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Anthropogenic vulnerability assessment of global terrestrial protected areas with a new framework☆

Jiahui Meng[a,b], Yaoqi Li[a,b,c], Yuhao Feng[a,b], Fangyuan Hua[a,b], Xiaoli Shen[d], Sheng Li[a,e], Nawal Shrestha[a,b], Shijia Peng[a,b], Carsten Rahbek[f,g,h], Zhiheng Wang[a,b,*]

[a] Institute of Ecology, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[b] Key Laboratory for Earth Surface Processes of the Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[c] Department of Health and Environmental Sciences, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China
[d] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing, China
[e] School of Life Sciences, Peking University, Beijing 100871, China
[f] Center for Macroecology, Evolution and Climate, University of Copenhagen, DK-2100 Copenhagen, Denmark
[g] Danish Institute for Advanced Study, University of Southern Denmark, Odense, Denmark
[h] Department of Life Sciences, Imperial College London, Ascot SL5 7PY, UK

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ABSTRACT

Protected areas (PAs) are the major conservation tool for ecosystem conservation, but function unequally in mitigating human pressures in practice. Assessing PA vulnerability caused by human pressures and its association with socioeconomic and PA characteristic factors is vital for improving conservation effectiveness and the post-2020 PA expansion. Here, using a new framework integrating the intensity and temporal changes of human pressures in PAs and their matched unprotected areas, we categorize global terrestrial PAs into four anthropogenic vulnerability levels: high (11.7 %), moderate (18.6 %) and low (21.9 %) vulnerability and wilderness (47.8 %). We find significant variations in the anthropogenic vulnerability of PAs between countries, continents, and IUCN categories. Europe has the highest proportion of high-vulnerability PAs (ca. 19.7 % of protected areas in Europe), while South America and Oceania have the highest proportions of low-vulnerability PAs and wilderness PAs, respectively (33.2 % and 75.0 % respectively). The vulnerability of PAs is not significantly associated with socioeconomic factors at the country level, which might reflect the trade-offs between positive and negative outcomes of development. With a new framework that integrated four significant factors for anthropogenic vulnerability assessment, this study demonstrates that global PAs have different anthropogenic vulnerability levels and suggest that some PAs function effectively in mitigating human pressures despite currently intense human pressures within them. Our results also suggest that future evaluations on the conservation status should pay attention not only to PA coverage but also to the anthropogenic vulnerability levels within PAs to achieve higher conservation effectiveness.

1. Introduction

Recent evaluations show that intense human activities have pushed global biodiversity into a crisis state, with significantly increased species extinction rates and widespread declines in wildlife (Ceballos et al., 2015). Protected areas (PAs) are widely viewed as a cornerstone of conservation strategies (Margules and Pressey, 2000). Currently, PAs cover ca. 15.8 % of the global terrestrial land and 7.7 % of the marine area (UNEP-WCMC, 2022), representing one of the most visible achievements in global biodiversity conservation (Lewis et al., 2019). Despite their areal coverage, the conservation relevance of PAs depends on that they are effectively protected and deliver actual biodiversity outcomes (Ervin, 2003; Gill et al., 2017). Given the prominence of PAs in global conservation policy, understanding their vulnerability to human pressures (anthropogenic vulnerability hereafter) and the factors affecting such vulnerability is crucial for future conservation planning, particularly as the post-2020 conservation framework requires that the PA coverage should be at least 30 % of the land and ocean areas by 2030

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* Corresponding author at: Institute of Ecology, Peking University, Beijing 100871, China.
E-mail address: zhiheng.wang@pku.edu.cn (Z. Wang).

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(i.e., also known as the "30 by 30 target")). The anthropogenic vulnerability of a PA reflects a combination of existing human pressures on the PA (*eg.*, urban and built-up, pasture lands, and roads) in addition to the PA's ability to mitigate the impact of human pressures on biodiversity through reasonable management (Geldmann et al., 2018). For example, a PA with moderate human pressures but effective management of such pressures could enhance natural habitat and would be less vulnerable than a PA with moderate pressures but poor management (Françoso et al., 2015).

