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Dynamic threats of nighttime light-represented human activities to giant pandas and their habitat

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Human activities are one of the main factors threatening the long-term survival of wild giant pandas. Long-term and large-scale human activities can be quickly assessed by night light remote sensing data, which has been more and more widely used. In this paper, we analyzed the spatial patterns of nighttime light intensity and their dynamic changes from 2000 to 2020 in the entire giant panda distribution area using long-term nighttime light remote sensing data, and evaluated the dynamic threats of nighttime light-represented human activities to giant panda populations by proximity of light source and its intensity. We also assessed the relationships between the nighttime light dynamics and the trends of habitat fragmentation. Results showed that the intensity and range of the nighttime light around panda habitat had increased significantly from 2000 to 2020. The nighttime light intensity inside the natural reserves is significantly lower than outside, and it becomes more obvious over time. The intensity and range of nighttime light inside the natural reserves first increased and then decreased during the two decades, indicating that the protection inside the natural reserves effectively reversed the rapid increase in human activities in the previous decade. From 2000 to 2020, nighttime light sources became closer to local panda populations. In particular, they approached the pandas in the first decade, and stayed away in the second decade. This is mainly reflected in the weakened threats of nighttime light-represented human activities on the core large populations of the Qinling, Minshan and Qionglai Mountains from 2010 to 2020, but the threats on the peripheral populations continued to strengthen, where nighttime light became not only closer but also more intensified. The increase in nighttime light intensity and range were also significantly positively correlated with the increase in habitat fragmentation, especially during 2000–2010. Our study reveals the dynamic changes of nighttime light-represented human activities' threats to wild giant panda and its habitat, gives advices for effectively protecting giant pandas and their habitats from human activities, and has implications for the assessment of human activities' threats to other species in the world.

KEYWORDS

nighttime light, giant panda, habitat, remote sensing, fragmentation

1 Introduction

The giant panda (*Ailuropoda melanoleuca*) is the flagship species of global biodiversity conservation. However, giant panda's habitat is becoming more fragmented (Xu et al., 2017; Swaisgood et al., 2018) and the species is separated to 33 isolated populations as a result of human factors such as roads, residential plots and tourism facilities and activity (Xu et al., 2017; Kong et al., 2021; Wei, 2022), which threaten giant panda's long-term survival (Lu et al., 2001; Xu et al., 2017). Assessing human activities and their impact on wild giant pandas is important for the effective protection of giant pandas and their habitats.

However, wild giant pandas inhabit virgin forests in high mountains, which distributed in three provinces with a wide range. Their habitats are difficult to reach, and the surrounding human activities and their impacts on giant panda and its habitat are complicated and difficult to monitor. Most of the previous related researches have been carried out only in natural reserves (Liu et al., 1999). Some studies assessed habitat quality dynamics and effectiveness of natural reserves based on changes in land use, vegetation coverage or socioeconomic statistics (Linderman et al., 2005; Li and Song, 2022; Chen et al., 2023). Other studies focused on field surveys of single human activity in giant panda natural reserves and studied its characteristics (Shen et al., 2022; Weng et al., 2022). Information on large-scale spatial patterns and long-term dynamic characteristics of human activities in the entire giant panda distribution area is still lacking, which is important for the assessment of long-term dynamic impacts of human activities on giant panda and habitat.

Since human growth has caused an unprecedented increase in artificial light at night (Lynn et al., 2021), nighttime light has been used as a proxy for monitoring the distribution and intensity of human activities (Huang et al., 2022). With the development of nighttime light remote sensing technology, nighttime light data provides a great opportunity to monitor human activities and settlements (Zheng et al., 2019; Elvidge et al., 2022; Ji et al., 2022). Because nighttime light data not only has the characteristics of large-scale and multi-phase, but also has the unique advantage of intuitively representing the intensity of human activities, the nighttime light data obtained by satellite observation has become one of the widely used geospatial data products. Long-term and large-scale human activities can be quickly assessed using nighttime light remote sensing data, which has been increasingly used in the monitoring and evaluation of human disturbances to wild species (Rodrigues et al., 2012; Bobkowska et al., 2016; Anand and Kim, 2021). Previous studies have pointed out that the presence of urban development can be inferred from the presence of temporally stable nighttime light (Small, 2011), which might influence species' selection of habitat, and artificial nighttime lights present a potentially heightened conservation concern for wild populations (McLaren et al., 2018). Some studies also has revealed that artificial nighttime light reduce the functional connectivity of migratory aerial habitat (Korpach et al., 2022) and has indirect effects on community structure (Lynn et al., 2021). A increasing amount of research suggests that nighttime light intensity and its spatial relationship with wildlife may have an impact on wildlife populations and habitats (Weishampel et al., 2016). However, few studies have revealed the characteristics of nighttime light-represented human activities around wild giant pandas and the threats to the wild populations and habitat on large spatial and temporal scales.

Based on the above research background, the objectives of our study are: 1) determine spatial patterns of nighttime light and their dynamic changes from 2000 to 2020 in the entire giant panda distribution area, and 2) reveal threats of nighttime light-represented human activities to giant panda populations and their habitat over time to determine practical policy implications.

2 Materials and methods

2.1 Study area

The study area (172,150 km^2) was defined by the six mountain regions (Qinling Mountain, Minshan Mountain, Qionglai Mountain, Daxiangling Mountain, Xiaoxiangling Mountain, and Liangshan Mountain) in China's Sichuan, Shaanxi, and Gansu provinces that are currently home to the wild giant panda (Figure 1). Southwest China Hotspot, one of the top 25 Biodiversity Hotspots on the planet, is located in this area (Myers et al., 2000). High mountains and deep valleys dominate most regions, which range in altitude from about 260 to 7,140 m. The region's great biodiversity is a result of the significant elevation fluctuation and the concomitant high degree of climatic and soil variability. Evergreen coniferous forests at higher elevations and evergreen broadleaf forests at lower elevations make up the majority of the region's vegetation. The understory of the forests is dominated by ca. Sixty bamboo species, with approximately 35 of them being the preferred food of giant pandas (Li, 1997; Hu and Wei, 2004). According to the Fourth National Giant Panda Census, there are more than 300 hydropower stations, about 470 mines and more than 20 scenic spots in the study area, while the length of the road network in the study area is about 1,300 km (Forestry and Grassland Administration, 2021).

