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Improving protected area effectiveness through consideration of different human-pressure baselines

Chun-Ting Feng[1,2] | Ming Cao[1,2] | Fang-Zheng Liu[1,2] | Yue Zhou[1,2] | Jin-Hong Du[1,2] | Li-Bo Zhang[1,2] | Wen-Jie Huang[1,2] | Jian-Wu Luo[1,2] | Jun-Sheng Li[1,2] | Wei Wang[1,2]

[1]State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, China

[2]Institute of Ecology, Chinese Research Academy of Environmental Sciences, Beijing, China

Correspondence
Wei Wang, State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China.
Email: wang.wei@craes.org.cn

Article Impact Statement: Protected areas with different human pressure baselines should have different management measures to improve conservation effectiveness.

Abstract

Previous assessments of the effectiveness of protected areas (PAs) focused primarily on changes in human pressure over time and did not consider the different human-pressure baselines of PAs, thereby potentially over- or underestimating PA effectiveness. We developed a framework that considers both human-pressure baseline and change in human pressure over time and assessed the effectiveness of 338 PAs in China from 2010 to 2020. The initial state of human pressure on PAs was taken as the baseline, and changes in human pressure index (HPI) were further analyzed under different baselines. We used the random forest models to identify the management measures that most improved effectiveness in resisting human pressure for the PAs with different baselines. Finally, the relationships between the changes in the HPI and the changes in natural ecosystems in PAs were analyzed with different baselines. Of PAs with low HPI baselines, medium HPI baselines, and high HPI baselines, 76.92% (n=150), 11.11% (n=12), and 22.86% (n=8) , respectively, showed positive effects in resisting human pressure. Overall, ignoring human-pressure baselines somewhat underestimated the positive effects of PAs, especially for those with low initial human pressure. For PAs with different initial human pressures, different management measures should be taken to improve effectiveness and reduce threats to natural ecosystems. We believe our framework is useful for assessing the effectiveness of PAs globally, and we recommend it be included in the Convention on Biological Diversity Post-2020 Strategy.

KEYWORDS

baseline-plus-change framework, conservation effectiveness, human pressure index, management effectiveness, natural ecosystems

Resumen

Las evaluaciones previas de la efectividad de las áreas protegidas (AP) se han enfocado principalmente en los cambios de las presiones humanas con el tiempo y no han considerado las diferentes líneas base de las presiones humanas en las AP, por lo que potencialmente han sobrestimado o subestimado su efectividad. Desarrollamos un marco de trabajo que considera las líneas base de presión humana y los cambios de las presiones humanas con el tiempo y evaluamos a la efectividad de 338 AP en China entre 2010 y 2020. Consideramos el estado inicial de la presión humana en las AP como la línea base y analizamos los cambios en el índice de presión humana (IPH) bajo diferentes líneas base. Utilizamos modelos de bosque aleatorio para identificar las medidas de gestión que más aumentaron

la efectividad de la resistencia a las presiones humanas en las AP con líneas base diferentes. Finalmente, analizamos con diferentes líneas base las relaciones entre los cambios en el IPH y los cambios en los ecosistemas naturales de las AP. De las AP con líneas base de IPH bajas, medianas y altas, 76.92% (n=150), 11.11% (n=12) y 22.86% (n=8), respectivamente, mostraron efectos positivos de resistencia a las presiones humanas. En general, si ignoramos las líneas base de las presiones humanas, se subestiman los efectos positivos de las AP de una u otra manera, especialmente aquellas con poca presión humana al inicio. En el caso de las AP que al inicio tienen diferentes presiones humanas, se deben tomar diferentes medidas de gestión para mejorar la efectividad y reducir las amenazas a los ecosistemas naturales. Creemos que nuestro marco de trabajo sirve para evaluar la efectividad mundial de las AP y recomendamos que se incluya en la Estrategia Post-2020 de la Convención sobre la Diversidad Biológica.
Mejoría de la Efectividad de un Área Protegida al Considerar Diferentes Líneas Base de Presión Humana

PALABRAS CLAVE
ecosistemas naturales, efectividad de la conservación, efectividad de la gestión, índice de presión humana, marco de trabajo de línea base más cambios

摘要
自然保护地保护成效评估过去主要关注两个时间段之间人类压力的变化, 较少考虑自然保护地不同的人类压力基线(初始背景状态), 这可能会过高或过低估计自然保护地保护成效。我们提出了一个同时考虑人类压力基线和人类压力随时间变化的评估框架, 并评估了2010-2020年中国338处自然保护地在不同基线下减缓人类压力的有效性。首先以人类压力的初始状态作为基线, 在不同基线下进一步分析了自然保护地内人类压力指数的变化;然后利用随机森林模型明确了对于不同基线的自然保护地提高其保护成效最重要的管理措施;最后进一步探讨了不同基线下人类压力指数变化与自然生态系统变化之间的关系。结果表明, 对于初始人类压力较低、中等和较高的自然保护地, 分别有76.92%、11.11%和22.86%在减缓人类压力方面表现出显著正效应。总体而言, 忽略人类压力基线在一定程度上低估了自然保护地的成效, 特别是对于初始人类压力较低的自然保护地。对于具有不同初始人类压力的自然保护地, 应采取不同的管理措施提高其保护成效并减少对自然生态系统的威胁。本研究提出的评估框架对评估全球自然保护地的保护成效具有重要作用, 我们建议将其纳入2020年后生物多样性战略目标的评估体系。

