[3] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: dingfy@igsnrr.ac.cn

Abstract

China has experienced extensive forest expansion alongside rapid urbanization and large-scale population redistribution over the past three decades, yet how these transformations have reshaped the spatial relationship between people and different forest types remains unclear. Here, we quantified changes in forest–population relationships across China from 1990 to 2020 using forest area per person (FAP), forest-proximate people (FPP), and the forest–human nexus (FHN), for all forests combined and for natural and planted forests separately. Although total forest area increased by 9.3%, population growth resulted in an 11.5% decline in FAP. The share of the population living within 5 km of any forest increased from 57.4% to 62.4%, but divergent trajectories emerged between forest types: proximity to natural forest declined from 56.2% to 51.3%, whereas proximity to planted forest increased from 30.5% to 47.5%. FHN for all forests increased by 26.2% and planted-forest FHN by 59.5%, while natural-forest FHN remained broadly stable (−1.9%). Shapley decomposition further revealed substantial spatial heterogeneity in the contributions of forest change and population redistribution, with forest change contributing most to increases in FHN for all forests and planted forests at the national scale, while the two processes acted in opposing directions for natural forests. These findings provide a more complete, population-explicit perspective on China's evolving human–forest relationship and offer a spatial basis for sustainable forest management, conservation, restoration, and land-use planning.

Keywords: forest–human nexus; forest proximity; natural forest; planted forest; population redistribution; China

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1. Introduction

Forests are fundamental to the Earth system, supporting biodiversity, regulating climate and water cycles, storing carbon, and sustaining ecosystem services and livelihoods essential to human well-being [1–3]. In China, large-scale afforestation, ecological restoration, and conservation programs have substantially expanded forest cover, enhanced terrestrial carbon uptake, and made the country a major contributor to global greening [4–7]. Meanwhile, rapid urbanization and large-scale internal migration have

profoundly reshaped population distribution, increasingly concentrating people in urban and economically developed regions [8,9]. These changes in forests and population have reshaped how forests and human populations are distributed across China.

The spatial relationship between forests and people has received increasing attention because proximity to forests shapes the context in which people and forest ecosystems interact [10–15]. Living closer to forests may increase opportunities to benefit from ecosystem services, recreation, cultural values and forest-based livelihoods, while exposure to natural environments has also been associated with physical and mental health benefits [3,16–18]. At the same time, closer human–forest contact is not universally beneficial. Expansion of settlements, infrastructure and other human activities into forested landscapes can intensify habitat degradation, fragmentation and biodiversity loss [19–21], while increasing contact among people, livestock and wildlife may create conditions conducive to zoonotic disease emergence and transmission [22–24].

Recent global studies have moved beyond conventional forest-area accounting by explicitly considering where forests occur relative to human populations. Forest area per person (FAP), forest-proximate people (FPP), and the forest–human nexus (FHN) provide complementary measures of forest availability and population proximity to forests [10,12]. Natural and planted forests differ substantially in biodiversity value, ecosystem functioning, carbon and water dynamics, and vulnerability to environmental stress [25–30]. These distinctions are particularly relevant in China, where large-scale afforestation and restoration have substantially increased planted-forest area while natural and planted forests have followed markedly different long-term trajectories [31,32]. However, these two dimensions of forest change—forest type and human proximity—have largely been considered separately. Consequently, aggregate increases in forest proximity may conceal fundamentally different trajectories in human relationships with natural and planted forests.

A second unresolved issue concerns the processes underlying changes in forest–population proximity. A population may become closer to forests because forests expand or redistribute relative to populated areas, because populations redistribute relative to forests, or because both processes occur simultaneously [10,12]. More broadly, migration and demographic redistribution can substantially reshape interactions between populations and forested landscapes [33,34]. China has undergone extensive ecological restoration and forest expansion over recent decades [35,36]. Over the same period, rapid urbanization and internal migration substantially reshaped the spatial distribution of its population [8,9,37,38]. Although different pathways can produce similar net changes in proximity metrics, they represent distinct land-system and demographic processes and may therefore have different ecological, societal, and management implications. Distinguishing them is necessary for determining whether an apparently stable or increasing human–forest relationship reflects forest recovery, demographic redistribution, or opposing processes that offset one another. Taken together, these gaps leave the following unresolved: whether aggregate forest gains conceal divergent trajectories in human relationships with natural and planted forests, and what the respective contributions of forest change and population redistribution are to observed changes in forest proximity.

To address these gaps, changes in China's forest–population relationship between 1990 and 2020 were examined during a period of extensive forest restoration, urbanization, and internal migration. FAP, FPP, and FHN were quantified for all forests combined and for natural and planted forests separately. A symmetric two-factor Shapley decomposition was then applied to attribute changes in forest–human proximity to forest change and population redistribution. By resolving these changes across forest types and separating the contributions of forest change and population redistribution, the study provides a spatially explicit basis for informing more sustainable forest restoration and land-use planning.

2. Materials and Methods

2.1. Study Design and Data

Forest–population relationships across China were characterized between 1990 and 2020. Analyses were conducted for all forests combined and for natural and planted forests separately using the same population surfaces, spatial framework, and metrics. For the aggregate analysis, all forests were defined as the union of natural- and planted-forest pixels.

Forest distributions were obtained from the 1 km China natural and planted forest map series for 1990–2020 [31,39]. Natural and planted forests were extracted from their corresponding mapped classes, and the annual layers were aligned to a common projected 1 km grid using nearest-neighbor resampling to preserve the categorical identity of forest classes. Total forest area was derived from the combined natural- and planted-forest layers.

Population counts were obtained from GHS-POP R2023A at 100-m resolution for the corresponding years [40,41]. The population data were first aggregated to 1 km by summation and then aligned with the forest grid using a mass-preserving reprojection procedure so that population totals were retained during spatial harmonization. All forest and population data were processed on a common 1 km grid. An aligned 10 × 10 km grid was used as the primary spatial reporting unit for grid-based analyses. Province-level summaries were additionally derived using provincial administrative boundaries as reporting units. Provincial estimates were recalculated directly from the underlying 1 km forest data rather than by averaging the 10 × 10 km grid-level estimates. All analyses were conducted using R software (version 4.5.1).

2.2. Forest–Population Metrics

Forest–population relationships were quantified using three complementary indicators: FAP, FPP, and FHN, following the general framework of previous global assessments [10,12]. These indicators describe different dimensions of the relationship between forests and human populations: FAP represents forest availability relative to population size, FPP quantifies the number of people living within a specified distance of forest, and FHN represents population-weighted spatial proximity to forest.

FAP in reporting unit w was calculated as

$$FAP(w) = \frac{A_w}{P_w},$$

where A_w is forest area in hectares and P_w is population.

For each year and forest class, we calculated the Euclidean distance from every 1 km cell to the nearest corresponding forest cell over the complete national domain. The resulting distance surfaces were then overlaid with the gridded population data. FPP was defined as the total number of people living within a specified distance of the corresponding forest. For each reporting unit, FPP was obtained by summing the population of all 1 km cells whose distance to the nearest corresponding forest did not exceed the specified threshold. For national and temporal comparisons, we also calculated the proportion of the total population living within the specified distance of forest. A 5 km distance was used as the primary threshold for defining FPP, consistent with the forest-proximity framework used in previous assessments [10,12]. To evaluate whether the observed patterns depended on this choice, alternative thresholds of 1, 10 and 20 km were examined in sensitivity analyses.