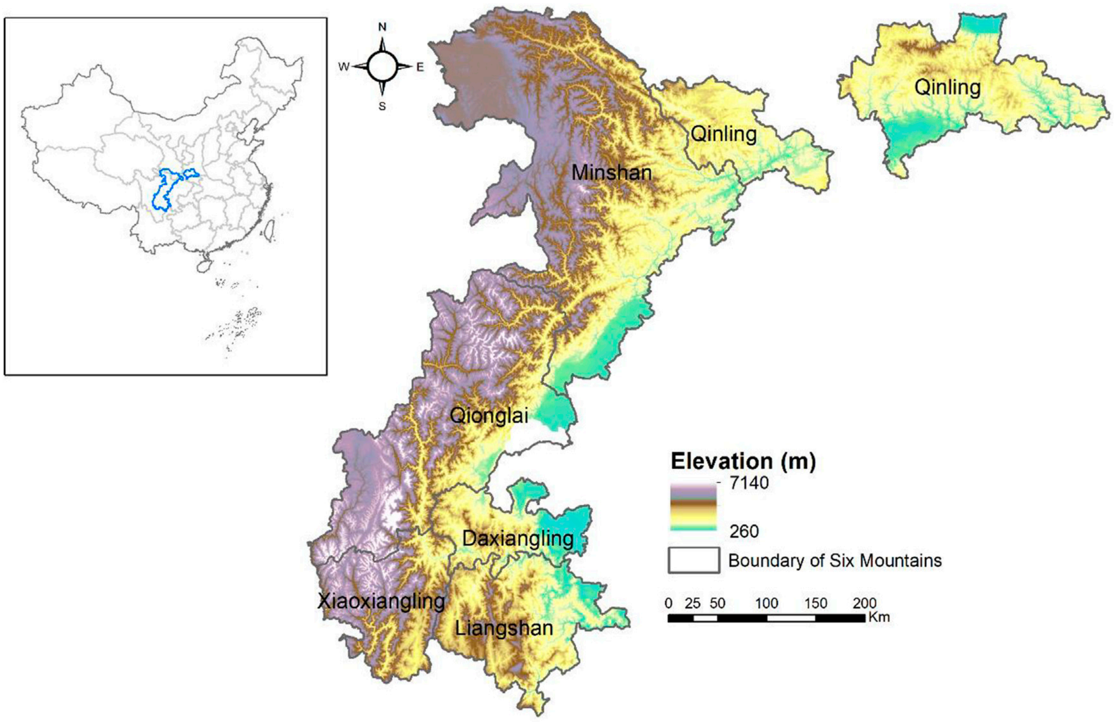

FIGURE 1
Study area.

2.2 Data sources

2.2.1 Nighttime light remote sensing data

Nighttime light (NTL) remote sensing data can reflect the intensity of nighttime lights on the Earth surface, such as urban light on the surface and natural fire light at night. It not only has the characteristics of large-scale and long-term data of traditional remote sensing data, but also has the unique advantages of intuitively representing the intensity of human activities. The Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) stable nighttime light data and Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP-VIIRS) nighttime light data are two widely used NTL datasets (Chen et al., 2021). However, differences in their spatial resolution and sensor design are flawed in analysing long-term changes in nighttime light (Chen et al., 2021). In our study, we used an extended time series (2000–2020) of NPP-VIIRS-like NTL data (download from https://doi.org/10.7910/DVN/YGIVCD) which is built through a new cross-sensor calibration from DMSP-OLS NTL data (2000–2012) and a composition of monthly NPP-VIIRS NTL data (2013–2018). The cross-sensor calibration is unique due to the image enhancement by using a vegetation index and an auto-encoder model. This data has an excellent spatial pattern and temporal consistency which are similar to the composited NPP-VIIRS NTL data (Chen et al., 2021). Its spatial resolution is 500 m × 500 m, and the pixel value represents nighttime light intensity with the unit of nanowatts per centimeter squared per steradian ($nW\,cm^{-2}\,sr^{-1}$).

2.2.2 Spatial data of vegetation

The spatial data of vegetation of the years 2000, 2010 and 2020 in the study area is obtained by ecosystem classification data from the China Ecosystem Assessment Project (2000-2010-2020) (Ouyang et al., 2016; Wu et al., 2017). The classes of the vegetation include three levels of classifications (e.g., forest, broadleaf forest, evergreen broadleaf forest). The ecosystems of the study area was classified into 7 primary categories (forest, shrub, grassland, wetland, cropland, urban land and others) according to the reported land-cover classification (Ouyang et al., 2015), with a spatial resolution of 30 m × 30 m. The object-oriented multi-scale segmentation and decision tree classification method were used to create the national land cover dataset from the Chinese Huan-Jing-1 satellite constellation (HJ-1A/B) and the US Landsat (Landsat OLI) data with the help of a land cover reference database made up of numerous field survey sample points. To verify the impartiality and credibility of the accuracy evaluation, independent data accuracy verification was also performed on the field survey sample points that were acquired using a random