The current intensity of human pressures within PAs has been used to evaluate the anthropogenic vulnerability of PAs. A recent study estimated that one-third of global PAs were experiencing intense human pressures (i.e., human footprint index ≥4) (Jones et al., 2018). However, because areas with high species and phylogenetic diversity often have suitable ecological conditions for human living (Myers et al., 2000; Balmford et al., 2001; Turley and Brudvig, 2016), these areas might unavoidably have a high intensity of human pressures in the current stage and we need seek co-existence between Man and Nature rather than simply reducing human activities. Considering only the current intensity of human pressures within PAs but not the ability of PAs to mitigate human pressures over time may provide incomplete assessments of the anthropogenic vulnerability of PAs. In another recent study, Geldmann et al. (2019) assessed the effectiveness of PAs to mitigate human pressures by comparing the temporal changes in human pressures within PAs with their matching unprotected areas, which are counterfactual areas that have a similar environment to PAs (Ferraro, 2009). This method could eliminate the bias of PAs toward the lands with low land use intensity and provide a reasonable assessment of the ability of PAs to mitigate human pressures (Almeida-Rocha and Peres, 2021; Ferraro, 2009; Vieira et al., 2019). However, the current intensity of human pressures representing the threat to wildlife habitats was not included in this assessment. Therefore, to thoroughly assess the anthropogenic vulnerabilities of PAs, a framework incorporating the current intensity and temporal changes of human pressures in PAs and their matched counterfactual areas is needed.

Understanding the factors affecting the anthropogenic vulnerability of PAs is critical (Balmford et al., 2009; Shrestha et al., 2021). Previous studies have shown that socioeconomic factors, like gross domestic product (GDP), governance, and the development level of countries are directly or indirectly related to the effectiveness of biodiversity conservation and PA coverage at the national level (Amano et al., 2018; Butchart et al., 2015; McCarthy et al., 2012; Newbold et al., 2015). Generally, countries with higher GDP per capita, higher development levels and better governance have been shown to provide better support for PA management and hence may be negatively associated with the anthropogenic vulnerability of PAs (Balmford et al., 2001; Bauer et al., 2015; Bruner et al., 2001; Amano et al., 2018; Geldmann et al., 2018). However, as socioeconomic development disturbs PAs, those socioeconomic factors could also be positively associated with the anthropogenic vulnerability of PAs (Koop and Tole, 1999; Oldekop et al., 2016). In addition to socioeconomic factors, PA characteristics (e.g., size, elevation, establishment time, etc.) may also influence the biodiversity outcomes of conservation interventions and hence anthropogenic vulnerabilities of PAs (Rodrigues et al., 2004; Barnes et al., 2016, 2017; Gill et al., 2017). However, to what extent these factors influence the anthropogenic vulnerability of PAs remains to be evaluated.

Here, we report a framework that focused on current human pressures and the ability of PAs to mitigate human pressures to assess the vulnerability of global PAs. When the human pressures in a PA are effectively mitigated, the intensity of human pressures within it tends to decrease, and the intensity and temporal changes of human pressures within it are normally lower than those in its matched unprotected areas (Kintz et al., 2006; Dimobe et al., 2015; Guetté et al., 2018). Therefore, both the temporal changes of human pressures in PAs and the difference in the temporal changes of human pressures within PAs and the matched unprotected areas could provide an indirect evaluation of the ability of PAs to mitigate human pressures (Guetté et al., 2018; Geldmann et al., 2019). Our framework evaluates both the current intensity and the temporal changes of human pressures in both PAs and their matched unprotected areas, which considers more scenarios than previous studies (Jones et al., 2018; Geldmann et al., 2019). We used the global human modification index (HM) (Theobald et al., 2020) to measure human pressures. Using this framework, we quantified global PA grid cells into four categories, i.e., high, moderate, and low vulnerability and wilderness (i.e., no anthropogenic vulnerability). Then we explored the relationships between the anthropogenic vulnerability of PAs and socioeconomic variables at the country level and PA characteristics variables at the PA level. Moreover, we also focused on the vulnerability of PA grid cells experiencing intense human pressures (Jones et al., 2018) to explore the difference between the assessments based on our framework and the previously wildly used framework that only consider the current intensity of human pressures. Understanding the anthropogenic vulnerability of global terrestrial PAs and their drivers could help improve the effectiveness of PA management in the future.