To calculate FHN, we first derived the population-weighted mean distance to the nearest corresponding forest as an intermediate quantity:

$$\overline{D}(w) = \frac{\sum_{j \in w} P_j D_j}{\sum_{j \in w} P_j}.$$

where P_j is the population of grid cell j, D_j is the Euclidean distance from that cell to the nearest corresponding forest, and the summation is over all population cells within reporting unit w.

FHN was calculated as

$$FHN(w) = \frac{\sum_{j \in w} P_j}{\sum_{j \in w} P_j (D_j + 1)}$$

with D_j expressed in kilometers. By definition, $FHN(w) = 1/\left[\overline{D}(w) + 1\right]$, such that FHN is a monotonic inverse transformation of population-weighted mean forest distance and the two measures contain equivalent information. Higher FHN values therefore indicate closer spatial proximity between the population and the corresponding forest type, whereas lower values indicate greater spatial separation. This transformation provides a positively oriented measure of forest–population proximity while preserving the ranking implied by the underlying population-weighted distance.

For province-level summaries, each province was treated as a reporting unit w, and all three indicators were recalculated directly from the underlying 1 km data. Provincial FAP was calculated from the total forest area and population within each province, while provincial FPP was obtained by summing the population of 1 km cells within the province that met the specified forest-distance threshold. Provincial FHN was calculated from the population-weighted forest distances of all 1 km population cells within each province using the same formulation described above. Because forest-distance surfaces were calculated over the complete national domain before provincial summarization, the nearest forest to a population cell could occur across a provincial boundary.

2.3. Symmetric Decomposition of FHN Change

A symmetric two-factor Shapley decomposition was used to separate changes in forest–population proximity associated with changes in forest spatial distribution from those associated with population redistribution between 1990 and 2020 [42,43].

In the present analysis, the framework was applied to two spatially varying components: forest distribution and population distribution. Four counterfactual endpoint combinations were constructed by combining the forest distribution in either 1990 or 2020 with the population distribution in either 1990 or 2020. These counterfactual states make it possible to estimate how much of the observed change in FHN is associated with changes in the forest landscape and how much is associated with redistribution of the population relative to that landscape.

For reporting unit w, let

$$D_w(P_a,\ F_b) = \frac{\sum_{j \in w} P_{j,a} D_{j,b}}{\sum_{j \in w} P_{j,a}},$$

where $P_{j,a}$ is the population of cell j in year a, and $D_{j,b}$ is the distance from that cell to the nearest corresponding forest under the forest distribution in year b. The corresponding FHN state was then calculated as

$$H_w(P_a,\ F_b) = \frac{1}{D_w(P_a,\ F_b) + 1}$$

Four counterfactual endpoint combinations were evaluated:

$$H_{00} = H(P_{1990}, F_{1990}),\ H_{01} = H(P_{1990}, F_{2020}),$$

$$H_{10} = H(P_{2020}, F_{1990}),\ H_{11} = H(P_{2020}, F_{2020}),$$

Here, H_{00} represents the observed baseline state in 1990 and H_{11} represents the observed endpoint state in 2020. The two mixed states, H_{01} and H_{10}, are counterfactual combinations in which either the population distribution or the forest distribution is updated to its 2020 state while the other component is held at its 1990 state. These four states allow the observed change in FHN to be decomposed into contributions associated with forest change and population redistribution.

The symmetric Shapley contributions of forest change and population redistribution were then calculated as

$$\triangle_F^H = \frac{1}{2}[(H_{01} - H_{00}) + (H_{11} - H_{10}),$$

$$\triangle_P^H = \frac{1}{2}[(H_{10} - H_{00}) + (H_{11} - H_{01}).$$

where $\triangle_F^H$ and $\triangle_P^H$ represent the contributions of forest change and population redistribution, respectively.

By construction,

$$\triangle_F^H + \triangle_P^H = H_{11} - H_{00}.$$

To facilitate comparison across reporting units, contributions were also expressed relative to baseline FHN as

$$C_F = 100 \times \frac{\triangle_F^H}{H_{00}},\ C_P = 100 \times \frac{\triangle_P^H}{H_{00}}$$

Accordingly,

$$C_F + C_P = 100 \times \frac{H_{11} - H_{00}}{H_{00}}$$

which equals the observed relative change in FHN between 1990 and 2020. Positive values indicate contributions toward increasing FHN, and therefore greater forest–population proximity, whereas negative values indicate contributions toward decreasing FHN.

The same decomposition was applied at the provincial level by treating each province as a reporting unit w. The four forest–population endpoint states and the corresponding Shapley contributions were recalculated directly from the 1 km population cells within each province and the nationally derived forest-distance surfaces for 1990 and 2020.

2.4. Sensitivity Analyses

Two sets of sensitivity analyses were conducted to evaluate whether the principal findings depended on analytical choices concerning forest proximity and spatial reporting scale. First, sensitivity to the definition of forest proximity was assessed by repeating the FPP analysis using distance thresholds of 1, 10, and 20 km in addition to the primary 5 km threshold. This analysis evaluated whether the direction of temporal change was robust to alternative definitions of FPP.

Second, sensitivity to spatial reporting scale was evaluated by repeating the grid-based analyses using an aligned 50 × 50 km grid instead of the primary 10 × 10 km grid. Changes in FAP, FPP, and FHN were then compared across reporting scales and forest types to determine whether the principal spatial and temporal contrasts were sensitive to the choice of aggregation scale.

3. Results

3.1. Forest Area per Person

China's population increased from 1.178 billion in 1990 to 1.454 billion in 2020 (+23.43%), outpacing the increase in total forest area from 2.339 to 2.556 million km^2 (+9.29%). Accordingly, national FAP decreased from 0.199 to 0.176 ha $person^{-1}$ (−11.46%), declining progressively through 2015 before showing a slight increase by 2020 (Table 1; Supplementary Figure S1).

Table 1. National forest–population indicators in 1990 and 2020.

Indicator	Year/Change	All Forests	Natural Forests	Planted Forests
Forest area (10^3 km^2)	1990	2339.0	1872.2	466.9
	2020	2556.2	1653.1	903.1
	Change (%)	+9.3	−11.7	+93.5
FAP (ha $person^{-1}$)	1990	0.199	0.159	0.040
	2020	0.176	0.114	0.062
	Change (%)	−11.5	−28.5	+56.7
Population share within 5 km of forest (%)	1990	57.4	56.2	30.5
	2020	62.4	51.3	47.5
	Change (percentage points)	+4.9	−4.9	+17.0
FHN (km^{-1})	1990	0.0773	0.0758	0.0338
	2020	0.0975	0.0743	0.0539
	Change (%)	+26.2	−1.9	+59.5

FAP varied substantially across China in 2020 (Figure 1a,b). The highest values occurred in sparsely populated, forest-rich regions, particularly Xizang, with relatively high values also observed in Inner Mongolia and parts of southwestern and northeastern China. By contrast, FAP was generally lower in the densely populated eastern and coastal provinces. Changes in FAP between 1990 and 2020 were also spatially heterogeneous, with substantial variation in both direction and magnitude across the country (Figure 1c,d).