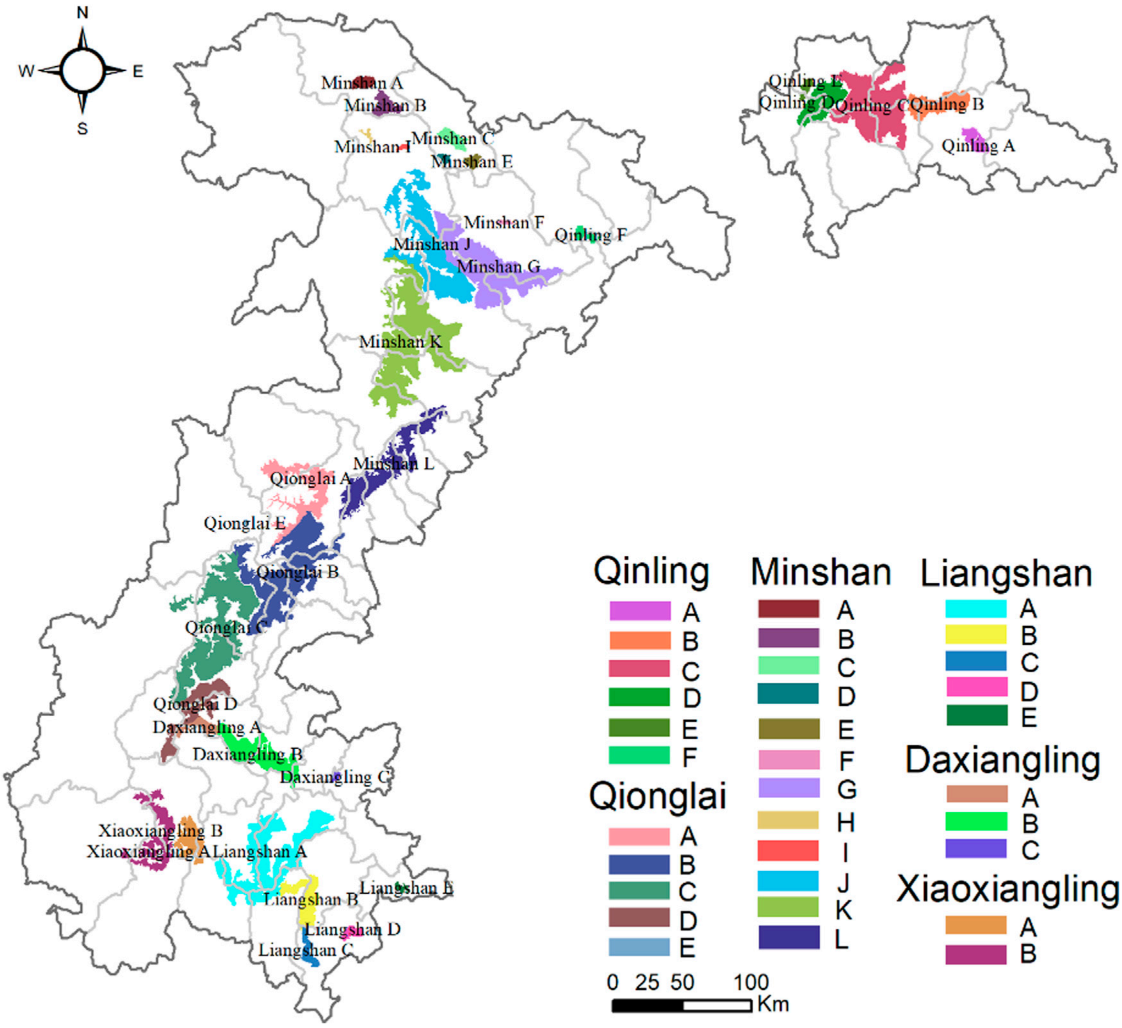

FIGURE 2
Wild giant panda populations (Forestry and Grassland Administration, 2021; Kong et al., 2021).

sampling procedure. In the provinces included in the research region, there were 4,452 sample sites in Sichuan, 1,738 in Shaanxi, and 752 in Gansu. Forest had a classification accuracy of 94.43%.

2.2.3 Data of giant panda populations and other basic geographic information

The spatial data of all wild giant panda populations and edible bamboo of giant pandas were from the Fourth National Giant Panda Census (Forestry and Grassland Administration, 2021). 1,864 wild giant panada individuals are in 33 isolated populations (six populations in Qinling Mountain with a total of 347 wild panda individuals, twelve populations in Minshan Mountain with a total of 797 wild panda individuals, five populations in Qionglai Mountain with a total of 528 wild panda individuals, three populations in Daxiangling Mountain with a total of 38 wild panda individuals, two populations in Xiaoxiangling Mountain with a total of 30 wild panda individuals, and five populations in Liangshan Mountain with a total of 124 wild panda individuals) (Figure 2). The Digital Elevation Model data (with a spatial resolution of 30 m × 30 m) and the spatial boundary of counties in the study area were from the National Geomatics Center of China.

2.3 Methods

2.3.1 Spatial pattern and dynamic changes of nighttime light

Based on nighttime light remote sensing images of the years 2000, 2010 and 2020, we used average intensity, maximum intensity and nighttime light area to measure the intensity and range of nighttime light in a certain area. We calculated these indicators separately for the entire study area, six mountains and natural reserves of each year. We subtracted the indicator values from different years to get the changes from 2000 to 2010, 2010 to 2020 and 2000 to 2020. Then we analyzed the change characteristics of nighttime light intensity and area in the entire study area, the differences between different mountains, and the differences inside and outside the natural reserves during the two decades. Average intensity, maximum intensity, and area of nighttime light in each year were calculated as follows:

$$ITN_{Average} = \frac{\sum_{i=1}^{n} ITN_{pixel_i}}{i} \quad (1)$$

$$ITN_{Max} = \max_{i} \left(ITN_{pixel_i}\right) \quad (2)$$

$$ILMA = \sum_{i=1}^{n} \left(pixel\_A \times ILM_i\right) \quad (3)$$

$$ILM_i = \begin{cases} 1, & BRN_{pixel_i} > 0 \\ 0, & BRN_{pixel_i} \le 0 \end{cases} \quad (4)$$

where $ITN_{Average}$ ($\mathrm{nW\,cm^{-2}\,sr^{-1}}$) is the average intensity of nighttime light within the analysis range, ITN_{pixel_i} ($\mathrm{nW\,cm^{-2}\,sr^{-1}}$) is the value of pixel i on the nighttime light image, n is the number of pixels within the analysis range, ITN_{Max} is the maximum intensity ($\mathrm{nW\,cm^{-2}\,sr^{-1}}$) of nighttime light, $ILMA$ is the total area where the nighttime light intensity > 0, and $pixel\_A$ is the area of a pixel.

2.3.2 Threats of nighttime light-represented human activities on giant panda populations

For each year, we calculated the distances from the nighttime light sources to wild giant pandas and the brightness intensity of the light source to evaluate the possible threats of nighttime light on giant pandas. We first calculated the distances from the pixels with nighttime light intensity > 0 on the remote sensing image of each year to every wild panda individual. Then we extracted the nighttime light pixel closest to each giant panda individual, and set the corresponding distance as the shortest distance from light sources to this panda. We performed this data processing on each individual so that each one corresponded to a distance. The light intensity of the nearest light pixel of each panda individual was also recorded. On this basis, we calculated the average shortest distance and the average nearest light intensity of all giant panda individuals to understand the overall threat of nighttime light-represented human activities on pandas in the entire study area. In order to analyse the differences of the threats between different mountains and between different populations, we compared the average shortest distance and the average nearest light intensity of the six mountains and all the 33 local populations. In addition, the changes of these threats from 2000 to 2010, from 2010 to 2020 and from 2000 to 2020 were analysed. We classified the dynamics of the threat to population into three levels as follows:

TABLE 1 Types of dynamics of threat to giant panda populations.

Level name	L value	Description
TA&TI	3	Threat approaches and intensifies
TA	2	Threat approaches
TD	1	Threat departs

$$L_{period_{t1-t2}} = \begin{cases} 3, & ASD_{t_1} > ASD_{t_2} \quad and \quad ANB_{t_1} < ANB_{t_2} \\ 2, & ASD_{t_1} > ASD_{t_2} \quad and \quad ANB_{t_1} \ge ANB_{t_2} \\ 1, & ASD_{t_1} < ASD_{t_2} \end{cases} \quad (5)$$

$$ASD = \frac{\sum_{i=1}^{n} \min_{j} D_{ij}}{n} \quad (6)$$

$$ANB = \frac{\sum_{i=1}^{n} N\_ITN_i}{n} \quad (7)$$

where $L_{period_{t1-t2}}$ is the level of nighttime light threat change from the year t_1 to the year t_2, ASD is the average shortest distance from light source to the population, ANB is the average nearest light intensity, D_{ij} is the distance from light source j to panda individual i in the population, N_ITN_i is the light intensity of the nearest nighttime light source to individual i, and n is the number of panda individuals in the population. The larger the value of $L_{period_{t1-t2}}$, the greater the threat to the panda population during the year t_1 to the year t_2. We named each level as shown in Table 1. We assigned each population a level and mapped the level of threat dynamic for each panda population. We finally analysed the differences between different populations, and identified populations with increased threats.

2.3.3 Relationships between nighttime light dynamics and habitat fragmentation

First, we used a conceptual model to assess wild giant panda habitat (Ouyang et al., 1995; Liu et al., 1999). This model takes into account both biotic and abiotic elements (e.g., vegetation types, elevation, slope and bamboo distribution) and is based on prior research on giant pandas (Ouyang et al., 2001; Xu et al., 2006a; Xu et al., 2009; Kong et al., 2017) and national panda surveys (State Forestry Administration, 2006; Forestry and Grassland Administration, 2021). Potential suitable habitat for the giant panda is considered to be a function of the four main criteria. Assessment criteria are listed in Table 2. The spatial extent of forest is obtained by the aforementioned ecosystem classification data. The elevation value of the grid scale came from the Digital Elevation Model data, and the slope value was obtained by the surface analysis tool in ArcGIS.