2. Data and methods

2.1. Data on human modification index

The human modification indexes (HM) in 1990, 2000, 2010, 2015 and 2017 at a spatial resolution of 0.3×0.3 km^2 were obtained from Theobald et al. (2020). This dataset integrates 14 stressors of human pressures on natural ecosystems, including 1) urban and built-up, 2) crop and pasture lands, 3) mining and quarrying, 4) power generation (renewable and nonrenewable), 5) roads, 6) railways, 7) electrical infrastructure, 8) logging and wood harvesting, 9) human intrusion, 10) reservoirs, and 11) air pollution, 12) grazing, 13) oil and gas wells, and 14) power lines. Particularly, current roads and railways were included as static layers in the temporal HM maps, while the other human pressure factors varied through time. The HM index ranges from 0 to 1, with 1 representing the strongest human pressures. Compared to previous human pressure indices, the HM index incorporates the latest global-scale datasets and a greater number of human pressure factors (Kennedy et al., 2019; Theobald et al., 2020) and provides data for more periods. This dataset has been used to represent human pressure on natural ecosystems in recent studies (Ingram et al., 2021). Following Theobald et al. (2020), we used the data from 1990 to 2015 rather than 1990–2017 to calculate HM changes, considering that the calculation of HM datasets in 1990–2015 used the first 11 stressors and the dataset in 2017 used all the 14 stressors.

2.2. Data on protected areas

The data on global protected areas (PAs) and their established years were obtained from the World Database on Protected Areas (WDPA) (*www.protectedplanet.net*) released in February 2021. In our analyses, we included only terrestrial PAs with a status of 'designated', 'inscribed', or 'established' (Jones et al., 2018). We also excluded the PAs that were classified as 'Man and the Biosphere' test areas. It is noteworthy that only 78 PAs of China are listed in the WDPA, and this number is far fewer than the current number of Chinese nature reserves (You et al., 2018; Xu et al., 2019). Following Pimm et al. (2018), we updated the global PA data by replacing the Chinese PAs in the WDPA with the Chinese provincial and national nature reserves (Zhang et al., 2015).

The protection categories of PAs in the WDPA followed the definition of the International Union for Conservation of Nature (IUCN) that includes 'Levels *I* to *VI*', 'Not Applicable', 'Not Assigned', and 'Not Reported' (Dudley, 2008). We combined the last three categories as 'NA' in the following analyses analysis. Chinese nature reserves are strictly protected through legislation (Xu et al., 2019) and work as the strictest type of protected area similar to the IUCN category *I*. We, therefore, assigned Chinese nature reserves as IUCN category *I* in our analyses.

2.3. Data on environmental and socioeconomic variables

We obtained the data of slope, aspect, soil type, and nutrient level of terrestrial lands from *Harmonized World Soil Database* (https://www.fao.org/), the data of land cover from the *European Space Agency* (*http://maps.elie.ucl.ac.be/CCI/viewer/download.php*), the data of precipitation, temperature from the *Worldclim* database (*https://www.worldclim.org/*), and the data of elevation from United States Geological Survey (*https://www.usgs.gov/*). The data of GDP per capita, human development index (HDI), and worldwide governance indicator (WGI) for each country during 1990–2017 were obtained from the *World Bank* (*http://www.worldbank.org*, accessed on Mar. 2021). GDP and HDI were used to reflect the level of socioeconomic development of a country, and the WGI was estimated by six facets of a government, including their voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption, and has been widely used to reflect a country's governance capacity.