INTRODUCTION

The establishment of protected areas (PAs) is a key global strategy to mitigate biodiversity loss and reduce human pressure (Dureuil et al., 2018; Schulze et al., 2018). The world has committed, by 2020, to increasing PA coverage and to achieving the stated management and conservation effectiveness of PAs (Aichi Target 11). In August 2020, the World Database on Protected Areas showed that approximately 15% of the world's terrestrial and freshwater environments were protected; approximately 7.5% of the marine area was protected (Global Biodiversity Outlook 5). However, one-third of global protected land is under intense human pressure (Jones et al., 2018), such as agriculture, forest product extraction, illegal hunting, and infrastructure construction (Achiso, 2020). Approximately 74 of the 111 nations that have reached a level of 17% PA coverage would no longer have 17% protected if protected land under intense human pressure does not contribute to the conservation targets of the Convention on Biological Diversity (CBD) (Jones et al., 2018). Therefore, in addition to focusing on fulfilling the quantitative coverage target, it is important to know whether existing PAs are effectively reducing human pressure and to understand what management measures make PAs more effective in resisting human pressure and protecting biodiversity features.

Assessing the effectiveness of PAs in resisting human pressure has attracted attention around the world (Jacobson et al., 2019; Riggio et al., 2020), but the extent to which PAs resist human pressure and protect biodiversity is debated (Achiso, 2020; Schulze et al., 2018). On average, human pressures increased in PAs from 1995 to 2010 compared with matched unprotected areas (Geldmann et al., 2019). Establishing a large number of PAs without ensuring appropriate mechanisms and measures to resist human pressure may lead to negative conservation outcomes. Compared with areas outside PAs, PAs play a positive role in resisting human pressure over time (Guetté et al., 2018). A global assessment of human pressure on the world's lakes shows that increases in human pressure are lower in lakes inside PAs than in lakes outside PAs (Mammides, 2020). However, assessments of the conservation effectiveness of PAs focused primarily on changes between two periods and did not consider the different human-pressure baselines of the PAs, thereby over or underestimating the effectiveness of PAs. For example, PAs with high human-pressure baselines may appear more effective than those with low baselines if one compares only changes between two periods, considering that there is commonly no significant difference in the changes in human pressure in PAs under strict management. Furthermore, few researchers have delineated what management measures should be taken to strengthen the capacity of PAs to resist human pressure or whether the reduction in human pressure can help improve functioning of natural ecosystems. Thus, it is important to identify different human-pressure baselines (hereafter baselines) of PAs as a first step in assessing their effectiveness in addition to assessing appropriate management measures for resisting human pressure and the impacts of resisting human pressure on natural ecosystems.

In 2022, the 15th meeting of the Conference of the Parties (phase two) to the CBD will be held in China, and parties will determine new global biodiversity conservation targets for the next decade. Currently, China has over 11,800 PAs, covering 18% of its land area and 4.1% of its sea area (Wang et al., 2020). Similar to other countries around the world, human pressure has been the most crucial driving factor behind biodiversity and habitat loss in China's PAs (Shrestha et al., 2021; Zhu et al., 2019). However, it is unclear whether human pressure has been controlled in the last decade (2010–2020), which management measures lead to better performance in resisting human pressure, and how to improve the conservation effectiveness of natural ecosystems. We developed a baseline-plus-change framework for assessing the effectiveness of PAs (Figure 1). We then applied the framework to China's PAs to assess the effectiveness of PAs with different baselines at resisting human pressure, identify the management measures that most effectively resisted human pressure for PAs with different baselines, and explore the relationships between changes in the human pressure index (HPI) and changes in natural ecosystems area in PAs with different baselines. We sought to supply guidance for standardized management of PAs with different baselines to improve conservation effectiveness.

METHODS

Human pressure index

We used built-up land area, cropland, and human population density to build the HPI, which has been used to characterize the degree of human pressure on terrestrial ecosystems (Geldmann et al., 2014). The data layer (1 km^2 resolution) of the percentage of built-up land and cropland area in 2010 and 2020 was calculated based on land-cover data with a resolution of 30 ×30 m (derived from the Resource and Environment Data Cloud Platform, http://www.resdc.cn). We performed a normalized transformation on the human population density data layer in 2010 and 2020 with a resolution of 1 km^2 (derived from the WorldPop website, https://www.worldpop.org). We then gave equal weight to the values of each data layer to generate the HPI data layer in 2010 and 2020 (Appendix S1). The difference between 2010 and 2020 was taken as the change in human pressure over the past 10 years.

Management effectiveness assessment

We assessed the management effectiveness from 2007 to 2016 of 395 PAs. These PAs are all national nature reserves and cover approximately 10% of China's terrestrial area. These PAs are generally managed by government agencies. We obtained the boundaries of 395 PAs from the Ministry of Ecology and Environment of the People's Republic of China (MEE). According to the 10 indicators (Appendix S1) issued by the former Ministry of Environmental Protection (currently MEE), we assessed the management measures of PAs with an expert scoring method (details in Appendix S1 and Feng et al. [2021]).