Then, we assessed the fragmentation of giant panda habitat based on the habitat assessment results. Assessing landscape pattern fragmentation is one of the main methods for analyzing the degree of habitat fragmentation (Fahrig, 2003). As the mean patch size and the number of patches are intuitive and effective indices for evaluating the basic characteristics of landscape fragmentation, we selected these indices to measure the fragmentation of giant panda habitat, and calculated the indices by fragstats 4.2 software (McGarigal, 1995).

TABLE 2 Potential habitat assessment criterion for the giant panda (Kong et al., 2017).

Mountains	Elevation (m)	Slope (degree)	Vegetation	Bamboo
Qinling	[1100, 3000]	[0, 55]	Evergreen coniferous forests; mixed broadleaf-conifer forests; evergreen-deciduous broadleaf forests	Bamboo
Minshan	[1200, 3800]	[0, 60]		
Qionglai	[1200, 3800]	[0, 60]		
Daxiangling	[1200, 3800]	[0, 60]		
Xiaoxiangling	[1200, 3800]	[0, 60]		
Liangshan	[1200, 3800]	[0, 60]		

Habitat with a smaller mean patch size and more isolated patches is more fragmented. Mean patch size is calculated as follows:

$$MPS_i = \frac{\sum_{j=1}^{n_i} a_{ij}}{j} \tag{8}$$

where MPS_i is the mean patch size of giant panda habitat in county i. n_i is the number of isolated habitat patches in county i, and a_{ij} is the area of habitat patch j in county i.

Finally, we analyzed the relationships between changes in giant panda habitat fragmentation and nighttime light intensity and area by linear regression method. We calculated the average nighttime light intensity and area in the years 2000, 2010 and 2020, as well as the habitat fragmentation indices mentioned above. Data was calculated and analyzed at the county level, and all changes in the variables represented the differences in their absolute values between 2000 and 2010, 2010 and 2020, and 2000 and 2020. Taking average nighttime light intensity and area as independent variables, and the mean habitat patch size and number of patches as dependent variables, linear regression analysis was performed by IBM SPSS statistics software. All variables were first normalized by the Z-score normalization method. The data normalization transformation formula is as follows:

$$z_i = \frac{x_i - \mu}{\sigma} \tag{9}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}} \tag{10}$$

where z_i is the variable value after normalization transformation, x_i is the original variable value, μ is the average value of the variable, σ is the standard deviation, and n is the number of samples.

3 Results

3.1 Spatial patterns and changes of nighttime light in giant panda distribution area

From 2000 to 2020, the average intensity, maximum intensity and range of nighttime light had all shown large increases (Figure 3; Table 3), indicating that human activities had increased significantly. From 2000 to 2010, the average nighttime light intensity of the giant panda distribution area increased by 34.31%, and from 2010 to 2020, the growth rate increased to 45.19%. The area of nighttime light had also expanded significantly, from 255.25 km^2 in 2000 to 5826.50 km^2 in 2020, an expansion of about 22 times. The maximum nighttime light intensity value increased in 2000–2010, but decreased in the next 10 years. The growth rates in area of nighttime light in the first decade were larger than those in the second decade. However, the growth rate of nighttime light intensity in the second decade was even larger than that in the first decade.

The distribution and change of nighttime light in the six mountains where giant pandas inhabit showed spatial differences (Figure 4). Minshan Mountain had the highest average nighttime light intensity, indicating the greatest intensity of human activities, followed by Daxiangling Mountain and Qionglai Mountain. Liangshan Mountain showed the lowest nighttime light intensity (Figure 4A). In terms of changes, Daxiangling Mountain had the highest increase in average nighttime light intensity (150.40%) from 2000 to 2020, followed by Minshan (114.34%) (Figure 4B). But looking at the two decades separately, the situation was different. Except for Qinling and the Minshan Mountains, the increases in the average nighttime light intensity of other mountains in the second decade were more dramatic than that in the first decade. In the first decade, Daxiangling Mountain and Minshan Mountain had the largest increase, and Xiaoxiangling Mountain had the lowest increase. However, the situation reversed from 2010 to 2020, the nighttime light intensity of Xiaoxiangling Mountain became the highest increaser, while Minshan Mountain became the lowest. Although Qinling Mountain initially had the highest nighttime light intensity, the increase in the two decades was the lowest.

The spatial pattern of the nighttime light area was similar. Minshan Mountain has the largest nighttime light area (80.25, 508.5 and 2057 km^2 in 2000, 2010 and 2020, respectively, and Xiaoxiangling and Liangshan Mountains had the smallest (Figure 4C). In terms of changes, Daxiangling and the Minshan Mountains had the largest growth rate of nighttime light area (3426.05% and 2463.24% respectively) from 2000 to 2020 (Figure 4D). It is worth noting that, the range of night light

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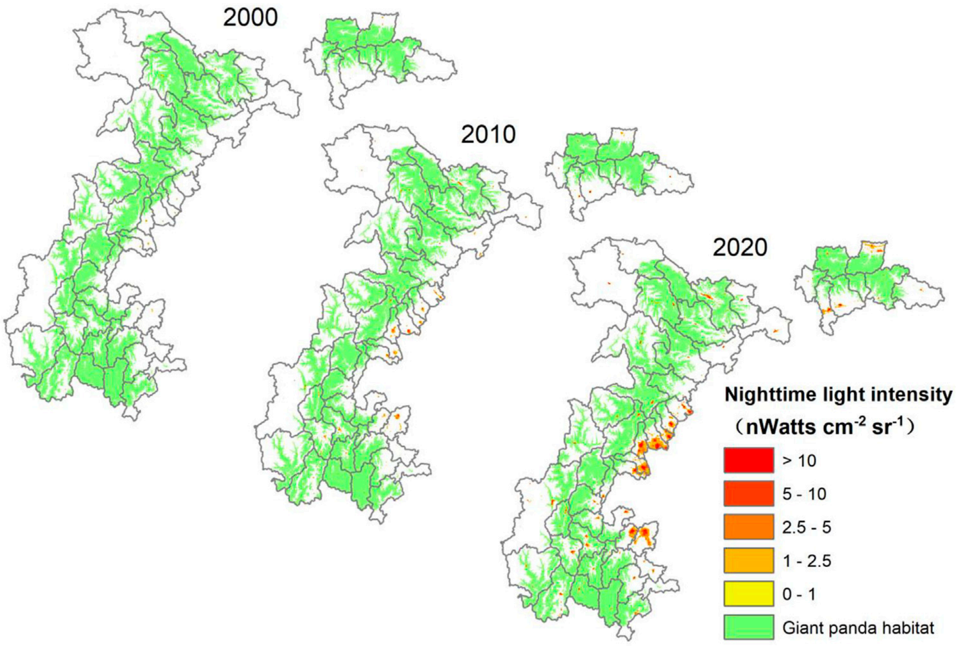

FIGURE 3
Spatial patterns of nighttime light intensity in giant panda distribution area (2000, 2010, and 2020).