Natural and planted forests showed contrasting temporal trajectories. Natural-forest area declined by 11.70%, and natural-forest FAP decreased almost continuously over the study period, from 0.159 to 0.114 ha $person^{-1}$ (−28.46%). In contrast, planted-forest area increased by 93.45%, accompanied by an overall increase in planted-forest FAP from 0.040 to 0.062 ha $person^{-1}$ (+56.73%; Table 1; Supplementary Figure S1).

3.2. Forest-Proximate People

Population proximity to any forest increased between 1990 and 2020. The absolute number of FPP increased throughout the study period, while the share of China's population living within 5 km of forest increased from 57.44% to 62.36%, a rise of 4.92 percentage points (Table 1; Supplementary Figure S2).

In 2020, FPP were concentrated primarily in the densely populated southern and eastern parts of China (Figure 2a). Guangdong had the largest number of FPP, with relatively high numbers also observed in Hunan, Sichuan and Yunnan (Figure 2b). Relative changes in the proportion of the population living within 5 km of forest between 1990 and 2020 varied substantially across the country, with marked differences among both grid cells and province-level units (Figure 2c,d).

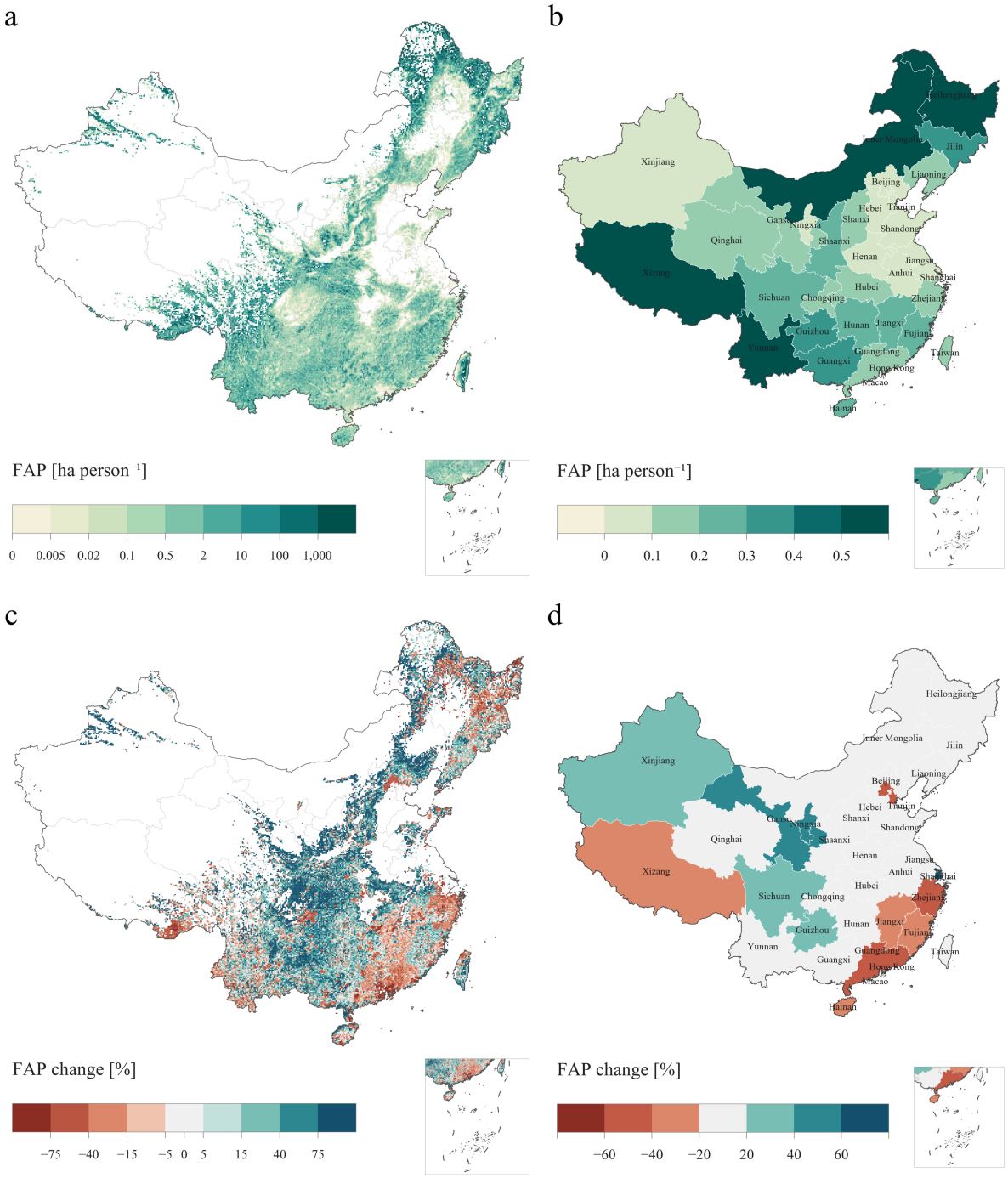

Figure 1. Spatial pattern and provincial distribution of FAP for all forests. Panels show (**a**) FAP in 2020, (**b**) province-level FAP in 2020, (**c**) relative change from 1990 to 2020, and (**d**) province-level relative change.

Natural and planted forests showed contrasting changes when population proximity was expressed relative to total population. The share of the population living within 5 km of natural forest decreased from 56.19% in 1990 to 51.31% in 2020, even though the absolute number of people living near natural forest increased modestly over the study period. In contrast, both the absolute number and population share associated with planted forest increased substantially, with the latter rising from 30.52% to 47.51% (Table 1; Supplementary Figure S2).