2.4. Identification of matched unprotected areas of PAs

Our framework assessed the current human pressures and the human pressure changes in PAs and their matched unprotected areas. We used the counterfactual areas of PAs as the matched unprotected areas, which were defined as areas that have similar initial socio-economic and natural conditions to PAs (Ferraro, 2009). In general, the counterfactual areas of PAs were identified using the propensity score matching (PSM) approach (Ferraro, 2009). This method could eliminate the potential bias in the location of PAs toward remote areas or specific environments Specifically, the counterfactual area of a PA was defined as the independent unprotected areas that 1) were in the same country of the PA, 2) were 10 km away from PA boundaries to avoid spillover effect (Zhao et al., 2019), and 3) had the most similar environmental conditions to the PA represented by the following 8 variables: elevations, slopes, aspects, temperature, precipitation, initial land cover, soil type and nutrient levels. Considering the limitation of the resolutions of environmental data and to reduce the computation load, environmental layers with a spatial resolution of 10×10 km^2 were used. Then each grid cell was separated into two types, under protection or without protection. The PA might be covered by several 10×10 km^2 grid cells and each of them corresponds to a unique unprotected grid cell that has the most similar environmental conditions. Then all matched unprotected grid cells for a PA were identified as the counterfactual areas of the PA. We removed those PAs with terrestrial areas smaller than 25 km^2 (this only reduced the total area of protected land analyzed by 1.6 %) to minimize miscalculations due to data resolution issues. We then converted the shapefile of global PAs and counterfactual areas into a raster with the same 0.3×0.3 km^2 spatial resolution as the HM data. Finally, 13,402 PAs (ca. 11 % of global land areas) were included to evaluate the vulnerability of PAs.

2.5. Temporal changes of human modification

To evaluate the temporal changes in HM within PAs and matched unprotected areas (i.e. counterfactual areas), we excluded PAs established later than 2010 and those without any record of establishment year. Considering the availability of the HM index, we evaluated the temporal changes of HM within each PA as the difference between its HM in 2015 and that in the nearest available year (e.g., 1990, 2000 and 2010) but not earlier than its established year. We calculated the temporal changes for each PA grid cell in a PA.

2.6. Assessing the anthropogenic vulnerability of PAs

Our framework calculated the following four indicators to represent the anthropogenic vulnerability of a given PA grid cell based on the HM data: (1) the current HM in 2017 in the PA grid cell (HMcurrent); (2) the difference in HM in 2017 between the PA grid cell and the mean value of the matched unprotected areas of the PA (i.e. the relative intensity, HMrelative); (3) the mean annual change in the HM in the PA grid cell (ΔHM); (4) the difference in the temporal change of HM between the PA grid cell and the mean value of the matched unprotected areas of the PA (i.e., the relative change of human modification, ΔHMrelative). The mean values of current intensity and temporal change of HM in the matched unprotected areas of a PA were estimated as the average of all grid cells within the matched unprotected areas.

Each of the above indicators then supplied a vote of 0 or 1 for the vulnerability of a given grid cell inside a given PA. The vote is 1 if a PA grid cell has the following: (1) HMcurrent >0.01; we assigned 0.01 as the threshold considering HMcurrent ≤ 0.01 represents very low levels of human modification according to Kennedy et al. (2019). (2) HMrelative >0 (i.e., the level of human modification inside the PA grid cell is higher than its matched unprotected areas). (3) ΔHM > 0 (i.e., human modification inside the PA grid cell increased after the establishment of PA); or (4) ΔHMrelative >0 (i.e., the increase of human modification inside the PA grid cell is faster than its matched unprotected areas). If a grid cell has none of these characteristics, the vote is 0. Here, we did not differentiate the positive extent of HMcurrent, Hmrelative, ΔHM and ΔHMrelative since a positive value indicates exceptional human pressure that may cause PA vulnerability. Based on tallied votes across the four indicators, we classified a grid cell of a PA as 'high vulnerability' if it had ≥ 3 votes, 'moderate vulnerability' if it had 2 votes, 'low vulnerability' if it had 1 vote, and 'wilderness' if it had 0 vote (i.e., no human