TABLE 3 Nighttime light intensity and ranges in giant panda distribution area.

Variables	2000	2010	2020	Rate of change (%)		
				2000–2010	2010–2020	2000–2020
Average intensity (nWaltts cm^{-2} sr^{-1})	1.95	2.62	3.81	34.31	45.19	95.01
Maximum intensity (nWaltts cm^{-2} sr^{-1})	24.06	62.66	60.67	160.43	-3.18	152.16
Area (km^2)	255.25	1531.75	5826.50	500.10	280.38	2182.66

in Liangshan Mountain is relatively small, but expanded significantly (with a growth rate of 2090.24%) during the two decades.

In terms of the maximum intensity of nighttime light, Minshan Mountain was also the highest (Figure 4E), and Daxiangling Mountain had the fastest growth from 2000 to 2020 (Figure 4F). Different from the continuous growth in other mountains, maximum intensity values in Minshan and Daxiangling Mountains showed sharp increases in the first decade and declines in the second decade. Besides, Liangshan and Xiaoxiangling Mountains had the fastest growth of maximum nighttime light intensity. In Qinling Mountain, maximum intensity of night light in the year 2000 is the largest, but its growth was the lowest.

The intensity of nighttime light inside the giant panda natural reserves was much lower than outside, and we found it became more obvious over time: the average intensity of nighttime light inside the natural reserves was 11.0% (2000), 6.5% (2010) and 1.1% (2020) of the average level in the whole study area, respectively. We also found that the characteristics of nighttime light changes inside the natural reserves were different from outside. Both of nighttime light intensity and area inside the natural reserves first increased and then decreased (Figures 5A,C). The average nighttime night intensity inside natural reserves had increased by 16.98% in the two decades, with a 41.28% increase in the first decade and a 17.20% decrease in the second decade. The nighttime light area inside natural reserves had increased by 1.25 times in the two decades, with 2.57 times increase in the first decade and a 37% decrease in the second decade. Compared to outside the natural reserves, the growth rate of nighttime light inside was much lower. From 2000 to 2020, the growth rate of the nighttime light area inside natural reserves was only 5.7% of the growth rate over the

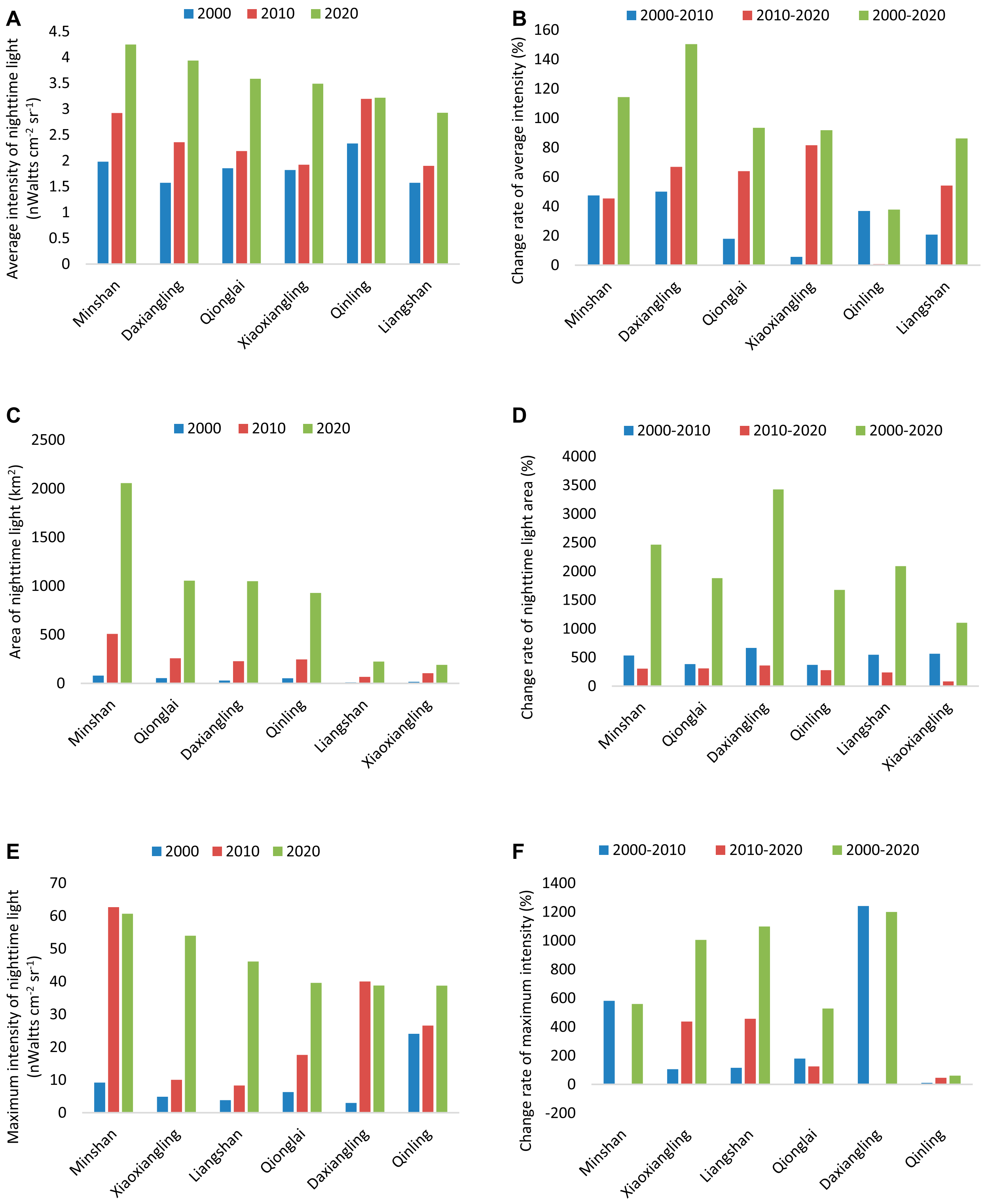

FIGURE 4
Intensity and area of nighttime light in different mountains where giant pandas inhabit. **(A)** Average intensities of nighttime light in the six mountains; **(B)** Change rates of average intensities of nighttime light in the six mountains; **(C)** Area of nighttime light in the six mountains; **(D)** Change rates of nighttime light area in the six mountains; **(E)** Maximum intensities of nighttime light in the six mountains; **(F)** Change rates of maximum nighttime light intensities in the six mountains.