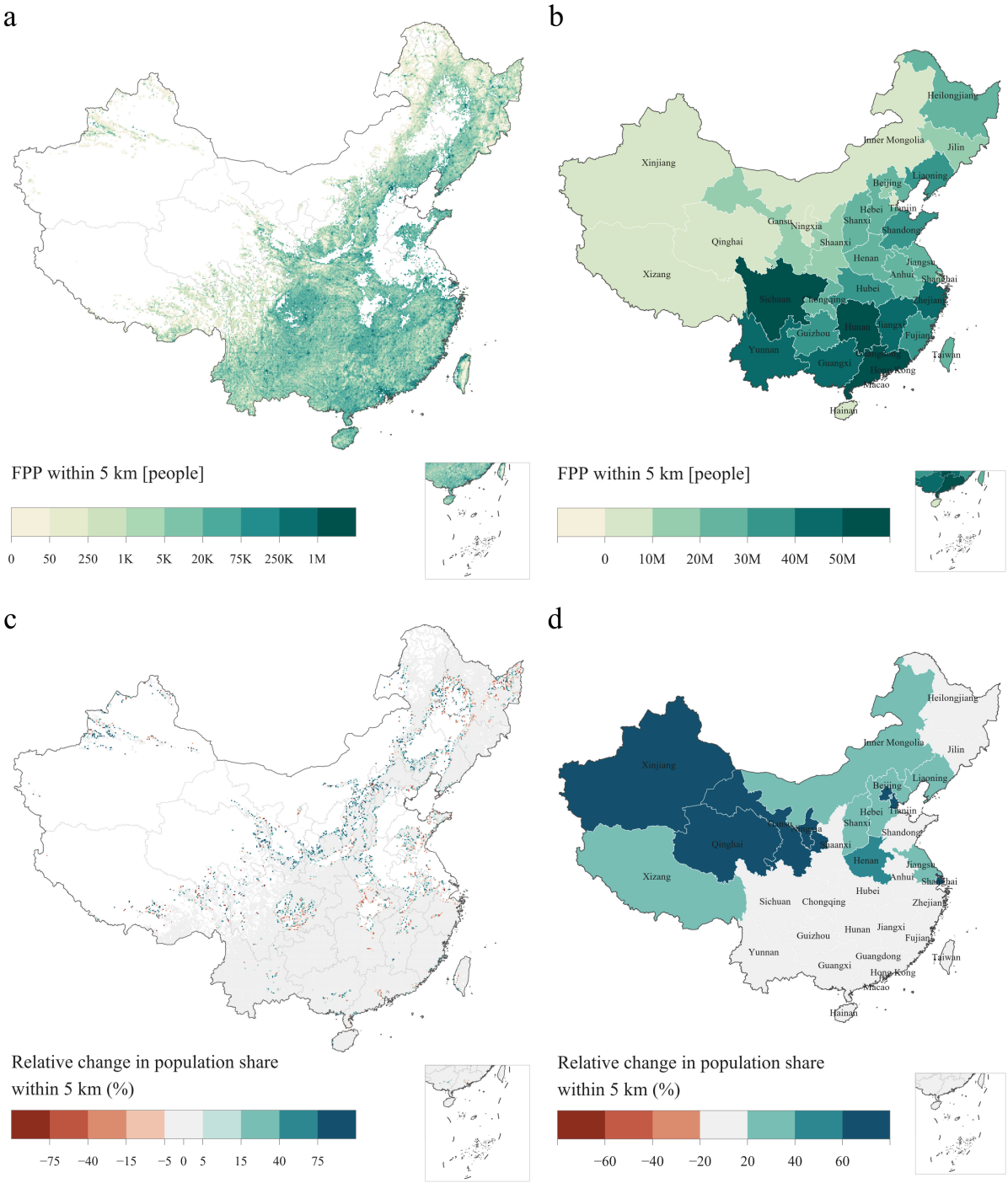

Figure 2. Spatial patterns of FPP and changes in population proximity to any forest. Panels show (**a**) FPP within 5 km of forest in 2020, (**b**) province-level FPP in 2020, (**c**) relative change in the proportion of the population living within 5 km of forest from 1990 to 2020, and (**d**) province-level relative change in this proportion.

3.3. Forest–Human Nexus

National FHN for all forests increased over the full study period, although its temporal trajectory was non-monotonic. National FHN declined modestly from 1990 to the mid-2000s before increasing thereafter (Supplementary Figure S3). Between 1990 and 2020, national FHN increased from 0.0773 to 0.0975 (+26.15%), indicating a substantial strengthening of the spatial proximity between population and forests.

In 2020, high FHN values were concentrated across southern and southwestern China, with additional high-value areas in the northeast (Figure 3a). At the provincial level, FHN was highest in Hong Kong, followed by Guizhou, Hainan and Yunnan, whereas the lowest values occurred in several northern and northwestern provinces, including Xinjiang, Ningxia and Henan (Figure 3b).

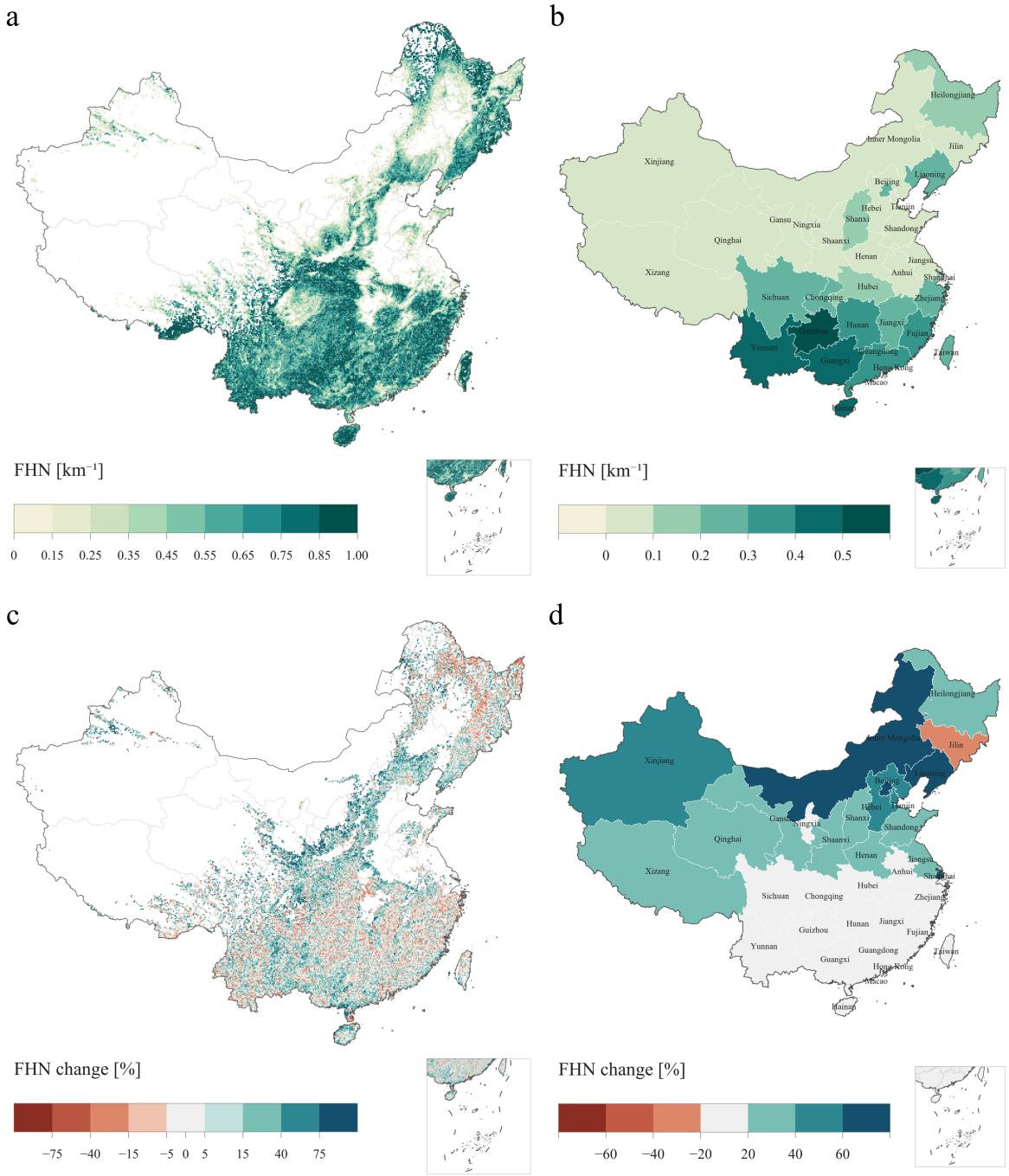

Figure 3. Spatial pattern and provincial distribution of FHN for all forests. Panels show (**a**) the forest–human nexus (FHN) in 2020, (**b**) province-level FHN in 2020, (**c**) relative FHN change from 1990 to 2020, and (**d**) province-level relative change.

