Effectiveness in protected areas at resisting development pressures in China

Ziqi Meng a, b, Jinwei Dong a, *, Jun Zhai c, Lin Huang a, Min Liu d, Erle C. Eills e

a Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
b University of Chinese Academy of Sciences, Beijing, 100049, China
c Satellite Environment Center, Ministry of Ecology and Environment of the People’s Republic of China, Beijing, 100094, China
d Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, East China Normal University, Shanghai, 200241, China
e Department of Geography and Environmental Systems, University of Maryland Baltimore County, Baltimore, MD, 21250, USA

* Corresponding author.
E-mail address: dongjw@igsnrr.ac.cn (J. Dong).

https://doi.org/10.1016/j.apgeog.2022.102682
Received 4 October 2021; Received in revised form 24 January 2022; Accepted 8 March 2022
Available online 16 March 2022
0143-6228/© 2022 Elsevier Ltd. All rights reserved.

ARTICLE INFO

Keywords:
Protected area
Development pressure
Impervious surface areas
Nighttime light
China

ABSTRACT

Protected areas (PAs) are designed to conserve biodiversity and protect the species within their boundaries. However, some PAs are not achieving these goals, partly due to human activities inside and outside PAs. Here we evaluated the ability of 290 national-level PAs in China to reduce the impacts of economic development pressures using remote sensing-based fine resolution impervious surface area (ISA) and nighttime light (NTL) data as proxies of development pressure. We measured and compared the development pressure in protected areas and within buffers the same size in the area of the PAs (namely outside of the PAs). We also investigated whether the performance of PAs will be threatened by outside development pressure. According to the ISA, we found that 176 of the PAs had more development pressure outside their boundaries than inside PAs in 2018. For 175 PAs, we found a higher increasing rate of impervious areas outside of the PAs from 2000 to 2018, which suggested that increased human activities outside of the PAs were placing increased development pressure on the PAs. The PAs with higher development pressure outside their boundaries were more common in populous regions, especially in eastern China. Consistent with our findings from the ISA data, the NTL data also indicated that national PAs in China have faced increasing development pressures from outside PAs from 2000 to 2018. Our study warns that more attention should be paid to economic development pressures from the areas surrounding PAs to sustain their biodiversity protection over the long run.

1. Introduction

Global changes in land use are causing striking declines in biodiversity and widespread habitat degradation (Ceballos et al., 2015; Steffen, Grinevald, Crutzen, & McNeill, 2011). The establishment of protected areas (PAs) is a central approach to curb declines in biodiversity, and PAs are increasingly becoming final refuges for threatened species (Laurance et al., 2012; Xu et al., 2017). The post-2020 global biodiversity framework developed by the Convention on Biological Diversity (CBD), part of the United Nations Environment Programme, aims to expand PAs to 30% of land area by 2030 (https://www.cbd.int/). Globally, coverage of terrestrial PAs has rapidly grown to an estimated 15.4% in 2021 (UNEP-WCMC and IUCN, 2021), which may continue to expand with future commitments (Yang et al., 2020). PAs are intended to serve as an effective tool for maintaining habitat integrity and species diversity by providing a buffer against direct human intervention (Geldmann et al., 2013; Geldmann, Manica, Burgess, Coad, & Balmford, 2019; Shrestha, Xu, Meng, & Wang, 2021).

Extensive human activities within PA boundaries and/or surrounding areas can undermine the conservation goals that PAs are intended to achieve (Jones et al., 2018), and the decline in biodiversity caused by human activities has been apparent (Newbold et al., 2015). For example, the effectiveness of PAs at mitigating pressures on habitat quality and biodiversity loss from human activities have been studied from the perspectives of human settlements (Guan, Elleason, Goodale, & Mamedes, 2021) and agricultural cultivation (Geldmann et al., 2019; Vijay & Armsworth, 2021). Also, some more comprehensive proxies of human activities related to biodiversity loss have been proposed to assess the effectiveness of PAs, including the Human Footprint (HF) (Jones et al., 2018) and Temporal Human Pressure Index (THPI) (Geldmann, Joppa,
& Burgess, 2014). In addition, other recent global maps of human influences, such as Low Impact Areas (LIA), Anthromes, and Global Human Modification (GHM), have been used to identify the last natural or intact areas where human influences were low (Ellis, Goldewijk, Siebert, Lightman, & Ramankutty, 2010; Ellis & Ramankutty, 2008; Jacobson, Riggio, Tait, & Baillie, 2019; Kennedy, Oakleaf, Theobald, Baruch-Mordo, & Kiesecker, 2019; Riggio et al., 2020). These datasets have different model structures and input data, which have led to different results at various spatial (1 km (HF, LIA, and GHM); ~5 km (Anthromes); and 10 km (THPI)) and temporal resolutions (1993–2009 (HF); 1990–2010 (THPI); 2015 (LIA, Anthromes); and 2016 (GHM)). Using the THPI data, Geldmann et al. (2014) found that PAs have generally experienced increased human pressure since the early 1990s. Moreover, Jones et al. (2018) used the HF data and found that one-third of the world’s PAs are under tremendous human pressure. From the perspective of having low human influences, the proportions of the Earth’s last natural areas (Ellis et al. (2021) found these areas generally exhibit long histories of use) using these various human influences maps were also different. For example, Jacobson et al. (2019) used LIA data and found that 56% of the terrestrial surface had low human influence, and Riggio et al. (2020) identified 49.2–53.6% of the world with low human influence using the HF, GHM, or Anthromes data. The discrepancies between these conclusions garnered from different datasets could be related to the different scales that the indicator used and the lack of calibration of the indicators. Also, those comprehensive indicators could miss some specific information. Thus, some specific physical indicators like impervious surface areas (ISA) and nighttime light (NTL) could be useful candidates for improving our understanding on the development pressures of PAs.