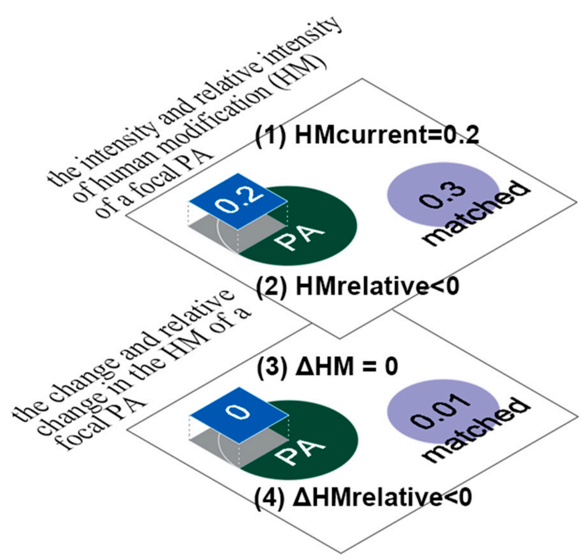

Fig. 1. A flowchart demonstrating the framework for the anthropogenic vulnerability assessment of global protected areas (PAs). Top panel, the intensity and relative intensity of human modification of a focal PA. Specifically, the focal PA is first rasterized into equal-area grid cells with a spatial resolution of 0.3 km × 0.3 km. The current human modification index is 0.2 for a protected grid cell, and 0.3 for its matched unprotected area of the PA. Therefore, the relative human modification index of this protected grid cell is HMrelative $= 0.2–0.3 = -0.1 < 0$. In other words, although the current human pressures in the protected grid cell are strong, they are lower than that in the unprotected buffer area. Lower panel, the temporal change in the human modification of a focal PA grid cell, and its difference in comparison with that in the unprotected buffer area of the PA. The human modification index remains unchanged over years (△HM = 0) in the protected grid cell but increases by +0.01 annually in the matched unprotected area of the PA. Therefore, the relative change in human modification in this protected grid cell is ΔHMrelative $= 0–0.01 = -0.01 < 0$. In other words, the human pressures in the protected grid cell remain unchanged, but those in the unprotected buffer area of the PA increase, suggesting that the PA is effective in mitigating human pressures in it.

pressures and no increase of human pressures in the PA grid cell) (Fig. 1).

In a recent study, Jones et al. (2018) identified PAs experiencing intense human pressures as those with a human footprint index ≥4 and found that one-third of global PAs are experiencing intense human pressures. To compare our results with those of Jones et al. (2018), we specifically focused on the PA grid cells with HMcurrent ≥0.08 (human footprint index = 4 that Jones et al. (2018) used and equals pasture lands corresponds to HMcurrent = 0.08 when the human footprint index (0–50) was rescaled as HMcurrent) but low or moderate vulnerabilities. These PA grid cells had intense current human pressures (HMcurrent) but low to moderate vulnerability and hence were termed as being 'overstrained'. The vulnerability level of the overstrained PA grid cells would be overestimated if the assessment considers only HMcurrent, but not HMrelative, ΔHM and ΔHMrelative (Jones et al., 2018).

2.7. Effects of national socioeconomic factors and PA characteristics on anthropogenic vulnerability of PAs

We used the GDP per capita, HDI, and the WGI of each country to explore the impacts of socioeconomic factors on the anthropogenic vulnerability of PAs at the country level. We used simple linear regressions to explore how national socioeconomic variables influenced the proportion of PA grid cells with different vulnerability levels summarized at the country level.