Propensity score matching

To avoid potential spillover effects (leakage, blockage, or no effect) of PAs on their unprotected adjacent surroundings, we demarcated a 10- to 50-km region outside the boundary of each PA and referred to this area as the wider landscape (Fuller et al., 2019). We made 1-km^2 grids of the whole country and assigned the grids inside and outside PAs values of 1 and 0, respectively. We removed the incomplete grids that were clipped by the boundaries of PAs or wider landscape regions and the grids in the wider landscapes that were overlaid by other PAs or overlaid a 0–10 km area outside the boundary of the PA (Appendix S1). The control variables in propensity score matching (PSM) are commonly elevation, slope, distance to the nearest road, distance to the nearest settlement, and soil type (Clements et al., 2014; Ren et al., 2015; Zhao et al., 2019), and the values of these control variables were extracted from each 1-km^2 grid (details in Feng et al. [2021]). Then, we used PSM to match the grids inside each individual PA with the grids in the wider landscape by comparing the most similar propensity scores. We executed the PSM in R 3.6.1 with the MatchIt package. The nearest method was chosen, the parameter ratio was set to 1, and the caliper was set to 0.2 (Cuenca et al., 2016). The PSM results showed that 30 PAs did not have a matching grid in their corresponding wider landscapes. To verify the validity of PSM, we used the standardized differences test to check the balance between the treated sites and the control sites in each individual PA (details in Appendix S1). The standardized differences test of each individual PA indicated that the PSM performed well in balancing the differences between inside PAs and their corresponding wider landscape (Appendix S1).

We calculated the HPI value of each matched grid inside a PA (matched treated site [MTS]) and its matched grid in the wider landscape (matched control site [MCS]). The MTSs inside PA and the MCSs with HPI values of 0 in 2010 were deleted,

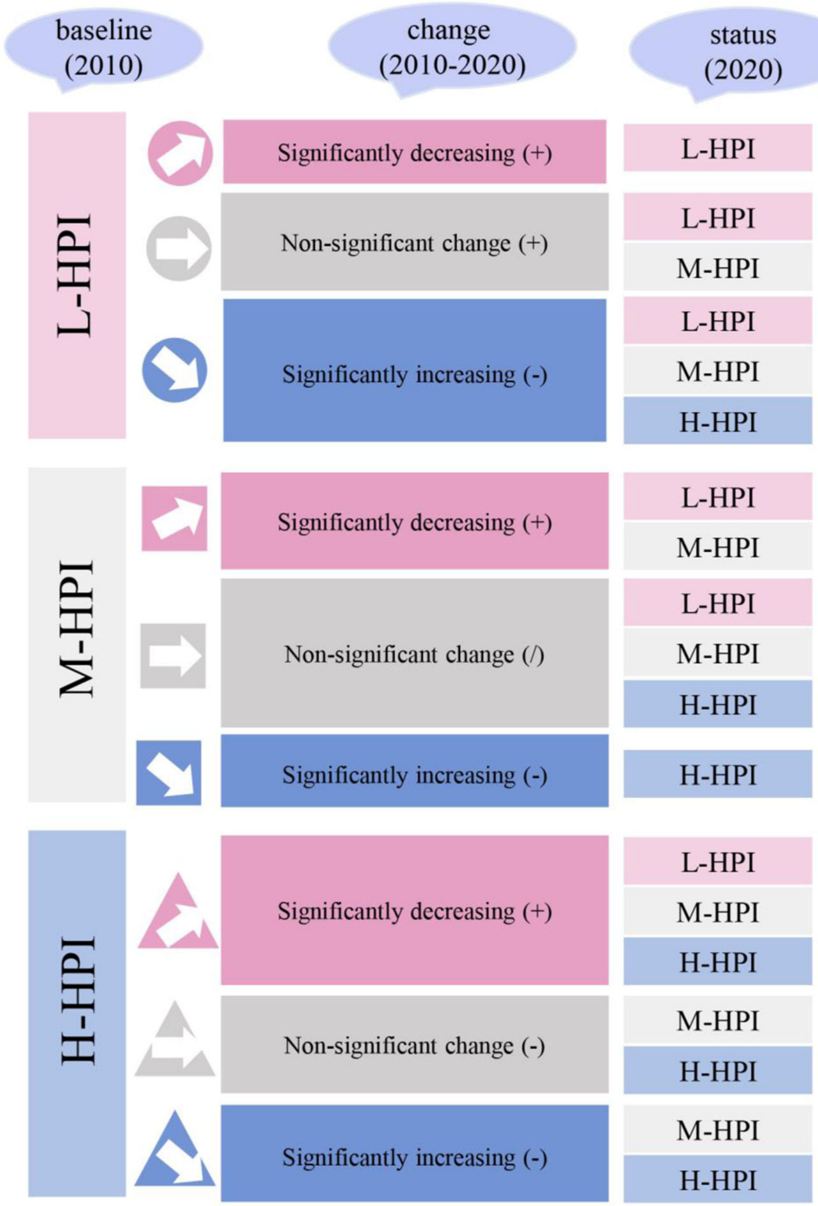

FIGURE 1 The baseline-plus-change framework for assessing the effectiveness of protected areas (PAs) in resisting human pressure (HPI, human pressure index; L, low; M, medium; H, high; +, PAs with positive effects in resisting human pressure over the past 10 years; –, PAs with negative effects in resisting human pressure over the past 10 years; /, PAs with nonsignificant effects in resisting human pressure over the past 10 years)

and the PAs with ≤ 5 grids after matching were deleted. Finally, 338 PAs established before 2010 were retained for subsequent analyses (Appendix S1).