The higher spatial and temporal resolutions of ISA and NTL data provide new opportunities for understanding human activities within and surrounding PAs. For example, changes in ISA are a predominant indicator for understanding the impact of urbanization on the environment and biodiversity (Gong et al., 2020). The NTL data also can quantitatively characterize economic development activities and is widely recognized as harmful to PA wilderness (Li, Gao, Li, & Hou, 2020).

In addition, previous studies have mainly investigated the effectiveness of PAs without comparison to non-PAs (Geldmann et al., 2014; Jones et al., 2018), and thus failed to adequately control for covariates that may have affected the effectiveness of conservation (Rasolofoson, Ferraro, Jenkins, & Jones, 2015). Assessing the effectiveness of PAs requires an appropriate counterfactual method—comparing the outcomes with protection and without protection (Ferraro & Pressey, 2015). This comparison is important because it may eliminate a bias that the apparent conservation outcomes of PAs may be related to their location rather than the protection per se (Gray et al., 2016; Joppa & Pfaff, 2009). Using remotely sensed data, previous studies have linked the effects of biodiversity protection inside PAs to different conservation governance regimes (Schleicher, Peres, Amano, Lictayo, & Leader-Williams, 2017; Smith, Muit, Walpole, Balmford, & Leader-Williams, 2003), to social and economic conditions (Symes, Rao, Maccia, & Carrasco, 2016), and to management capacities (Leverington, Costa, Pavese, Lisle, & Hollings, 2010). These studies have mainly focused on the performance of existing inside PAs; however, the assessment of the development pressures caused by outside human activities on PAs has been largely neglected.

China supports all species living on Earth and hosts many globally important ecosystems (Ren et al., 2015). However, due to China’s swift economic growth and urban expansion, China’s biodiversity and natural habitats are being degraded at a rapid rate. Thus, the designation of PAs is considered as a valuable conservation strategy for China (Liang, He, et al., 2018). Although PAs are generally believed to be the safest stronghold for wilderness (Armento, Roazzi, Smith-Ramirez, & Arroyo, 1998) and the number of PAs in China continues to increase (11,800 PAs in 2019, spanning 18% of China’s land surface) (http://www.cnemc.cn/), human encroachment and disturbances remain very common in PAs (Liu, Linderman, et al., 2001; Liu, Liu, et al., 2001). Previous nationwide assessments of the effectiveness of China’s PAs have mainly focused on changes in habitats (Zhu, Huang, Xiao, & Wang, 2018), vegetation diversity (Sun, Sang, & Axmacher, 2020), and threatened species (Li, Xing, et al., 2018). Only a few studies assessed the impacts of human activities within China’s PAs, and mainly used nighttime light data to represent development pressure (Li, Zhou, Zhao, & Zhao, 2020; Shrestha et al., 2021; Xu, Wang, Jin, & Jin, 2019). However, these studies did not investigate the spatiotemporal variations of human activities at the PA level over a continuous period because of the inconsistency of the data and did not compare levels of human activities between inside and outside of the PAs.

To address these knowledge gaps, we assessed the effectiveness of 290 national PAs in China at mitigating economic development pressures by assessing spatiotemporal changes from 2000 to 2018 inside and outside of the PAs using fine resolution (30 m) data on impervious areas (Gong et al., 2020) and 500-m nighttime light (NTL) data (Chen et al., 2021). In this study, we want to answer two questions: (1) What was the spatiotemporal pattern of the development pressure changes in the protected areas of China from 2000 to 2018? (2) Whether the performance of PAs would be threatened by development pressure outside PAs?