We used the size, establishment year, and mean elevation of each PA to explore the effects of PA characteristics on vulnerability. Then we used simple linear regressions to explore how PA characteristics influenced the proportion of PA grid cells with different vulnerability levels summarized at the PA level. To increase the normality of the data, we log-transformed the proportion of PAs with different vulnerability levels and the data of GDP per capita, PA elevation, and PA size.

3. Results

Approximately 33.9 %, 11.1 %, 43.7 %, and 14.6 % of the global PAs were voted to be vulnerable (i.e. voted as 1) in terms of HMcurrent, HMrelative, ΔHM and ΔHMrelative, respectively (Fig. 2). Approximately 11.7 %, 18.6 %, and 21.9 % of the global PAs were identified as high, moderate, and low vulnerability, respectively, and 47.8 % of PAs were identified as wilderness (Fig. 3a & b). Among six continents, Europe had the highest proportion (19.7 % of protected area) of high-vulnerability PAs, followed by Africa (15.5 %), while Oceania had the lowest proportion (5.4 %) of high-vulnerability PAs (Fig. 3c). The proportion of PAs with different vulnerability levels varied noticeably between countries (Fig. 4). Among countries with land areas >40,000 km^2, Bhutan, Venezuela, and Suriname had the highest proportion (>12 %) of low-vulnerability PAs (Fig. 4a); Latvia, Guinea, and Slovak had the highest proportion (>9.8 % of land area) of high-vulnerability PAs (Fig. 4b). Wilderness PAs were mainly distributed at high latitudes of the Northern Hemisphere, in the Amazonian rainforests and Australian drylands, and on the Qinghai-Tibetan Plateau in China (Fig. 3a). Oceania had the highest proportion (75.0 % of protected area) of wilderness PAs among all continents (Fig. 3c), and Greenland, Namibia, and Botswana had the highest proportion (>21.1 % of land area) of wilderness PAs among countries with land areas >40,000 km^2. The IUCN categories I and II (i.e., the strictly protected PAs) and VI had the lowest proportions of high-vulnerability PAs (7.6 %, 5.6 % and 10.9 % for categories I, II and VI, respectively) and the highest proportions of wilderness PAs (57.9 %, 58.6 % and 52.9 % for categories I, II and VI, respectively) (Fig. 3d). Category V had the highest proportion (27.3 %) of high-vulnerability PAs and the lowest proportion (16.7 %) of wilderness PAs (Fig. 3d).

Approximately 16.5 % of the global terrestrial PAs were experiencing intense human pressures (HMcurrent ≥0.08) following the definition by Jones et al. (2018). However, 49.9 % of these PAs were evaluated to have moderate (43.2 %) or low (6.7 %) vulnerability and hence were identified to be overstrained PAs (Fig. 5). Among six continents, Europe had the highest proportion (17.6 % of protected area) of overstrained PAs, while Oceania had the lowest (2.8 %) (Fig. 5c). In Europe, 36.7 % of all PAs had HMcurrent ≥0.08, but 50.9 % of these PAs were identified as being overstrained (Appendix S2). Among countries with land areas >40,000 km^2, 19 countries had >5.0 % of their land area identified as overstrained PAs (Appendix S2). Among the different IUCN categories, the proportion of overstrained PAs was the highest in categories III (19.6 %) and V (15.4 %) and the lowest in categories VI (4.4 %) (Fig. 5d).

The PA characteristics influenced the anthropogenic vulnerability of PAs. The proportions of the high-vulnerability PAs were negatively correlated with the elevation of PAs. The proportion of the low-