Changes between 1990 and 2020 showed considerable spatial variation (Figure 3c). Increases were widespread across parts of northern, northeastern, and southwestern China, while decreases occurred in parts of eastern and southern China. At the provincial level, the largest relative increases were observed in Shanghai and Beijing, followed by Liaoning

and Inner Mongolia. By contrast, FHN declined most strongly in Jilin and Hubei, with decreases also observed in Zhejiang, Guangdong and Jiangxi (Figure 3d).

3.3.1. Natural-Forest FHN

Population proximity to natural forest showed relatively little net change but varied appreciably within the study period. Natural-forest FHN declined from 1990 to the mid-2000s and subsequently partially recovered, ending slightly below its 1990 level (Supplementary Figure S3). Natural-forest FHN changed little over the full study period, decreasing slightly from 0.0758 to 0.0743 (−1.94%; Table 1).

In 2020, high natural-forest FHN values were concentrated mainly in southwestern and southern China, together with parts of northeastern China (Figure 4a). Guizhou had the highest province-level FHN, followed by Yunnan and Guangxi, with relatively high values also observed in Hunan and Fujian (Figure 4b).

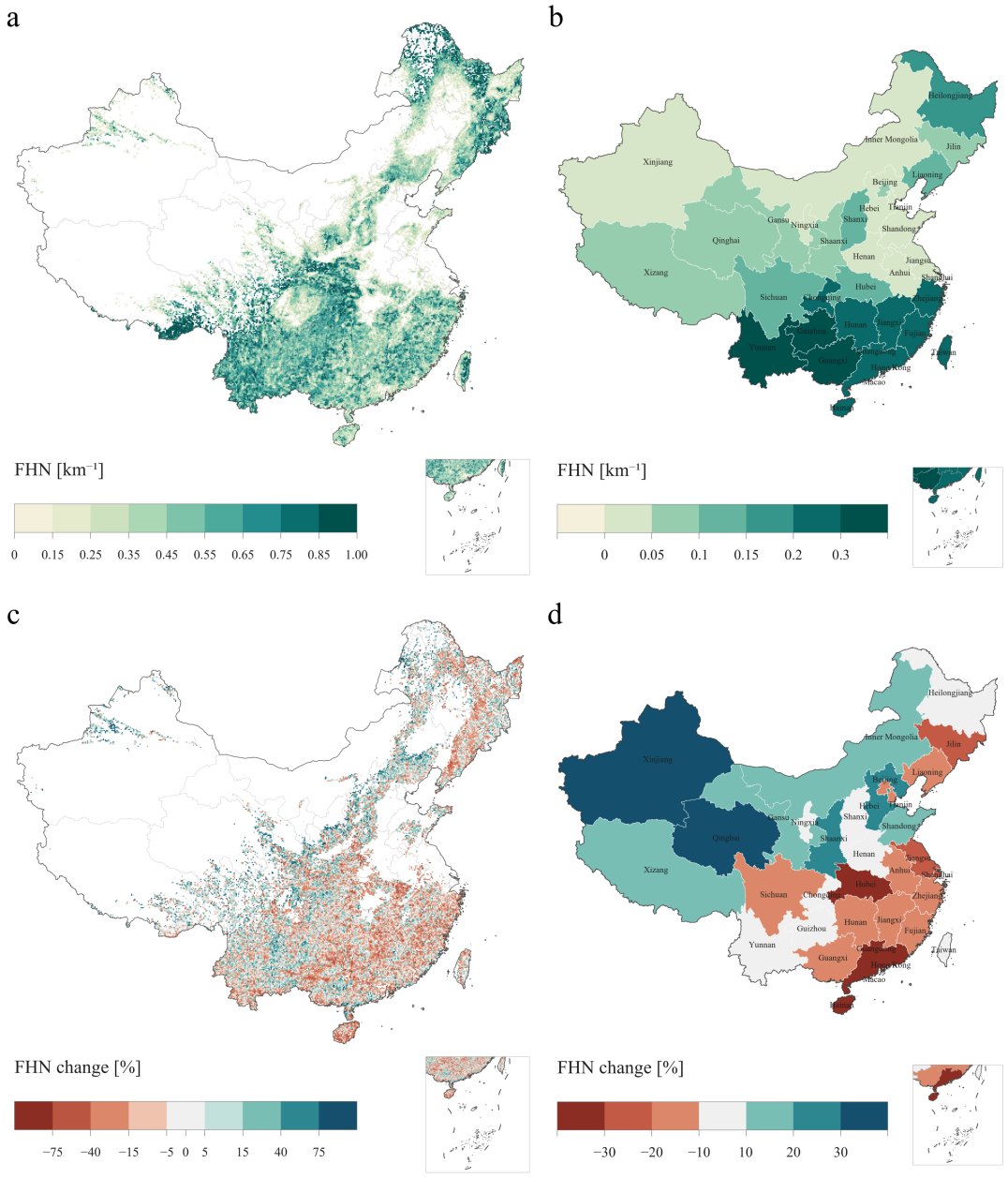

Figure 4. Spatial pattern and provincial distribution of FHN for natural forest. Panels show (**a**) natural-forest FHN in 2020, (**b**) province-level natural-forest FHN in 2020, (**c**) relative change from 1990 to 2020, and (**d**) province-level relative change.

Changes in natural-forest FHN were spatially mixed (Figure 4c). Increases occurred in parts of northern and northwestern China, whereas decreases were widespread across southern and eastern regions. At the provincial level, the largest increases occurred in Xinjiang and Qinghai, followed by Hebei, Shaanxi and Gansu. The largest declines occurred in Macao and Hong Kong, with substantial decreases also observed in Hubei, Guangdong and Hainan (Figure 4d).

3.3.2. Planted-Forest FHN

Population proximity to planted forest increased markedly over the study period, with planted-forest FHN showing an overall upward trajectory from 1990 to 2020 (Supplementary Figure S3). Planted-forest FHN increased markedly from 0.0338 to 0.0539 (+59.46%; Table 1).

In 2020, high planted-forest FHN values were concentrated in southern and southeastern China (Figure 5a). Hong Kong had the highest province-level value, followed by Macao, Hainan and Fujian; relatively high values were also observed in Guangxi and Guangdong (Figure 5b).

Planted-forest FHN increased across much of its mapped distribution between 1990 and 2020, particularly in southern and eastern China and along parts of the northeast (Figure 5c). At the provincial level, FHN increased in all province-level units except Qinghai. The largest relative increases occurred in Shanghai and Tianjin, followed by Beijing, Gansu, and Hainan (Figure 5d).

3.3.3. Decomposition of Changes in FHN

Shapley decomposition showed distinct contributions of forest change and population redistribution to national changes in FHN (Table 2). For all forests combined, FHN increased by 26.15% between 1990 and 2020, with forest change contributing 21.70 percentage points and population redistribution contributing 4.44 percentage points to this relative change. Natural-forest FHN decreased slightly by 1.94%; the negative contribution from forest change (−4.09 percentage points) was partly offset by a positive contribution from population redistribution (2.15 percentage points). In contrast, planted-forest FHN increased by 59.46%, with a forest-change contribution of 57.93 percentage points and a population-redistribution contribution of 1.53 percentage points.