2. Materials and methods

2.1. Study area

As of 2019, China had established 474 national PAs according to Ministry of Ecology and Environment of the People’s Republic of China (https://www.mee.gov.cn/). Here we focused on the terrestrial PAs, and the marine PAs were not considered. We also excluded the paleontological and geological PAs from our analyses as they are not related to the protection of animals, plants, or biodiversity. In total, we included 290 national PAs in our study, which cover about 10% of China’s land surface area. These PAs include 144 forest ecosystems, 3 grassland meadows, 42 inland wetlands, 10 desert ecosystems, 12 wild plants, and 79 wild animal refuges (Fig. 1). More details about the types could be found in Supplementary Material. The 290 PAs are located in distinctive economic development regions: 144 (868,562 km²) are located in western China (1,145,860 km²), 52 (11,773 km²) in eastern China (186,468 km²), 47 (51,050 km²) in northeastern China (452,544 km²), and 47 (14,021 km²) in central China (156,784 km²).

2.2. Data

2.2.1. Impervious surface area (ISA) map

The impervious surface area and nighttime light intensity were used to represent development pressure in our study. We derived annual maps of global artificial impervious area (GAIA) from Gong et al. (2020). This dataset has a spatial resolution of 30 m during 1985–2018, which was generated using a combination of supervised classification and temporal consistency checks. The impervious surface area data was mapped using the full archive of 30-m resolution Landsat satellite images on the Google Earth Engine platform. It was combined the nighttime light data and the Sentinel-1 Synthetic Aperture Radar data to improve the performance in arid areas. Impervious pixels are defined as above 50% impervious. Globally, the accuracy of the data was higher than 89% (Gong et al., 2020).

2.2.2. Nighttime light (NTL) data

The nighttime light satellite data have been extensively used to investigate human activities due to the artificial electric light widely equipped in most buildings and infrastructures (Elvidge et al., 1997). In this study, we used a temporally consistent global NTL dataset with 500-m resolution (2000–2018) produced by Chen et al. (2021), which
was generated 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 proposed cross-sensor calibration is unique due to the image enhancement by using a vegetation index and an auto-encoder model. The author developed an auto-encoder (AE) model including convolutional neural networks to integrate DMSP-OLS NTL and NPP-VIIRS NTL data and generated the extended time series of global annual NPP-VIIRS-like NTL data from 2000 to 2018. Compared to other products, this product had good spatial and temporal consistency and has been proven to be useful for monitoring the dynamics of human activities over a longer period of time.

2.2.3. Population data

In order to understand the environment PAs located and to separate the different populous zones PAs located, we used population data as a proxy. Population data for China were sourced from the Resource and Environment Science and Data Center (Xu, 2017). This dataset has a spatial resolution of 1 km and has been produced in 5-year intervals since 1990. Different gradients of population intensity were analyzed to show the impact of the population outside of the PAs on the effectiveness of PAs in mitigating development pressure.

2.3. Methods

2.3.1. Comparing development pressures inside and outside of the PAs

We generated geometries representing the unprotected area surrounding each PA using a buffer the same size in area of the PA (Fig. 1, outside PAs), using Python 3.8 and the geopandas and descartes packages (https://www.lfd.uci.edu/~gohlke/pythonlibs/). We used the ‘equal area method’ to generate the buffers of outside of the PAs mainly because the imbalanced area distribution of PAs in China, that is, extremely large PAs has been established in western China, while PAs in northeastern, southern, and central China are particularly small (Sun et al., 2020). If we used a certain distance to create buffer zones such as 2 km, it may only be suitable for small PAs, while there will be uncertainties when analyzing for large PAs. Therefore, the area difference between inside and outside of the PAs may produce incomparable phenomena when analyzing the effectiveness of PAs at resisting development pressure. We calculated and compared the ISA and NTL values of the inside and outside of the PAs to reflect the development pressure inside and outside of the PAs.

2.3.2. Trends and significance of changes in development pressure

We evaluated the changes in development pressure (i.e., ISA and NTL) from 2000 to 2018 using the unitary linear regression model, which was represented as:

$$\theta_{\text{slope}} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

(1)

where $\theta_{\text{slope}}$ is the slope of the regression equation, $i$ is the year serial number ($i = 1, 2, ..., 19$), $x_i$ is the independent variable, $y_i$ is the dependent variable. $\theta_{\text{slope}} > 0$ indicates increasing development pressure, $\theta_{\text{slope}} < 0$ indicates decreasing development pressure, and $\theta_{\text{slope}} = 0$ indicates no change.

An F-test was used to assess the significance of the trend (Cao, 1988), expressed as:

$$F = U \times \frac{n - 2}{Q}$$

(2)

$$U = \sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2$$

(3)
where $Q$ represents the squared deviation of the regression value of ISA (NTL) inside and outside a protected area, $U$ is the average value of ISA (or NTL) for many years. $Q$ represents the sum of squares of the deviation between the true value of ISA (or NTL) inside and outside a protected area and the regression value, which is called the sum of squares of errors. $\hat{y}_i$ is the true value of development pressure value (ISA or NTL) of year $i$, $\hat{y}_i$ is the regression value of development pressure value (ISA or NTL) of year $i$, $y_i$ is the mean development pressure value over the monitoring period, and $n$ is the number of monitoring years. Based on the test results, the trends could be classified into three levels: a significant increase ($\theta_{slopes} > 0$, $p < 0.05$), a significant decrease ($\theta_{slopes} < 0$, $p < 0.05$), or no significant change ($p > 0.05$).