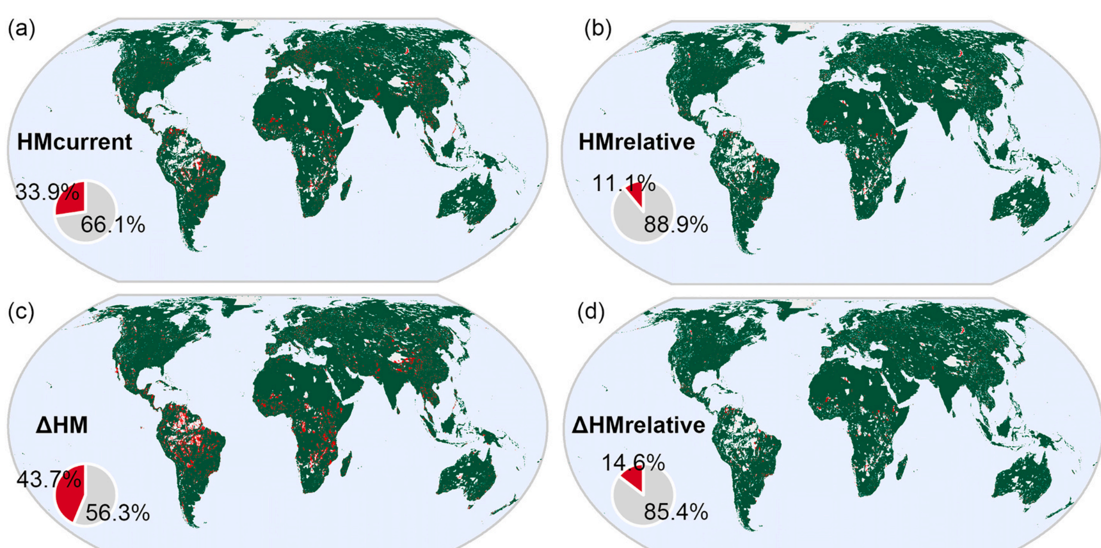

Fig. 2. The global patterns of PAs voted for vulnerability in terms of four indicators. (a), the current human modification indexes (HM) in 2017 in PA grid cells (HMcurrent); (b) the difference in HM in 2017 between PA grid cells and the mean value of the matched unprotected areas of each PA (HMrelative); (c) the mean annual change in HM in PA grid cells (ΔHM); (d) the difference in the temporal change of HM between PA grid cells and the mean value of the matched unprotected areas of each PA (ΔHMrelative). red, vote for 1; gray, vote for 0.