Table 2. National Shapley decomposition of change in FHN, 1990–2020.

Forest Class	FHN Change (% Relative to 1990)	Forest Contribution (% of Baseline FHN)	Population Contribution (% of Baseline FHN)
All forests	26.147	21.704	4.443
Natural forests	−1.940	−4.086	2.146
Planted forests	59.455	57.929	1.526

Spatial decomposition revealed substantial geographic heterogeneity in these contributions (Figure 6a,b; Supplementary Tables S1–S3). For all forests combined, increases in several province-level units were dominated by positive forest-change contributions, including Beijing, Hebei, Shanghai, Tianjin, Xizang and Xinjiang. In contrast, declines in Guangdong, Jiangxi and Zhejiang were more strongly associated with negative population-redistribution contributions, whereas the decline in Hubei was dominated by forest change. Offsetting effects were also widespread. For example, positive forest contributions were partly counteracted by negative population contributions in Gansu, Inner Mongolia, Qinghai, Sichuan and Yunnan, while negative forest contributions were partly offset by positive population contributions in Anhui and Jilin (Supplementary Table S1).

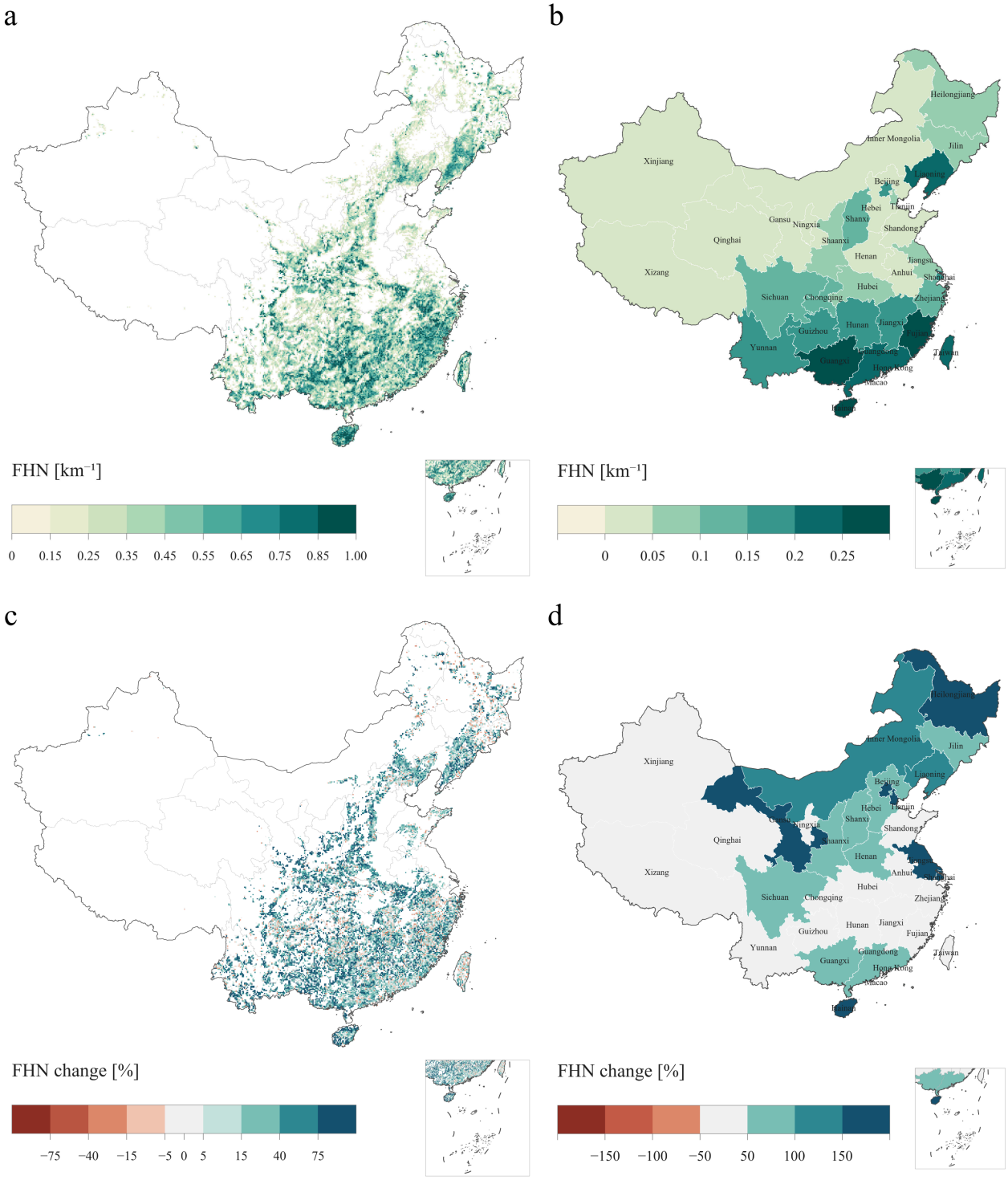

Figure 5. Spatial pattern and provincial distribution of FHN for planted forest. Panels show (**a**) planted-forest FHN in 2020, (**b**) province-level planted-forest FHN in 2020, (**c**) relative change from 1990 to 2020, and (**d**) province-level relative change.

For natural forests, negative forest-change contributions dominated the declines in several southern and eastern province-level units, including Fujian, Guangdong, Guangxi, Hong Kong, Hubei and Zhejiang. By contrast, increases in Hebei, Xizang and Xinjiang were dominated by positive forest-change contributions. In several northern and northwestern regions, including Gansu, Qinghai and Shaanxi, positive forest contributions were partly offset by negative population-redistribution contributions, while in Anhui, Hainan, Henan,

Jiangsu and Jilin, positive population contributions partially compensated for negative forest contributions (Figure 6c,d; Supplementary Table S2).