Framework for assessing PA effectiveness based on baseline plus change

Our framework for assessing the effectiveness of PAs is based on a baseline-plus-change concept (Figure 1). The initial state of human pressure on PAs was taken as the baseline. The equation $B = B_{MCS} - B_{MTS}$ represents the difference between the mean HPI of the MTSs inside one PA and the mean HPI of the MCSs in 2010, where B_{MTS} represents the mean HPI of the MTSs inside one PA in 2010, and B_{MCS} represents the mean HPI of the MCSs in 2010. The Wilcoxon signed ranks test was applied to estimate whether there was a significant difference in the HPI between the MTSs and MCSs of each PA. The low HPI baselines indicated that B_{MTS} was significantly lower than B_{MCS} ($B > 0$, $p < 0.05$). The medium HPI baselines indicated that B_{MTS} did not differ significantly from B_{MCS} ($p > 0.05$). The high HPI baselines indicated that B_{MTS} was significantly higher than B_{MCS} ($B < 0, p < 0.05$).

Then, changes in HPI were further analyzed under different baselines. The equation $C = C_{MCS} - C_{MTS}$ represents the difference between the mean change in HPI of the MTSs inside one PA and the mean change in HPI of the MCSs from 2010 to 2020, where C_{MTS} represents the mean change in HPI of the MTSs inside one PA from 2010 to 2020 and C_{MCS} represents the mean change in HPI of the MCSs from 2010 to 2020. The Wilcoxon signed ranks test was applied to estimate whether there was a significant difference in the change in HPI between the MTSs and MCSs in each PA. When $C > 0$ and $p < 0.05$, PAs underwent significant decrease in human pressure over the past

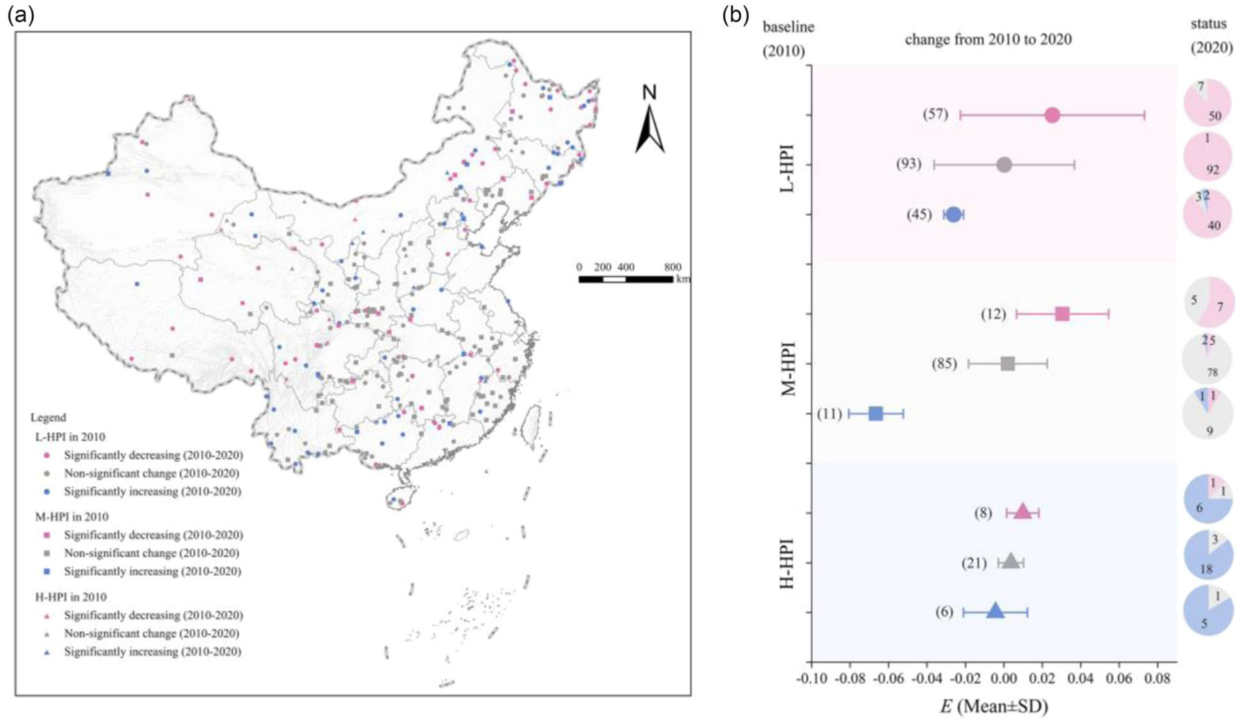

FIGURE 2 In China (a) spatial distribution of protected areas (PAs) with different human pressure index (HPI) values and (b) changes in and status of the HPI in PAs compared with matched control sites under different baselines (numbers in parentheses and in pie charts, number of PAs; red, number of PAs with significantly lower human pressure [L-HPI] compared with their matched control sites in 2020; blue, number of PAs with significantly higher human pressure [H-HPI]; gray, number of PAs with no significant differences in human pressure [M-HPI] compared with their matched control sites in 2020; horizontal lines, standard deviation)

10 years relative to the MCSs. When $p > 0.05$, PAs underwent no significant change in human pressure over the past 10 years relative to the MCSs. When $C < 0$ and $p < 0.05$, PAs underwent significant increase in human pressure over the past 10 years relative to the MCSs.