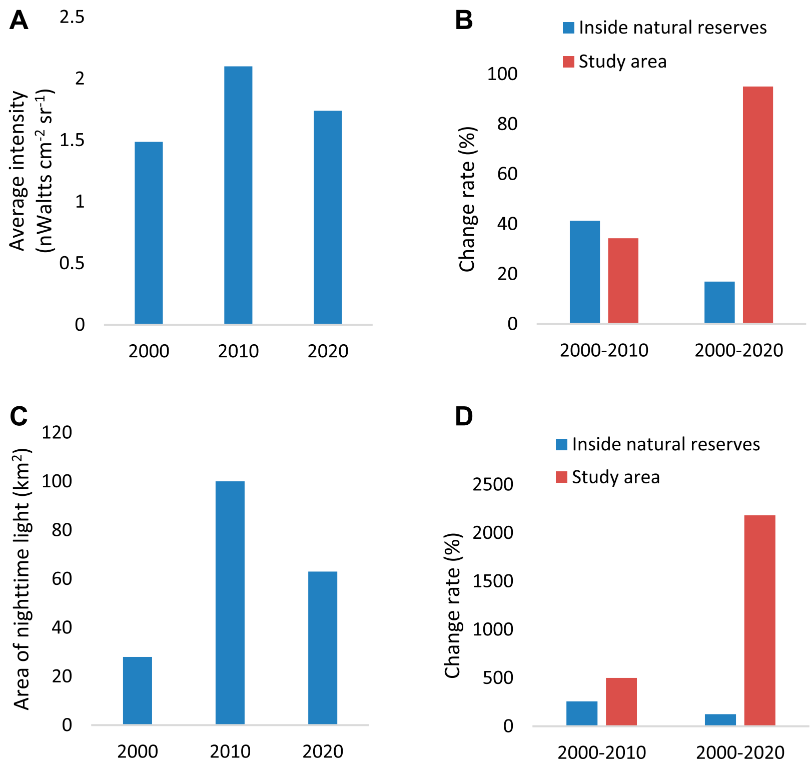

FIGURE 5
Intensity and area of nighttime light inside natural reserves. **(A)** Average intensity of nighttime light inside natural reserves; **(B)** Comparison of change rates of average intensity inside natural reserves and the whole study area; **(C)** Area of nighttime light inside natural reserves; **(D)** Comparison of change rates of nighttime light area inside natural reserves and the whole study area.

whole study area (Figure 5D). Differently, the growth rate of nighttime light intensity inside natural reserves was 120% of the average level in the study area from 2000 to 2010, but the effective protection made it fall to 17.9% from 2000 to 2020 (Figure 5B), which indicated that the protection inside the natural reserves effectively reversed the rapid increase in human activities in the previous decade.

3.2 Threats of nighttime light-represented human activities to giant panda populations

In general, the average distance between the closest nighttime light source and the giant panda individuals became shorter from 2000 to 2020, and it had experienced a process of first decreasing and then increasing (Figure 6A). That is to say, the nighttime light approached wild pandas from 2000 to 2010, and stayed away from 2010 to 2020. However, the average intensity of the closest nighttime lights gradually increased during the 20 years (Figure 6B). Judging from the different mountains where giant pandas inhabit, nighttime light in Daxiangling Mountain was the nearest to wild pandas, and the nighttime light around Liangshan Mountain's populations was the farthest. Different from other mountains, the nighttime light continued to approach pandas in Liangshan and Qionglai Mountains from 2000 to 2020 (Figure 6A).

Nighttime light was getting closer to local wild giant panda populations from 2000 to 2020. In the year 2000, only 9.1% of the local populations were less than 10 km away from night light, it rose to 18.2% in 2010, and further rose to 36.4% in 2020. We also found that the proportion of local populations with a distance 10–20 km from nighttime light increased first and then decreased (66.7% in 2000, 90.9% in 2010 and 84.8% in 2020). On the contrary, the populations with a distance > 20 km first decreased and then increased (Figure 6C). That is to say, after the rapid approach of nighttime light to panda populations from 2000 to 2010, the threat of nighttime light to some populations became weaker from 2010 to 2020, while the threat to other populations became stronger.

Further, we analyzed the specific situation of each local wild panda population. In the year 2000, only Qinling E, Minshan A, and Daxiangling C, which were small peripheral populations to the large panda populations, were close to the night light, and the distances were less than 10 km. In the year 2010, the situation became worse, and nighttime light became closer to almost all panda populations. The distances from nighttime light to all the Xiaoxiangling populations and Qinling B population became less

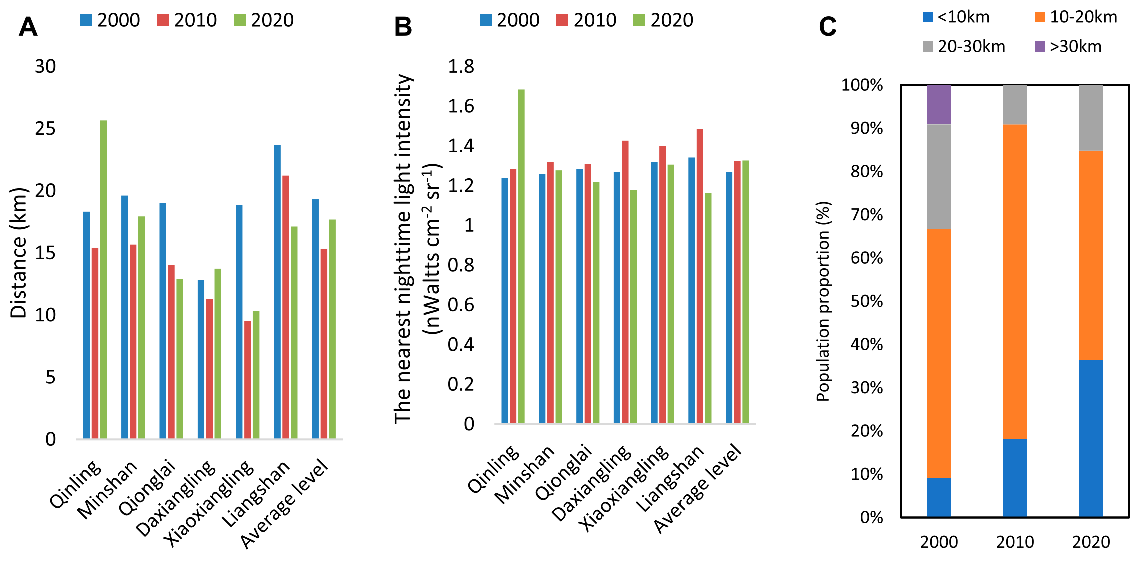

FIGURE 6
Changes of the distance from nighttime light to giant panda populations and light intensity. **(A)** The shortest distance from nighttime light to panda populations in of different mountains; **(B)** The intensity of the nearest nighttime light of panda populations in different mountains; **(C)** Proportions of panda populations with different distances from the light source in each year.

than 10 km. Nighttime light also obviously approached the large populations in Minshan and Qionglai Mountains in the core area. By 2020, the situations had improved for the core populations of Qinling, Minshan K, Minshan C, Minshan H, and Xiaoxiangling B population, nighttime light tended to stay away from them, while nighttime light got closer to other populations in the periphery of Minshan (Minshan L, Minshan G), populations at both ends of the Qionglai Mountains, and most of the populations in Liangshan (Figure 7).