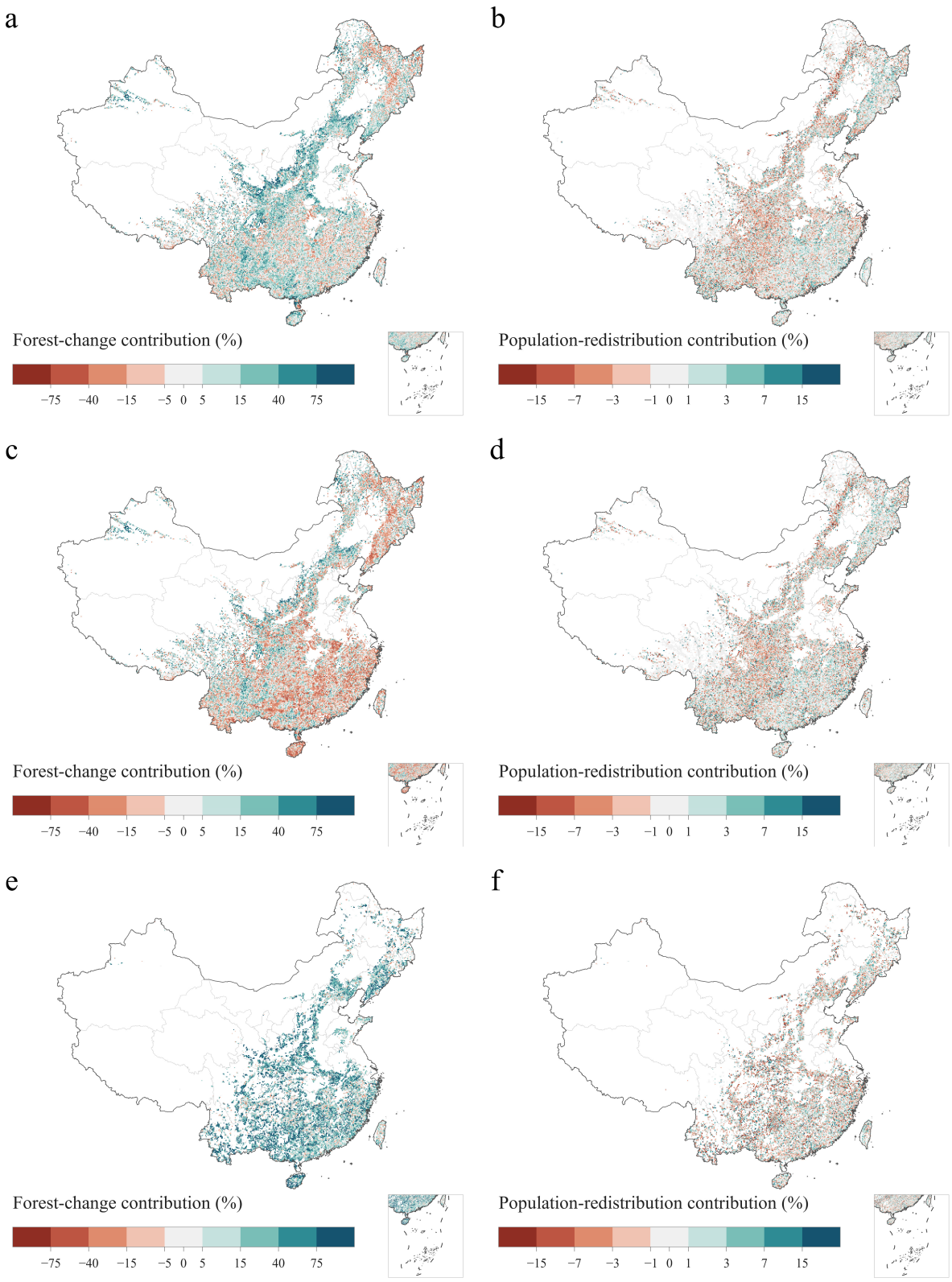

Figure 6. Spatial Shapley decomposition of changes in the FHN from 1990 to 2020. Maps show the contributions of forest change (left column) and population redistribution (right column) to relative changes in FHN for all forests (**a**,**b**), natural forests (**c**,**d**), and planted forests (**e**,**f**). Positive values indicate contributions toward increasing FHN, corresponding to greater forest–population proximity, whereas negative values indicate contributions toward decreasing FHN.

Planted forests exhibited a more consistent pattern. Forest-change contributions were positive in every province-level unit, and planted-forest FHN increased in all province-level units except Qinghai (Figure 6e,f; Supplementary Table S3). In many regions, including Chongqing, Fujian, Gansu, Guangxi, Guizhou, Hainan, Inner Mongolia and Zhejiang, these positive forest contributions were partly offset by negative population-redistribution contributions. Qinghai represented the clearest example of this offsetting pattern: despite a positive forest-change contribution, the larger negative contribution from population redistribution resulted in an overall decline in planted-forest FHN.

3.4. Sensitivity Analyses

The main results were robust to alternative forest-proximity thresholds and reporting scales. Across distance thresholds of 1, 5, 10 and 20 km, the direction of change in FPP remained unchanged: the proportion of the population living near any forest and near planted forests increased between 1990 and 2020, whereas that near natural forest decreased at all thresholds (Supplementary Figure S4).

Increasing the reporting scale from 10 × 10 km to 50 × 50 km likewise preserved the main contrasts among forest types. FHN increased for all forests combined and for planted forests, but decreased slightly for natural forests at both spatial scales, while the direction of FAP change was also unchanged (Supplementary Figure S5). Although local FPP distributions varied with reporting scale, these differences did not alter the overall contrasts among forest types.

4. Discussion

Between 1990 and 2020, the spatial relationship between forests and people in China underwent substantial reorganization. Despite a continued increase in total forest area, population proximity to natural and planted forests followed markedly different trajectories. Proximity to planted forests increased substantially, whereas proximity to natural forests remained broadly stable or declined slightly. The contributions of forest change and population redistribution also varied considerably across space, with contrasting regional trajectories collectively shaping the national pattern. By resolving these changes across forest types and spatial scales, our analysis extends existing forest–population frameworks by revealing how China's human–forest relationship has been reshaped in both spatial configuration and forest composition over the past three decades.

The contrasting spatial patterns of FAP, FPP and FHN reflect both the different dimensions captured by these indicators and China's pronounced geographic heterogeneity in population and forest distribution. Population is strongly concentrated in eastern and coastal regions, whereas large parts of western and northern China remain sparsely populated [8,9]. This helps explain the relatively high FAP in regions such as Xizang and Inner Mongolia and the lower FAP in densely populated eastern provinces. FPP shows a different spatial pattern, with high values concentrated in the densely populated south and east and lower values generally occurring in more sparsely populated regions. FHN captures another dimension, with high values in southern and southwestern China reflecting the close spatial juxtaposition of population and forests, whereas lower values in several northern and northwestern provinces reflect greater spatial separation between the two.

The observed changes occurred against the background of an exceptional period of forest restoration and land-system transformation in China [35,36]. Satellite observations have identified China as one of the dominant contributors to global greening, with land-use management, including large-scale forest expansion, playing a major role [4]. Since the late twentieth century, a succession of national ecological programs has reshaped vegetation and land-cover patterns across large parts of the country [35,36]. Afforestation and reforestation

accelerated particularly after 2000 through programs such as Grain for Green, the Three-North Shelterbelt Program and other restoration initiatives [36,44]. Many restoration interventions converted formerly cultivated, degraded, or otherwise intensively used land to woody vegetation [32,45], meaning that forest expansion frequently occurred within landscapes already strongly influenced by human settlement and land use. At the same time, China experienced profound demographic redistribution associated with internal migration and urbanization, with population increasingly concentrated in major cities and economically developed regions [37,38]. Together, these concurrent changes suggest that the observed restructuring of human–forest relationships should be understood in the context of multiple, interrelated processes, including forest restoration and land-system transformation, shifts in forest composition, and population redistribution associated with urbanization and internal migration.

One important dimension of this restructuring is the contrasting trajectories of natural and planted forests. Although large-scale restoration has contributed substantially to increases in tree and forest cover [4,36], gains in aggregate forest cover do not necessarily reflect equivalent changes in natural and planted forests. The forest dataset used here indicates a net decline in mapped natural forest alongside rapid expansion of planted forest between 1990 and 2020 [31]. Natural-forest conservation policies, including the Natural Forest Protection Program and the expansion of protected areas, have reduced forest loss in many regions [46], but their effects have been geographically uneven. Regional studies further show that increasing tree cover can coincide with the loss of diverse natural forests and their replacement by plantations [47]. The increase in FHN for all forests alongside a slight decline in natural-forest FHN therefore reveals an important compositional shift: planted forests have become increasingly prominent in the forests spatially associated with where people live.