Finally, combining baseline and change, the effectiveness of PAs in resisting human pressure was identified (Figure 1). For PAs with low HPI baselines, it was difficult to continue to substantially reduce human disturbance in PAs; that is, it was difficult to continue to improve the effectiveness of PAs in resisting human pressure. However, for PAs with high HPI baselines, no significant change would mean that the PAs were still in the state of high human pressure. Therefore, for PAs with low HPI baselines, PAs that underwent significant decrease or no significant change in human pressure over the past 10 years relative to the MCSs were both considered positive effects. Protected areas that underwent significant increase were considered negative effects. For PAs with medium HPI baselines, effects were positive when the HPI inside the PAs underwent significant decrease over the past 10 years, nonsignificant when those underwent no significant change, and negative when those underwent significant increase. For PAs with high HPI baselines, PAs with significant decrease in human pressure over the past 10 years had positive effects. Protected areas with significant increase or no significant change had negative effects.

Statistical analyses

Under the three different baselines (low, medium, and high HPI values), the positive effects and negative effects of PAs in resisting human pressure were used as binary classifications. We further used the random forest model to identify the most important management measures that contribute to improving the effectiveness of PAs in resisting human pressure under the three baselines. The mean decrease Gini index was used to compare the importance of the management measures. Larger values indicated that the management measures were more important. The area under the curve was used to test the performance of the model. To further explain the contribution trend of important management measures to the effectiveness of PAs in resisting human pressure under the three baselines, we computed and visualized the partial dependence of different management measures on the positive effects probability based on the random forest model. Partial dependence plots are essential for interpreting random forest models. They can show the marginal effect of individual predictor variables on the probability of the response in the case of binary classification (Friedman, 2001).

To understand the relationships between human pressure and different natural ecosystems, we calculated changes in the HPI and the areas of forest, wetland, grassland, and desert

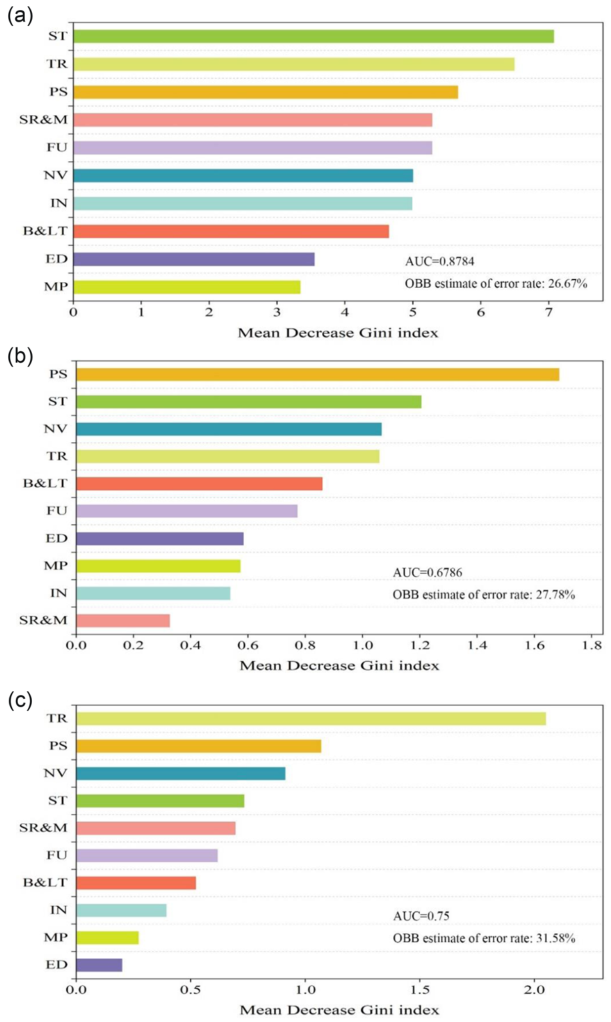

FIGURE 3 Relative importance of different management measures in resisting human pressure in protected areas (PAs) with (a) low baseline of human pressure index (HPI) (area under the curve [AUC]=0.8784; out-of-bag error [OBB]= 26.67%), (b) medium baseline of HPI (AUC = 0.6786, OBB = 27.78%), and (c) high baseline HPI based on the results of the random forest model (AUC = 0.75, OBB = 31.58%) (ST, adequate numbers of skilled staff from an independent management institution; TR, control of illegal threats; PS, patrol and surveillance; SR&M, scientific research and monitoring; FU, funding; NV, clear demonstration of the values of associated biodiversity and ecosystem services; IN, adequate, functional, and safe equipment and infrastructure; B&LT, clear identification of boundary and land tenure; ED, education and public awareness programing; MP, master plan development and implementation)

ecosystems in each PA from 2010 to 2020. We removed PAs with forest, wetland, grassland, and desert areas of <10 km^2. The areas of forest, wetland, grassland, and desert ecosystems were calculated based on land cover data with a resolution of 30 ×30 m (derived from the Resource and Environment Data Cloud Platform, http://www.resdc.cn). We used linear regression to analyze the relationship between the changes in HPI and the changes in the area of the four types of natural ecosystems inside PAs with different baselines from 2010 to 2020. The random forest model and linear regression were performed in R 3.6.1.