The slopes and significance of the ISA and NTL values inside and outside the PAs were also analyzed by economic zones: northeastern China, eastern China, central China, and western China.

2.3.3. Effects of development pressure outside of the PAs on PAs

Hansen et al. (2011) showed that human activities outside PAs could affect biodiversity within PAs. We can therefore assume that some changes inside PAs can be attributed to outside changes, as they are spatially proximal and have nearly the same environmental conditions. Here we used the Pearson correlation analysis to examine the possible effects of development pressure outside of the PAs on the PAs, as shown by the following formula:

$$Corr(r) = \frac{n \sum XY - (\sum X)(\sum Y)}{\sqrt{\{n \sum X^2 - (\sum X)^2\}\{n \sum Y^2 - (\sum Y)^2\}}}$$

(5)

where $Corr(r)$ is the Pearson correlation coefficient, $n$ is the number of protected areas that used in our study, $\sum XY$ is the sum of the paired variables, $\sum X$ and $\sum Y$ represent the sum of the x and y values, $\sum X^2$ and $\sum Y^2$ represent the sum of the squared $X$ and $Y$ values, respectively. We used a $t$-test to determine the significance at a level of 0.05 (Maishella, Dewantoro, & Aji, 2020).

2.3.4. Effects of development pressure outside of PAs on PAs (outside-to-inside pressure index) along different population gradients

We devised a new indicator to quantify the effects of development pressure outside of the PAs on PAs, the outside-to-inside pressure index ($OtoI_{pres}$), which we calculated using the following equation:

$$OtoI_{pres} = \frac{Slope_{outPA}}{Area_{outPA}} \times \frac{Slope_{inPA}}{Area_{inPA}}$$

(6)

where $OtoI_{pres}$ is the outside-to-inside pressure index; $Area_{outPA}$ and $Area_{inPA}$ represent the areas inside and outside the PAs, respectively. The value of $Area_{outPA}$ is equal to the value of $Area_{inPA}$, as we used the ‘equal area method’ to generate the buffers of outside of the PAs. Using ISA as an example, the $Slope_{outPA}$ and $Slope_{inPA}$ represent the slopes of ISA inside and outside of the PAs, respectively. A positive $OtoI_{pres}$ value indicates that PAs are subject to greater external threats from outside PAs than inside PAs, while a negative value indicates that the rate of development pressure is higher inside the PAs than outside. $OtoI_{pres}$ can better evaluate the relative effectiveness of PA performance, it can also reduce the uncertainty of the spatial data scale caused by the different area of PAs.

We also analyzed the dependence of these outside-to-inside pressures on population densities using linear regression along different population gradients. Thus, the higher the $R^2$ value, the higher the percentages of the variation in outside-to-inside pressure could be explained by population densities.

3. Results

3.1. Development pressure inside and outside of the PAs

Generally, the development pressure inside the PAs was lower than outside, as shown by the lower proportion of impervious surface areas (ISA, Fig. 2) and total nighttime light intensities (NTL, Fig. 3) inside the PAs. For example, the average proportion of ISA outside of the PAs was 0.29% in 2018, which was higher than ISA inside the PAs of 0.06% (Fig. 2). Of the 290 PAs, 176 had a larger ISA outside of the PAs than inside the PAs.

There was a considerable variation of ISA among the sites. Out of the 290 PAs, the majority (151) had no ISA and 139 PAs had some ISA. Also, a majority of the PAs (195) had a higher proportion of ISA outside of the PAs than inside in 2018. For example, the Lalu Wetland PA had the largest difference in the proportion of ISA inside and outside of the PA, with outside of the ISA being 31.3% and the inside ISA being 8.9%.