A second dimension concerns the respective contributions of forest change and population redistribution to changes in forest–human proximity. The Shapley decomposition further reveals that changes in forest–human proximity can arise through two distinct spatial processes: changes in forest extent and configuration alter where forests occur relative to people, whereas population redistribution changes where people are located relative to forests. At the national scale, forest change dominated the increased proximity to all forests combined and to planted forests, but the spatial contributions of forest and population redistribution varied markedly across China (Figure 6). For natural forests, forest change contributed to a decline in FHN at the national scale, whereas population redistribution made an opposing positive contribution that partially offset this decline, indicating that the small net change in natural-forest FHN reflects two opposing processes rather than a stable human–forest relationship. Province-level results further revealed substantial heterogeneity in the direction and magnitude of these contributions. This contrast was especially evident for natural forests, where forest and population contributions frequently offset one another, while planted forests showed a more consistent positive contribution from forest change. Thus, relatively similar net changes in forest–population proximity may arise from markedly different combinations of forest and demographic processes, highlighting the importance of distinguishing these components rather than interpreting net changes alone. The spatial pattern is consistent with the loss and fragmentation of natural forests under intensifying human land use, a process recently documented across China and associated particularly with plantation expansion, forest harvesting, and cropland change [48]. These contributions describe the proximate spatial processes underlying changes in FHN rather than the specific socioeconomic, policy, or land-use drivers that produced those changes.

Such fragmentation can reduce habitat connectivity, biodiversity, and ecosystem functioning [20], and may also weaken forest resilience to climatic disturbance in tropical and

temperate forests and alter wildfire susceptibility through edge-related drying and human ignition pathways [49,50]. Meanwhile, population redistribution toward areas closer to the remaining natural forests may intensify anthropogenic pressure and opportunities for wildlife–livestock–human contact and pathogen spillover at the human–forest interface [22–24,51], while simultaneously increasing human exposure to wildfire [52]. Planted forests showed a contrasting trajectory: their increasing proximity to people was driven primarily by forest expansion and spatial redistribution, consistent with large-scale afforestation and ecological restoration in already human-modified landscapes [32,36,45]. Greater proximity may increase opportunities for recreation and other human well-being benefits [3,16–18], while planted forests can also provide ecosystem functions such as carbon storage and erosion control [25,32]. However, these gains are not ecologically equivalent to greater proximity to natural forests: biodiversity and ecosystem-service outcomes depend strongly on forest composition, structure, and management [25,27,29,30], and planted forests in China may also be more vulnerable to drought than natural forests [28]. Therefore, different pathways of change in human–forest proximity should not be considered ecologically equivalent, as they reflect distinct land-system processes and may lead to different ecological and management consequences.

From a sustainable development perspective, these findings have implications for forest restoration and spatial planning in China. Conventional targets based on forest area remain important, but they could be complemented by information on where forest gains and losses occur relative to population and whether they involve natural or planted forests. China's investments in natural capital have generated measurable improvements in multiple ecosystem services, and ecosystem-service assessments are increasingly incorporated into spatial planning instruments such as the Ecological Conservation Redline [53,54]. However, the province-level results indicate that forest-rich but sparsely populated regions, densely populated regions with limited forest area per person, and regions in which planted forests increasingly dominate the human–forest interface represent distinct planning contexts. In regions where forest change is the dominant contributor to increasing proximity, greater attention may be directed toward maintaining forest quality, connectivity and ecological function; where population redistribution makes a large or opposing contribution, demographic change and settlement patterns may need to be considered more explicitly in spatial planning. Because natural and planted forests differ substantially in biodiversity, ecosystem functioning and management requirements [25,27,29,30], increasing proximity to planted forests should not be regarded as ecologically equivalent to maintained or increased proximity to natural forests. Spatial planning could therefore complement broad forest-cover targets with differentiated strategies that balance natural-forest conservation, planted-forest management and restoration, and the benefits and risks associated with human–forest proximity in different regions.

Several limitations should be considered when interpreting the results. Firstly, natural and planted forests were derived from remotely sensed classifications, and errors in forest-type identification may affect estimated long-term changes, particularly in heterogeneous landscapes and along forest edges [31]. Secondly, the 1 km forest product also cannot resolve small patches or fine-scale changes in forest structure. GHS-POP is a modeled gridded population dataset, and uncertainty in historical population allocation propagates into population-weighted metrics. Thirdly, our analysis distinguishes forest types but not forest condition: forests with similar FHN values may differ substantially in age, species composition, structural complexity, integrity, and management. This distinction is particularly relevant given evidence that forest structure can strongly influence the biodiversity outcomes of restoration [29,30]. Nevertheless, the principal contrasts among the three analyses—all forests combined, natural forests and planted forests—were retained

across alternative forest-proximity thresholds and reporting scales, suggesting that the main conclusions are not dependent on a single analytical definition.

Future work could extend this framework beyond forest type and proximity alone by incorporating forest characteristics such as age, species composition, structural complexity, integrity, and connectivity, together with socioeconomic characteristics of nearby populations. Linking these spatial relationships with ecological and societal outcomes could help determine whether changes in forest proximity translate into measurable differences in ecosystem services, biodiversity, human well-being, or environmental pressures. Finally, future studies could investigate the socioeconomic and environmental drivers underlying regional heterogeneity in human–forest relationships by integrating the timing of restoration programs, land-use transitions, demographic change, and other region-specific processes, thereby moving beyond the descriptive decomposition used here toward explicit tests of the processes and policies shaping these spatial relationships.

5. Conclusions

Between 1990 and 2020, the spatial relationship between forests and human populations in China underwent substantial reorganization. Although total forest area increased, forest area per person declined because population growth outpaced forest expansion. At the same time, the proportion of the population living near forests increased overall. However, this increase in forest proximity was largely associated with planted forests: the proportion of people living within 5 km of planted forests increased markedly, whereas the corresponding proportion for natural forests declined. Consistent with these patterns, the forest–human nexus strengthened substantially for all forests combined and for planted forests, while remaining broadly stable for natural forests.

The decomposition analysis showed that these changes reflected the combined contributions of changes in forest distribution and population redistribution. Forest change accounted for most of the increase in the forest–human nexus for all forests and planted forests, whereas natural forests showed offsetting contributions from forest change and population redistribution, with substantial provincial variation indicating that similar net changes could arise from different combinations of forest and demographic processes. Forest expansion in China over the past three decades has therefore been accompanied by substantial shifts in both the composition and spatial configuration of human–forest relationships, with planted forests becoming increasingly prominent in forest landscapes located near human populations.

From a sustainable development perspective, these findings provide a more comprehensive understanding of where and how forest–human relationships are changing across China, offering a spatial basis for more targeted conservation, restoration and land-use planning and helping to inform policymakers, practitioners and researchers in their efforts to foster more sustainable relationships between people and forests.

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Abbreviations

The following abbreviations are used in this manuscript:

FAP	Forest area per person
FPP	Forest-proximate people
FHN	Forest–human nexus

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