RESULTS

Effectiveness of PAs with different baselines

Comparing HPI values inside PAs with their MCSs, we found that 195 PAs (57.69%) had low HPI baselines ($p < 0.05$), 108 PAs (31.95%) had medium HPI baselines ($p > 0.05$), and 35 PAs (10.36%) had high HPI baselines ($p < 0.05$) in 2010. From 2010 to 2020, most PAs underwent no significant change in human pressure: 47.69% (n =93) of low HPI baselines, 78.70% (n =85) of medium HPI baselines, and 60.00% (n =21) of high HPI baselines (Figure 2 & Appendix S2).

Based on the definition of positive effects and negative effects in the baseline-plus-change assessment framework, for PAs with low HPI baselines, 76.92% (n =150) showed positive effects in resisting human pressure and 23.08% (n =45) showed negative effects. For PAs with medium HPI baselines, 11.11% (n =12) showed positive effects in resisting human pressure and 10.19% (n =11) showed negative effects. For PAs with high HPI baselines, 22.86% (n =8) showed positive effects in resisting human pressure and 77.14% (n =27) showed negative effects (Figure 2 & Appendix S2).

Important management measures relative to PAs with different baselines

For PAs with different baselines, management measures that contributed to the effectiveness of PAs in resisting human pressure differed (Figure 3). The mean decrease Gini index based on the random forest model suggested that for PAs with low HPI baselines, the most important management measure to resist human pressure was the staff, that is, adequate numbers of skilled staff and independent management institutions (Figure 3a). For PAs with medium HPI baselines in 2010, the most important management measure to resist human pressure was patrol and surveillance, that is, effective patrol and surveillance systems with appropriate procedures (Figure 3b). For PAs with high HPI baselines in 2010, the most important management measure to resist human pressure was effective illegal threat control (Figure 3c). The partial dependence plots based on the random forest approach showed that the positive effects probabilities had generally nonlinear increasing trends and increasing normalization scores for the above three management indicators (Appendix S2).

Effects of resisting human pressure on natural ecosystems

Generally, resisting human pressure had significant positive effects on forest ecosystems. From 2010 to 2020, the rate of forest area decrease was the fastest for PAs with high HPI