When the nighttime light intensity was added into consideration, there were 18 populations that were getting closer to nighttime light and their nearest light intensity also became stronger from 2000 to 2010, including most of the Qinling populations, the large populations at both ends of the Minshan and Qionglai Mountains, Daxiangling populations, Xiaoxiangling A, and all popoulations in Liangshan. Although this trend reversed from 2010 to 2020, the peripheral panda populations of Qinling Mountain, southern Minshan population (Minshan L) and southern Qionglai population (Qionlai D) might be more affected by nighttime light-represented human activities, which became not only closer but also more intensified (Figure 7).

3.3 The relationship between habitat fragmentation and nighttime light dynamics

We found that giant panda habitat fragmentation were significantly correlated with nighttime light dynamics. The fragmentation of the giant panda habitat from 2000 to 2020 were significantly positively correlated with the increases of intensity and area of nighttime light, which is shown as follows: the changes of the average intensity and area of nighttime light were significantly negatively correlated with change of the mean patch size of panda habitat, and significantly positively correlated with change in the number of habitat patches (Table 4). The correlations were highly significant from 2000 to 2010 and weakened from 2010 to 2020. This indicated that the fragmentation of giant panda habitat was mainly due to the human activities' enhancement and expansion from the first decade.

4 Discussion

The threat of human activities has exacerbated the fragmentation of wild giant panda habitats, posing risks to the long-term survival of giant pandas. Assessing human activities and their impact on wild giant pandas is important for the effective protection of giant pandas and their habitats. Nighttime light is one of the dominant human activity factors. Long-term and large-scale human activities can be quickly assessed using nighttime light remote sensing data, which has been increasingly used in the monitoring and evaluation of human disturbances to wild species. Using nighttime light remote sensing data from 2000 to 2020, we analyzed the spatial pattern and trend of nighttime light intensity and range in giant panda distribution areas, and clarified the possible threats to giant panda populations and habitats and their

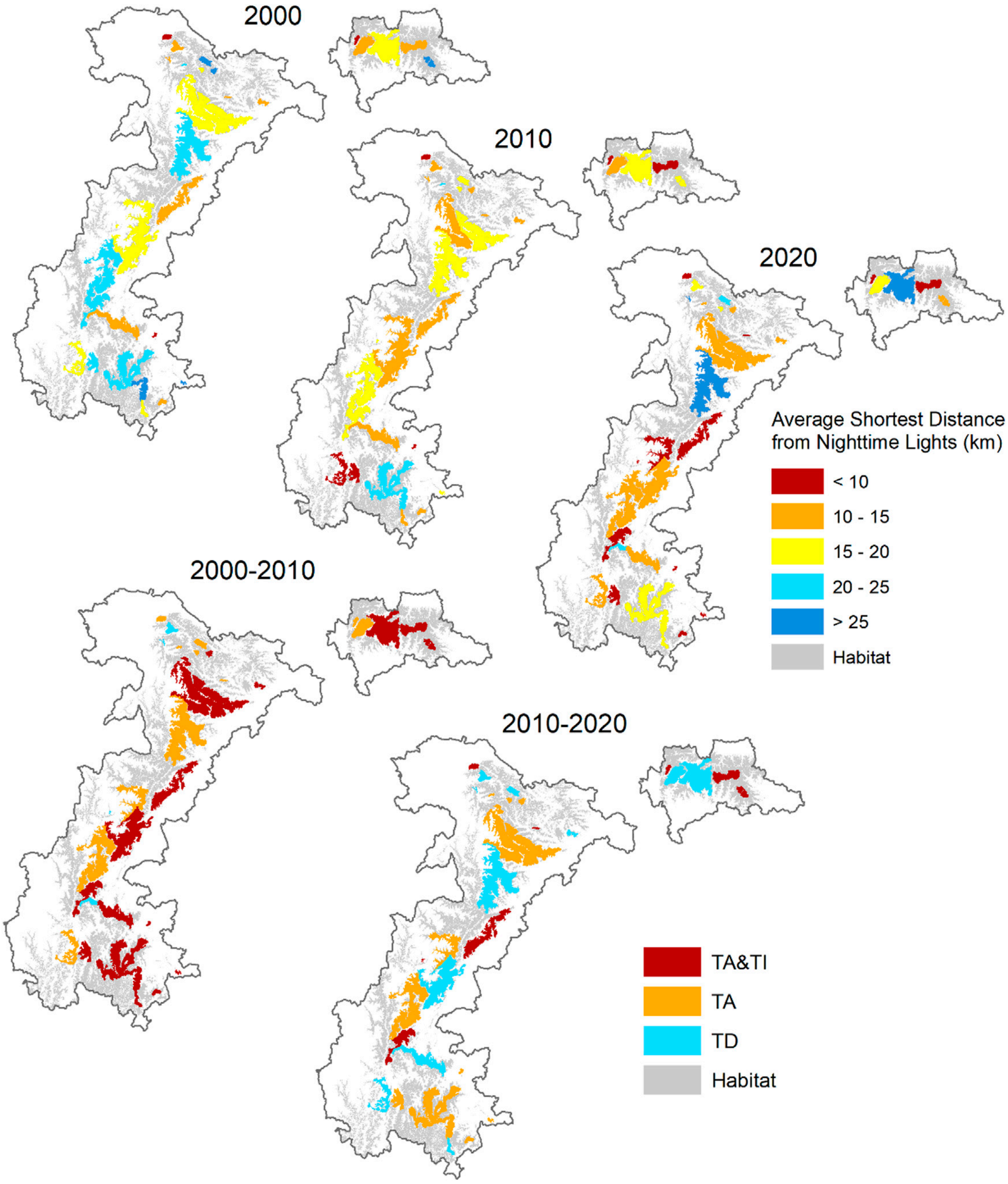

FIGURE 7
Spatial patterns and dynamics of giant panda population threatened status. (TA&TI, light sources are closer to the population and more intensified; TA, light sources are closer to the population; TD, light sources are further away from the population).

changing characteristics. Our findings could have implications for the future monitoring and assessment of human activities around giant panda habitats, the protection of giant pandas and their habitats from human threats, and the conservation of other wild species that are increasingly threatened by human activities in the world.

4.1 Spatial pattern of nighttime light and its dynamic changes

Clarifying the spatial pattern and dynamic changes of nighttime light intensity and range is meaningful for understanding the distribution and changing characteristics of

TABLE 4 Correlation between habitat fragmentation and nighttime light intensity and area. Dependent variables are changes in mean habitat patch size and number of habitat patches, respectively. Standardized coefficients and robust standard errors are reported outside and inside parentheses, respectively. Model results passed standard regression diagnostics. Variance inflation factors (VIFs) were tested to be < 5.