Specifically, as for different types of protected areas in China, all types showed higher in outside PAs than inside PAs in 2018 (Fig. 2). For wetland ecosystem ($n = 42$) and wild plant (12) PAs, all their PAs showed higher ISA in outside PA than inside PA. Besides, there was only one PA showed higher ISA in PA than outside PA for grassland ecosystem and desert ecosystem PAs, while other PAs (grassland ecosystem: 2, desert ecosystem: 9) showed higher ISA in outside PA than inside PA. For the other two PAs, forest ecosystem and wild animal PAs, which the number of PA occupied 77% of total 290 PAs, also showed higher ISA in outside PA than inside PA (forest ecosystem: 133, wild animal: 68). These patterns in ISA were similar to those of total NTL intensities, with 161 PAs having higher total NTL intensities outside of the PAs than inside in 2018 (Fig. 3). Specifically, the total NTL intensity outside of the PAs was 246,997 nW cm$^{-2}$ sr$^{-1}$, higher than the 46,905 nW cm$^{-2}$ sr$^{-1}$ inside of the PAs. There was a considerable variation of NTL among the sites. Out of the 290 PAs, the majority (162) had no NTL and 128 PAs had some NTL. Also, a majority of the PAs (161) had a higher proportion of NTL outside of the PAs than inside in 2018. Specifically, as for different types of protected areas in China, the NTL in 2018 was higher in outside PAs than inside PAs among all types (Fig. 3). For desert ecosystem and wild plant PAs, 8 PAs showed higher NTL in outside PA than inside PA, while no PA showed higher NTL inside PA than outside. For other types of PAs, a few PAs (forest ecosystem: 11, grassland ecosystem: 1, wetland ecosystem: 4, wild animals: 9) exhibited higher NTL inside PAs than outside PAs, while most PAs (forest ecosystem: 73, grassland ecosystem: 2, wetland ecosystem: 24, wild animals: 46) showed higher NTL in outside PAs than inside PAs.

3.2. Changes in development pressure inside and outside of the PAs

3.2.1. The national scale

The ISA outside of the PAs increased at a much faster rate (118.9 ± 2.3 km$^2$ a$^{-1}$) than inside of the PAs (26.1 ± 0.4 km$^2$ a$^{-1}$) between 2000 and 2018 (Fig. 4). Specifically, ISA did not change in 151 of the PAs and the remaining 139 PAs experienced increased ISA. There was no change in the ISA outside of 99 of the PAs, and the remaining 191 PAs had substantial increases in ISA outside of the PA. For example, the growth rate of ISA (29.7 km$^2$ a$^{-1}$) outside of the Dalian Spotted Seal PA was 99 times higher than inside PA (0.3 km$^2$ a$^{-1}$).

Differences between the ISA growth rates inside and outside of the PAs can indicate the potential impacts of outside development pressure on the PAs. Most PAs (175) suffered potential threats from the areas outside of the PA. Conversely, a small number of PAs (28) experienced larger increases in ISA within their borders than outside. Specifically, as for different types of protected areas in China, the growth rate of ISA was higher in outside PAs than inside PAs among all types (Fig. 4). For desert ecosystem and wild plant PAs, most of their PAs (desert ecosystem: 8, wild plant: 10) showed a higher growth rate of ISA in outside PA than inside PA, while no PA showed a higher growth rate of ISA inside PA.
than outside. Besides, among the other types of PAs, there are 10, 1, 6, and 11 PAs showed a higher growth rate of ISA inside PAs than outside PAs for forest ecosystem, grassland ecosystem, wetland ecosystem, and wild animal PAs, respectively, while other PAs (forest ecosystem: 83, grassland ecosystem: 2, wetland ecosystem: 26, wild animal: 46) showed a higher growth rate of ISA in outside PAs than inside PAs.

These patterns in the change of ISA were similar for total NTL intensity, with a high growth rate in total intensity outside of the PAs ($9247.6 \pm 129.3 \text{nW cm}^{-2} \text{sr}^{-1} \text{a}^{-1}$) and a lower growth rate inside of the PAs ($2230.6 \pm 46.4 \text{nW cm}^{-2} \text{sr}^{-1} \text{a}^{-1}$). There was an increasing trend in NTL intensity outside of 186 of the PAs, and 177 of the PAs experienced larger increases in NTL intensity outside of the PA than inside (Fig. 5). Specifically, as for different types of protected areas in China, the growth rate of NTL from 2000 to 2018 was higher in outside PAs than inside PAs among all types (Fig. 5). For desert ecosystem and grassland ecosystem PAs, most PAs (desert ecosystem: 8, grassland ecosystem: 3) showed a higher growth rate of NTL in outside PA than inside PA, while no PAs showed a higher growth rate of NTL inside PA than outside. For other types of PAs, a few PAs (forest ecosystem: 25, wetland ecosystem: 7, wild animals: 15, wild plants: 1) exhibited a higher growth rate of NTL inside PA than outside. For most PAs (forest ecosystem: 78, wetland ecosystem: 29, wild animals: 52, wild plants: 7) showed a higher growth rate of NTL in outside PAs than inside PAs.

### 3.2.2. Economic zones

We analyzed the changes in ISA and NTL in the four different economic zones and found similar patterns in that both ISA and NTL and their growth rates were higher outside of the PAs than inside (Fig. 6). We also found that the growth rates of ISA and NTL inside and outside of the...
PAs were highest in western China and lowest in eastern China during 2000–2018. This pattern may be due to the size of the PAs, with large PAs in western China and small and fragmented PAs in eastern China (Sun et al., 2020). Thus, the absolute change of the ISA in western China was large and in eastern China it was small.