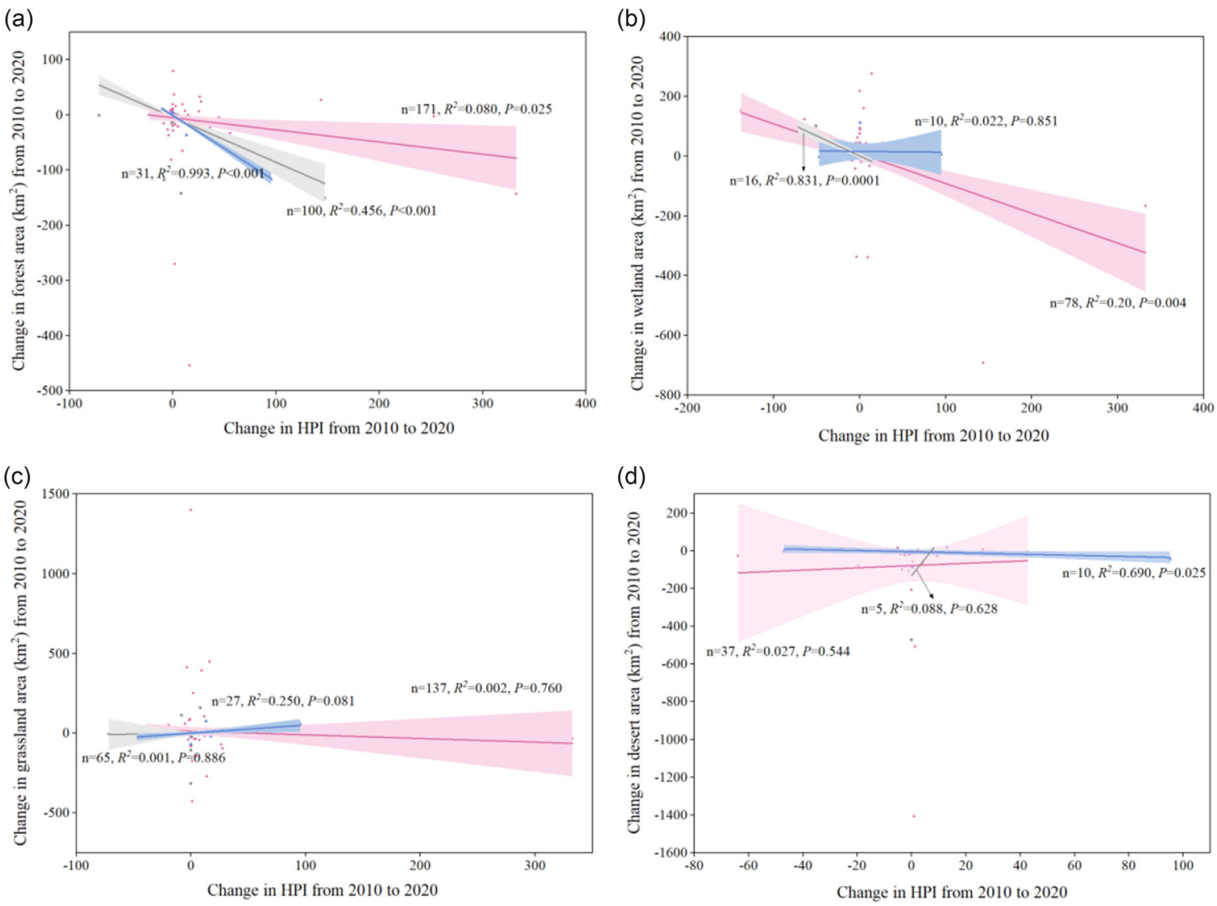

FIGURE 4 Relationship between changes in human pressure and changes in (a) forest, (b) wetland, (c) grassland, and (d) desert in protected areas (PAs) with different human-pressure baselines (lines, simple linear regressions; shading, 95% confidence intervals; pink, PAs with significantly lower human pressure; blue, PAs with significantly higher human pressure; gray, PAs with no significant differences in human pressure compared with their matched control sites)

baselines, followed by PAs with medium HPI baselines and PAs with low HPI baselines (Figure 4a). However, there was no correlation between the change in HPI and grassland area (Figure 4c).

The effects of resisting human pressure on wetland and desert ecosystems were different for PAs with different baselines. For PAs with low HPI and medium HPI baselines, wetland area had a significant negative correlation with change in HPI (Figure 4b). For PAs with high HPI baselines, the desert area decreased significantly as HPI increased (Figure 4d).

DISCUSSION

Effectiveness of PAs with different baselines

Our results suggested that 170 of the 338 PAs (50.30%) had significant positive effects, including 150 PAs with low HPI baselines, 12 PAs with medium HPI baselines, and 8 PAs with high HPI baselines (Figure 2b). However, when the different baselines of PAs were ignored, only 22.78% of PAs played a positive role in resisting human pressure from 2010 to 2020. This may be an underestimate of the positive effects of PAs in resisting human pressure for PAs with low HPI baselines. Furthermore, when we focused only on changes in human pressure without considering the baseline, the results of effectiveness assessment of PAs may somewhat underestimate the positive effects. For example, for PAs with low HPI baselines, only two (1.03%) were downgraded to high HPI in 2020. For PAs with no significant change in human pressure from 2010 to 2020 (n=93), 98.92% maintained the low HPI in 2020. Additionally, even when PAs experienced significant increases in HPI (n=45), 88.89% of these (n=40) maintained low HPI in 2020 (Figure 2b).

To maintain consistency of data source and resolution, we used the difference between the HPI in 2020 and 2010 to represent the change in human pressure over the past 10 years and the difference between natural area in 2020 and 2010 to estimate the change in natural area over time. In recent years, assessments of conservation effectiveness of PAs have also mostly used the difference over 2 years (Geldmann et al., 2019; Lu et al., 2020; Mammides, 2020; Zhang et al., 2021a). If there are data on annual human activity pressures, land cover, and PA management effectiveness, the impact of management measures on the conservation effectiveness of PAs can be more accurately identified with our framework. Therefore, improving the update frequency and resolution of large-scale data, such as land cover, roads, and population density, is of great significance for future research. In addition, the management effectiveness assessment of the PAs should be carried out at least once every 10 years to promote the improvement of the management effectiveness of PAs and the storage of basic data.

Optimal management measures for PAs with different baselines

Our results provide direct evidence that PAs with different baselines should adopt different management measures to improve effectiveness. If differing baselines of PAs are ignored, the results may lead to misdirected management measures in resisting human pressure (Appendix S2).

It is most urgent to enhance the conservation effectiveness of PAs in resisting human pressure for PAs with high HPI baselines, and our results indicated that effectively controlling illegal threats was the most important management measure (Figure 3c). Illegal activities, such as resource development, are becoming the key factor leading to biodiversity loss in these PAs, which serve as repositories of natural resources, such as forests (Achiso, 2020). Nearly half of the world's PAs are used illegally for agriculture, forest product extraction, and hunting of wild animals, so there is an urgent need to strengthen the management and control of these threats, which is consistent with our results (Achiso, 2020). These types of PAs often face more serious illegal threats than those with low HPI baselines according to Liu et al. (2020). Thus, there should be stronger measures for controlling illegal threats to improve the probability of positive effects of PAs in resisting human pressure (Appendix S2). Fortunately, the Chinese government has carried out an annual Green Shield supervision and inspection campaign to investigate and punish illegal activities inside PAs since 2017, thereby promoting the withdrawal and enforcement of such illegal activities.

For PAs with medium HPI baselines, the most important management measure was an effective patrol and surveillance system (Appendix S2). Protected areas with full-time patrol and enforcement teams and effective patrol and surveillance systems exhibit decreased human pressure (Jachmann, 2008; Geldmann et al., 2018). Surveillance and other equipment can make patrolling and law enforcement more effective and cost-efficient (Jachmann, 2008). However, our results indicated that only 10% of PAs have an effective patrol and surveillance system with appropriate procedures (Appendix S2).