Independent variable	Mean habitat patch size			Number of habitat patches		
	2000–2010	2010–2020	2000–2020	2000–2010	2010–2020	2000–2020
Average intensity of nighttime light	−0.615*** (0.110)	−0.096 (0.300)	−0.246† (0.136)	0.562*** (0.116)	0.124 (0.139)	0.238† (0.136)
Area of nighttime light	−0.397** (0.129)	−0.014 (0.140)	−0.270† (0.135)	0.337* (0.132)	0.171 (0.138)	0.288* (0.134)

†$p < 0.1$; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

human activities. We found that Southern Minshan Mountain, Qionglai Mountain, and Daxiangling Mountain housed the majority of the nighttime light around giant pandas, and the nighttime light intensity within the giant panda distribution area had increased largely from 2000 to 2020, indicating that human activities had increased significantly. This is consistent with the conclusions of existing studies and surveys (Xu et al., 2006b; State Forestry Administration, 2006; Forestry and Grassland Administration, 2021). In particular, the growth of the nighttime light intensity in Xiaoxiangling Mountain has increased significantly over time, and existing studies have also indicated that the possible threat of human activities there is great (Ran et al., 2003; Ran et al., 2004). It is worth noting that the growth rate of nighttime light intensity inside the nature reserves even exceeded that outside from 2000 to 2010. Among the main resource utilization behaviors of the community residents around the giant panda natural reserves, grazing, ecotourism, herbal medicine collection and poaching are the main types of human disturbance (Zhang et al., 2017). Existing studies have also shown that human population size and the number of households in the natural reserves has increased largely and human activities has increased since its establishment (Liu et al., 1999; Liu et al., 2001). The intensity of human interference has enhanced with the increasing number of tourists in recent years, such as the famous Jiuzhaigou and Huanglong Nature Reserves (State Forestry Administration, 2006). After the year 2000, the community residents around the giant panda distribution area began to adjust the industrial structure, and herdsmen in many areas entered the natural reserves to graze (Ran et al., 2004; Hull et al., 2014; Sichuan, 2016; Zhang et al., 2017). We also found that the rapid increase in nighttime light intensity had been reversed inside natural reserves during 2010–2020. This may be largely due to the implementation of ecological protection and restoration projects. Two of the largest ecosystem service compensation programs (Projects of Natural Forest Protection and Returning Sloping Cropland to Forest) have invested billions of dollars in financial allocations to remote communities and forest restoration and management (Liu et al., 2008; Ouyang et al., 2016), which has largely reduced the disturbance of human activities (Li et al., 2013; Tuanmu et al., 2016; Yang et al., 2017). There are also studies showing that tourism in the Wolong Nature Reserve was largely stagnant from 2008 to 2016 because of earthquakes (Liu et al., 2016), which may also be the reason for the slowdown in the growth of nighttime light intensity.

4.2 Dynamic threats of nighttime light-represented human activities to giant panda populations

The dynamic relationship between nighttime light intensity and wild giant panda populations can reflect changes in the threat of human activities to giant pandas to a certain extent. Long-term data on threats of human activities to panda populations are fundamentally important for conservation policy and management decisions (Wei et al., 2018). Using the long-term nighttime light data, our study found that the nighttime light was gradually approaching the giant panda populations from 2000 to 2020, which could be the consequence of the gradual increase in the scope of human activities (Linderman et al., 2005). This illustrated the increased threat of human activities to the giant panda populations because pandas avoid areas impacted by human activities, such as roads, livestock, mining, and tourism (Hull et al., 2014; Wei et al., 2018). The results of the Third and the Fourth National Giant Panda Census can also verify this effect of nighttime light-represented human activities on the population: we found that almost all counties with declining panda numbers in the surveys were close to the intensified nighttime light. Although the threat of human activities to giant pandas has been approaching from 2000 to 2020, we also found that nighttime light was moving away for some populations during 2010–2020, such as the core large populations of the Qinling, Minshan and Qionglai Mountains. These populations are mainly distributed in major giant panda natural reserves, and also inside what is now the giant panda national park. It indicates that the management of human activities in giant panda nature reserves has alleviated the threat of human activities to the core large populations in recent years, which are also protected by the Giant Panda National Park (Kong et al., 2021). The situation is not optimistic for those small peripheral populations. Our study found that the human threats on the peripheral populations continued to intensify, manifesting in the fact that the nighttime light was not only getting closer, but also brighter. Studies have shown that these peripheral isolated small populations are mostly outside the Giant Panda National Park. Due to the small size of population and climate change, the risk of future extinction of them is high (Kong et al., 2021). Therefore, we can infer that they will be at greater risk of extinction if surrounding human activities intensify further.

4.3 Nighttime light dynamics and habitat fragmentation

Human activity is one of the major factors leading to habitat fragmentation of giant pandas, and quantifying the relationships between changes in the intensity and extent of human activities and the process of habitat fragmentation is a matter of concern (Li et al., 2019). Our study found that the increase in nighttime light intensity and area were both significantly positively correlated with the increase in habitat fragmentation from 2000 to 2020, which confirms that the enhancements in the intensity and extent of human activities (such as road construction and expansion of urban land) have contributed to increased habitat fragmentation. This conclusion is consistent with the inference of existing studies (Li et al., 2010; Xu et al., 2017; Luo et al., 2022). We also found that these strong correlations were mainly contributed by the period from 2000 to 2010, and the they were becoming less significant over time. This finding also echoes previous studies. In recent years the implementation of ecological restoration projects has largely promoted the transfer of rural to urban populations, reduced the rural population in mountainous areas to a certain extent, contributing to restoration of giant panda habitats (Zhang et al., 2018; Li et al., 2019; Han et al., 2022; Li and Song, 2022).

4.4 Implications for giant panda conservation

Wild giant pandas are in 33 isolated populations, and their habitat has become more fragmented in the past decades (Xu et al., 2017; Kong et al., 2021). If human activities further exacerbate the habitat fragmentation and population isolation of wild giant pandas, the risk of population extinction will further increase. Peripheral populations, in particular, are more and more threatened. It is necessary to strengthen the restoration of giant panda habitat connectivity and improve habitat quality, so as to improve the habitat stability and promote population exchanges. It is important to improve monitoring technology and carry out dynamic monitoring of human activities, giant panda populations and habitats. On this basis, the spatial distribution of human activities around giant panda and its habitat should be further optimized. We need to pay special attention to monitoring and controlling the expansion of human activities around peripheral populations. In addition, the management in giant panda national park and natural reserves should be further improved to prevent increased stress from human activities.

In this study, we used long-term remote sensing data to evaluate the dynamic changes of nighttime light in the giant panda distribution area from 2000 to 2020 for the first time, and specifically discussed the dynamic threats to giant panda populations and habitat from human activities represented by nighttime light. In future studies, we could further supplement other human activity factors and data of panda population dynamics to analyze the mechanism of human activities' impact on giant panda population dynamics. In addition, the dual effects of future climate change and human activities on giant panda populations and habitats is also a topic that could be further studied in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

LK, ZO, and WX designed the research. LK, WX, and CW performed the research. LK and CW analysed the data. LK, ZO, WX, and CW wrote the paper. All authors have read and approved the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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