Specifically, the growth rate of ISA inside PAs over the past 19 years was faster in western China (10.4 km\(^2\) a\(^{-1}\)) and central China (6.6 km\(^2\) a\(^{-1}\)) than elsewhere (Fig. 6). We also examined ISA dynamics outside of the PAs, and found that the growth rate of ISA was faster in western China (58.4 km\(^2\) a\(^{-1}\)) and northeastern China (40.0 km\(^2\) a\(^{-1}\)), increased 3.2 times from 0.6% to 1.9%), while the growth rate was only 9.4 km\(^2\) a\(^{-1}\) (increased 1.7 times from 1.8% to 3.1%) in eastern China.

We found the same patterns for our NTL-based analyses. Specifically, the growth rate of NTL inside PAs during 2000–2018 was faster in western China (0.9 nW cm\(^{-2}\) sr\(^{-1}\) a\(^{-1}\)) and central China (0.2 nW cm\(^{-2}\) sr\(^{-1}\) a\(^{-1}\)) than elsewhere (Fig. 6). We also examined NTL dynamics outside of the PAs, and found that the growth rate of NTL was faster in western China (6.5 nW cm\(^{-2}\) sr\(^{-1}\) a\(^{-1}\)) and northeastern China (1.6 nW cm\(^{-2}\) sr\(^{-1}\) a\(^{-1}\)), while the growth rate was only 0.15 nW cm\(^{-2}\) sr\(^{-1}\) a\(^{-1}\) in eastern China.

3.2.3. Representative sites

Different PAs could exhibit diverse growth rates of ISA and NTL during 2000–2018, thus development pressure in each PA could be a different story. In this part we choose the representative sites for in-
depth analysis. We combined the results of ISA and NTL inside and outside PAs with Google Earth imagery, and we want to intuitively know how human activities inside and outside the protected area have changed from 2000 to 2018. Our principles for selecting the representative PAs are the change of human activities inside and outside the PA from 2000 to 2018 is obviously different, which can highlight higher development pressure in outside PA than inside PA. Besides, the images can be clearly identified on Google Earth, while human activities were not strong for some PAs, so we cannot clearly observe the changes in human activities on Google Earth.

As an example, for the Lingwubaijitan PA in western China we used high-resolution historical imagery from Google Earth to validate and verify our ISA and NTL results. The ISA value increased by 0.5 km² a⁻¹ (NTL: 0.19 nW cm⁻² sr⁻¹ a⁻¹) inside the PA compared to a larger increase outside of the PA (ISA: 2.5 km² a⁻¹, NTL: 0.79 nW cm⁻² sr⁻¹ a⁻¹), which we verified using the very high-resolution images from Google Earth (Fig. 7). An evident growth of development pressure outside of the PA was observed in Lingwubaijitan over the past decades, indicating the potential impacts of outside development pressure on the PAs. This mainly occurred in the western of Lingwubaijitan, where built-up land had grown significantly and towns expanded. The large increase in development pressure outside of the PA reflects that protected areas tend to be threatened by human activity from the surrounding area.

In addition to this case in western China, other PAs in other economic zones had different stories. For example, Zhalong Protected Area from northeastern China had a large difference in the ISA growth rate between the area inside the PA and the area outside of the PA, with a relatively low ISA growth rate (1.1 km² a⁻¹) inside of the PA and a relatively high growth rate (3.0 km² a⁻¹) outside of the PA. Also, the ISA growth rate in the Zhangjiajie Giant Salamander Protected Area from
central China was nearly constant within the PA between 2000 and 2018, increasing by 0.01 km$^2$ a$^{-1}$ compared to a large increase of 1.8 km$^2$ a$^{-1}$ outside of the PA.

Interestingly, some PAs, such as the Dafeng Elk Protected Area in eastern China, had very high levels of development pressure inside their boundaries compared to outside, with average proportions of ISA of 8.4% and 3.2% in 2018, respectively. For the rare and endemic fish in the upper reaches of the Yangtze River Protected Area in western China, the ISA growth rate inside of the PA was 2.8 km$^2$ a$^{-1}$ compared to 2.4 km$^2$ a$^{-1}$ outside of the PA.

3.3. Potential effects of development pressure outside of the PAs on PAs

The interannual variations of ISA and NTL between inside of the PAs and outside of the PAs showed a significant correlation with $r$ values of 0.46 and 0.50, which may indicate that development pressure outside of the PAs could have an impact on that inside the PAs (Fig. 8).