Our results showed that for PAs with low HPI baselines, it was important to have adequate numbers of skilled staff and independent management institutions. Our previous studies also showed that unlike PAs with high HPI or medium HPI baselines, PAs with low HPI baselines are more likely to have effective management if they have good patrol and surveillance, which helps control illegal threats in PAs (Wang et al., 2021). Independent and well-established management institutions and adequate professional staff represent fundamental factors for the effective management of PAs (Li et al., 2013; Banjac et al., 2019; Zhang et al., 2021b). These results are as expected because independent and well-established management institutions, with departments for administration, protection, scientific research, education, resource utilization, community affairs, and policy, are conducive to coordinating the tasks of PAs (Quan et al., 2011; Pfaff et al., 2015). In addition, adequate and well-trained staff can perform their protection and management duties more effectively and have more acute insight into the external threats of PAs (Quan et al., 2011). For example, Kraaij and Milton (2006) found that adequate professional staff correlates with increasing mammal populations following reintroduction in Karoo National Park, South Africa.

Effects of human pressure on natural ecosystems within PAs with different baselines

As human pressure increased, forest area decreased the fastest in the PAs with high HPI baselines, followed by those with medium HPI baselines and low HPI baselines. From 2010 to 2020, as human pressure increased, the forests in PAs under all three baselines were mainly converted to grassland and farmland (Appendix S2). Many studies have indicated that human activities, such as deforestation, grazing, and agricultural expansion, are the main reasons for conversion of forests into grassland and cropland (e.g., Curtis et al., 2018; Acheampong et al., 2019; Williams et al., 2021).

For example, from 1958 to 1997, large-scale grazing in Yunnan Province led to the conversion of natural forest ecosystems to alpine meadows, reducing the forest area by 31% (Xiao et al., 2003). Specific human activities, such as cardamom planting in China, have reduced forest area and thus degraded the quality of gibbon habitat in China (Zhang et al., 2021b). Compared with PAs with low HPI and medium HPI baselines, the area of forests in PAs with high HPI baselines of built-up area was relatively higher (Appendix S2). One possible reason may be that natural forest ecosystems in PAs with high human pressure often have poor resistance to external disturbances. And infrastructure constructions, such as hydropower projects and tourism infrastructure, also pose serious threats to the effective conservation of forest ecosystems (Tardieu et al., 2015; Siqueira-Gay et al., 2020). Orderly withdrawal and management of hydropower projects and tourism infrastructure in the core areas of PAs can also improve forest ecosystem restoration (Schulze et al., 2018; Achiso, 2020). Therefore, the management and control of such threats inside PAs should be strengthened in accordance with regulations. At the same time, daily patrols and numbers of skilled staff inside PAs should be increased. An assessment of two PAs dominated by forest showed that increasing the number of patrol staff and introducing performance appraisals reduced poaching by 17% (Jachmann, 2008). Therefore, strengthening the control of human threats and increasing the number of skilled staff and patrol and surveillance activities are important for the conservation of forest ecosystems in PAs.

For PAs with low HPI and medium HPI baselines, wetland area decreased as human pressure increased, and wetland was mainly converted to cropland. However, for PAs with high HPI baselines, there was no correlation between wetland area and change in HPI (Figure 4b & Appendix S2). Large areas of natural wetlands have declined due to, for example, pollutant emission and infrastructure construction (Hu et al., 2017; Mammides, 2020). For example, the wetland area inside PAs in China's midtemperate humid zone decreased by 227.36 km^2 from 2000 to 2015 (Zhu et al., 2019). What is more, the loss of natural wetlands worldwide is largely caused by wetland conversion to croplands, such as in the Sanjiang Plain in China (Wang et al., 2011; Song et al., 2014), North and South Dakota in the United States (Johnston, 2013), and Kampala in the Uganda (Isunju & Kemp, 2016). About 60% of China's lost natural wetlands were due to agricultural expansion for grain production, 74.7% of which occurred from 1990 to 2000 (Mao et al., 2018). Therefore, to prevent human activities, such as agricultural expansion, carrying out regular daily patrols, installing surveillance systems, and strengthening the professional skills of staff can help improve the effectiveness of PAs in resisting human pressure and protect wetlands, especially for PAs with low human pressure initially. Furthermore, the loss of wetland area caused by climate change cannot be ignored (Erwin, 2009).

For PAs with high HPI baselines, desert area decreased significantly as human pressure increased, and it was mainly converted to grassland and wetland (Appendix S2). For PAs with low HPI and medium HPI baselines, there was no significant correlation between desert area and human pressure. This is reasonable because desert ecosystems are inherently harsh environments; thus, minor disturbances may not cause significant changes in the ecosystem (Li et al., 2021). Land-cover changes in desert ecosystems are mainly affected by climate change, especially precipitation (Chang et al., 2019; Zhao et al., 2019). China's desert PAs are largely in the northwest, and the precipitation in the northwest has decreased significantly in the past four decades (Peng & Zhou, 2017; Wang & Zhong, 2020). The area converted from desert to built-up land was highest in desert PAs with low HPI and medium HPI baselines. Therefore, the interference caused by illegal human activities to the desert ecosystem cannot be ignored, especially for PAs with high HPI baselines.

Grassland area and human pressure inside PAs with different baselines were not correlated. Grassland degradation is mainly driven by climate factors (Harrison et al., 2015; Liu et al., 2019). However, this does not mean human activities do not pose a threat to the grassland ecosystem. Grassland was primarily converted to cropland in PAs with high HPI baselines (Appendix S2). The most likely reason for this is that agricultural expansion and grazing are important driving factors for grassland degradation (Gang et al., 2014; Cao et al., 2019; Bardgett et al., 2021).

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