We further found that the potential effects of development pressure outside of the PAs on that inside the PAs tend to be more evident along with the economic development levels. Across all the four economic regions, ISA (NTL) correlations between inside of the PAs and outside of the PAs were strongest in eastern (ISA: $R^2 = 0.89$, NTL: $R^2 = 0.65$) or central (ISA: $R^2 = 0.85$, NTL: $R^2 = 0.74$) China. These may exhibit a consistent trend of both the economic growth and the development pressure outside of the PAs on that inside the PAs, suggesting the intensive economic activities outside of the PAs could threaten the management of PAs. The weakest correlations of ISA (NTL) between inside and outside of the PAs that appeared in northeastern China (ISA: $R^2 = 0.25$, NTL: $R^2 = 0.34$) could be related to the declining economic activities and human population in northeastern China. For example, in
2019, the GDP of the three northeastern provinces in Northeast China accounted for a 3.92% drop from 2014 (http://www.ce.cn/). And in 2020, the total population of the three northeastern provinces decreased by 11.01 million compared with 2010 (http://www.stats.gov.cn/).

3.4. Different outside-to-inside pressure in different population gradients

The trends in ISA inside and outside of the PAs were highly variable among the different economic regions (Fig. 8). The strongest correlations of ISA inside and outside of the PAs in eastern China may be related to higher human activity. Not only can economic development reflect human activities, but also the population. Economic growth has been shown to be consistent with rapid increases in population (Johnson, 1999), so we further investigated the influence of population densities outside of the PAs on the effectiveness of the PAs using the outside-to-inside pressure index ($O_{\text{toI}}_{\text{pres}}$). Using linear regression, we found that the population densities outside of the PAs could explain a significantly larger part of the $O_{\text{toI}}_{\text{pres}}$ variations for PAs (Fig. 9) ($R^2 = 0.49$ for ISA ($p < 0.05$), $R^2 = 0.22$ for NTL ($p < 0.05$), respectively). Thus, it was more common for there to be higher pressures outside of the PAs than inside of the PAs in the more populated regions.

4. Discussion

4.1. Effectiveness of protected areas at mitigating development pressure

PAs have been widely recognized as cornerstones of biodiversity conservation (Maxwell et al., 2020). However, systematic research in assessing the effectiveness of PAs is still in its infancy (Watson, Dudley, Segan, & Hockings, 2014). As far as we know, our analysis is the first to investigate the ability of PAs to mitigate development pressure in China using the 30-m GAIA data and 500-m extended NTL data. These two

Fig. 6. Growth of ISA and NTL in different economic zones. The first row represents changes in ISA during 2000–2018 in northeastern China, eastern China, central China, and western China. 'Slope' in the figure represents the growth rate. The bottom row represents changes in total NTL intensity in northeastern China, eastern China, central China, and western China. The black line represents 'slope' in PAs, and the blue line represents 'slope' outside PAs.

Fig. 7. Dynamics of ISA and total NTL intensity and Google Earth images from 2000 to 2018 in the Lingwubaijitan protected area. (a) the changes of NTL and ISA inside and outside of the Lingwubaijitan PA; (b) Google Earth images from 2000 to 2018 in Lingwubaijitan PA, the yellow and red lines in (b) represent the boundary of the PA and the buffer outside of the PA, respectively; (c) very high-resolution images of the black box in (b).
datasets are timely, accurate, and frequent proxies of the direct and indirect development pressure on the environment (Chen et al., 2021; Gong et al., 2020). We also showed the differences in the development pressure inside and outside of the PAs at the national scale and for different economic zones. Moreover, our ISA-based and NTL-based results were validated with Google Earth images.

Lower pressure (shown as ISA and NTL) increases occurred inside the PAs compared to outside of the PAs in most protected areas showed that these PAs are facing larger development pressures from their surrounding areas. This finding was consistent with previous studies that found development pressure inside of the PAs was lower in globally protected areas that are more strictly managed (International Union for Conservation of Nature (IUCN) categories I and II) (Jones et al., 2018). This tendency was also observed in other protected areas around the world. For example, Bruner, Gullison, Rice, and da Fonseca (2001) concluded that almost all parks in 22 tropical countries were under lower pressure inside their borders and 80% of parks had better conditions than their surrounding areas. Tapia-Armijos et al. (2017) found that the Podocarpus National Park in South Ecuador seemed to have been largely successful in avoiding development pressure inside their boundaries since the observed increase in the levels of development pressure during 1982–2008 was less than that observed in the unprotected surrounding area. However, these studies investigated the effectiveness of PAs at slowing the deterioration of the area inside their boundaries, while few studies considered the effectiveness of PAs at resisting outside development pressure (Fuente et al., 2020b), which is an innovation of our study.

However, a few protected areas showed high levels of development pressure inside their boundaries compared to outside. Take the most prominent Dafeng Elk Protected Area in eastern China as an example, we found this protected area allows tourists to enter and play, so managers have built a large area of construction land within the PA, such as roads (Fig. S1). When elk crossed the road in the PA, they collided with driving vehicles, resulting in vehicle damage and elk casualties (Liu et al., 2021). Besides, some individuals illegally entered the protected area to engage in aquatic product development and business activities, excavated
aquaculture ponds, connected high-voltage lines, and built development facilities such as greenhouses, production and living rooms (http://www.mee.gov.cn/). However, we can observe a large area of crop-land in outside of the Dafeng Elk PA from 2000 to 2018, maybe that is why ISA or NTL growth rates were lower in outside PA than inside PA (Fig. S2).

4.2. Potential reasons of the outside-to-inside pressure

The remarkably higher current state and growth rates of development pressure outside of the PAs than inside may have multiple causes. For example, many protected areas were designated in areas with little human influence in the past (Joppa & Pfaff, 2009). After the PAs were established, their boundaries are often delineated in such a way that human settlements were kept outside of the PAs. Once PAs have been established in a given area and new construction is restricted, the demand and density of newly built structures increases adjacent to the PAs (Fuente et al., 2020a). The “Regulations of the People’s Republic of China and Natural Reserves” promulgated by the state in 1994 played an important role in controlling human encroachment into PAs. Logging, grazing, hunting, fishing, reclamation, burning, mining, quarrying, and digging were prohibited in the PAs, especially the core area of the nature reserves. Therefore, these restrictions may be one reason that development pressure were higher outside of the PAs than inside.

Besides, some PAs may be attractive due to the benefits and ecosystem services that PAs provide, so new residential areas (such as holiday facilities or second houses) are usually constructed near PAs for people to enjoy the entertainment, aesthetic values, and air quality that the PAs provide (Brambilla & Ronchi, 2016; Radeloff et al., 2010). The high density of human activities outside of the PAs may affect the biodiversity and ecological processes inside of the PAs. It may limit the dispersal of species, reduce the landscape connectivity, increase PAs isolation, hamper the ability of species to shift their ranges to adapt to climate change, and increase the isolation of species assemblages and PAs due to urbanization processes (Bierwagen, 2007; Ewers & Rodrígues, 2008; Renwick, Bode, & Venter, 2015). Therefore, it is important to comprehensively manage urbanization surrounding PAs in order to restore the suitable habitat and enhance the ecosystem services that PAs provide (Fuente et al., 2020a).

Despite a relatively higher proportion of PA extent and lower population density in western China, we found higher increasing rates of development pressure for the PAs in western China, which could be related to increasing economic activity, including transportation development (Xiang & Tan, 2017) and mineral extraction (Jiang et al., 2018; Li et al., 2013). The different performance of PAs in China at resisting development pressure from outside reflected the differences in the implementation of PAs conservation actions in different regions. The better the conservation actions are implemented in PAs, the stronger their resistance to outside pressure will be. Therefore, improved management of the PAs and the synergies of ecological security and socioeconomic development are most needed in western China, especially in the Tibetan Plateau, where 41.4% of the area is covered by national PAs (Sun et al., 2020).

4.3. Uncertainty and implications

Although we have provided a detailed assessment of development pressures inside and outside PAs across China, some uncertainties remain. First, we selected ISA as an indicator for development pressure and NTL as a supplement to reduce uncertainties in the results. Our study lacked many important indicators of human activities that threaten biodiversity, such as hunting, logging, and mining. These are important pressures that can greatly damage PA habitats and species diversity, especially in wilderness areas.

Second, our study only investigated the potential effects of development pressure outside of the PAs on PAs and the influence of population density on outside-to-inside pressure when considering the drivers of PAs at mitigating development pressure in China. However, development pressure in each PA could be a different story, and the cause may be complicated. Therefore, further work may explore the interactions between development pressure outside of the PAs and those inside of the PAs, and consider a wider range of anthropogenic drivers. This additional work would provide more comprehensive recommendations for socioeconomic development in broader landscapes where PAs are embedded.

5. Conclusions

We assessed economic development pressures inside and outside of China’s national PAs from 2000 to 2018 using impervious surface area and nighttime light data. Results showed that development pressures outside PAs were higher than inside at the national level in 2018. We also found that the rate of increase in development pressures was higher outside than inside PAs from 2000 to 2018. Development pressures, reflected by ISA and NTL, were lowest in eastern China and increased the most inside the PAs of western China. In addition, increased human activities outside of the PAs could have an influence on the PAs, and the phenomenon of higher pressures outside than inside PAs was more common in the more populous regions. Our research suggested that conservation agencies should pay more attention to human activities surrounding PAs, especially in western China. Through more comprehensive and higher spatial and temporal resolution indicators of human activities, especially those relating to build infrastructure and economic development, the effectiveness of PAs at mitigating development pressures can be monitored and improved.

CRediT authorship contribution statement


Declaration of competing interest

None.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 41871349), the Chinese Academy of Sciences the Strategic Priority Research Program (XDA19040301), the Key Research Program of Frontier Sciences (QYZDB-SSW-DQC005).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appgeo.2022.102682.

References