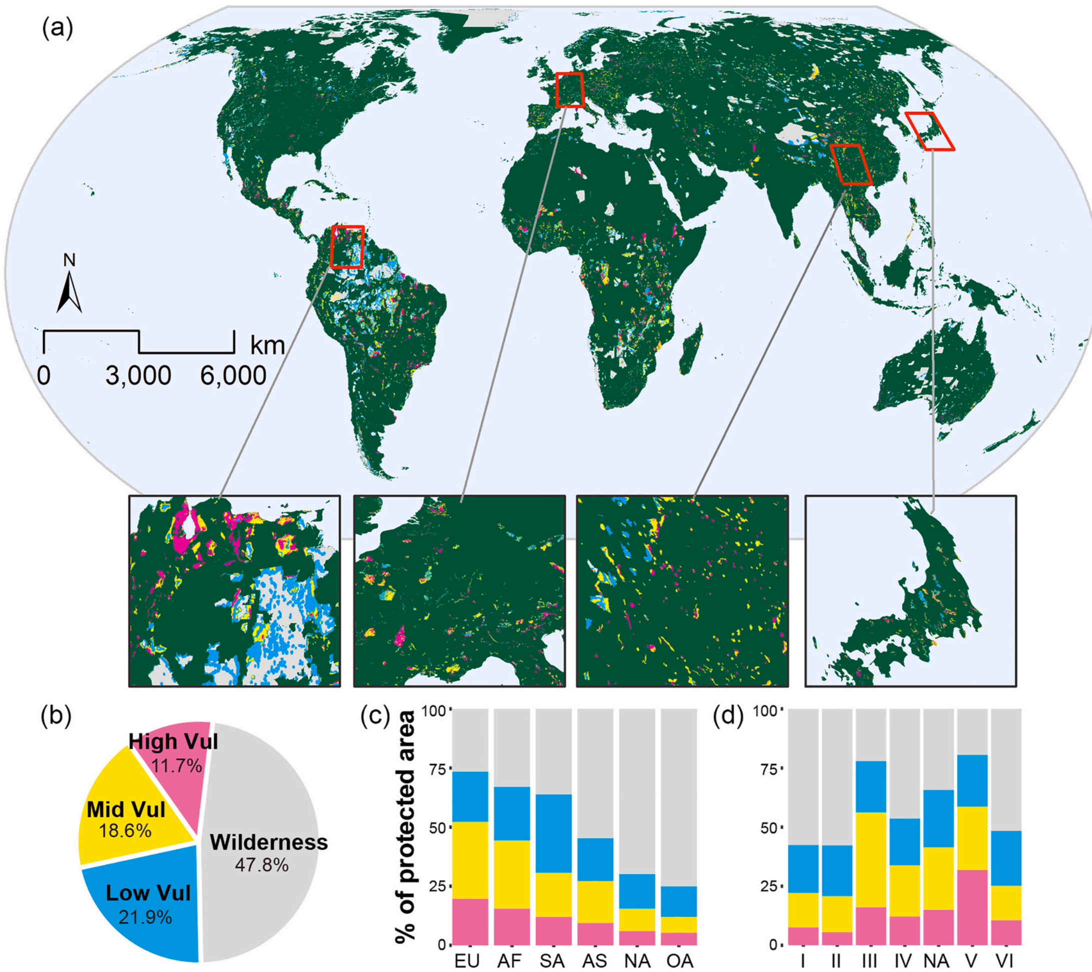

Fig. 3. Vulnerability of global protected areas (PAs) across continents and the IUCN protection categories. (a) Global patterns in the vulnerability of PAs. (b, c, and d) The proportion of PAs belonging to different vulnerability categories at the global scale (b), in different continents (c), and in different IUCN protection categories (d). high-Vul, high-vulnerability PAs; mod-Vul, moderate-vulnerability PAs; low-Vul, low-vulnerability PAs; and wilderness PAs. AF, Africa; EU, Europe; AS, Asia; SA, South America; NA, North America, and OA, Oceania. The color schemes in (a,c and d) are the same as that in (b).

vulnerability PAs was positively correlated with PA size. The proportion of the wilderness PAs was positively correlated with the elevation, establishment year and PA size (Fig. 6). The variability of the proportion of PAs with different vulnerability levels across countries was not significantly correlated with socioeconomic factors (Appendix S3).

4. Discussion

4.1. A new framework for the assessment of anthropogenic vulnerability of PAs

In this study, we present a framework assessing the vulnerability of PAs based on human pressures. Specifically, this framework assesses the anthropogenic vulnerability of PAs by integrating the current intensity and the temporal changes in human pressures within PAs and the comparisons of these values with those in the matched unprotected areas (represented by counterfactual areas). Compared with our framework, previous assessments are mainly based on one or two dimensions of human pressures. For example, Jones et al. (2018) focused on the current intensity of human pressures in PAs (i.e., the HMcurrent in our framework), while Geldmann et al. (2019) focused on the temporal change in human pressures inside PAs (i.e., the ΔHM in our framework) and its comparison with their matched unprotected areas (i.e., ΔHMrelative in our framework). The significance of the current intensity of human pressures within PAs (HMcurrent) is that it could strongly influence the function of PAs and hence is critical for the assessment of anthropogenic vulnerability of PAs (Jones et al., 2018). Additionally, the change in human pressures within PAs and its comparisons with unprotected areas are also important because these dimensions could reflect the ability of PAs to mitigate human pressures through effective PA management (Geldmann et al., 2019; Wolf et al., 2021). Therefore, the current intensity and the temporal change of human pressures within PAs and the comparisons with unprotected areas are all significant for the anthropogenic vulnerability assessment of PAs. Our framework integrates all these dimensions of human pressures and provides a new approach to understanding the anthropogenic vulnerability of the global PAs compared with previous assessments.

The Post-2020 global biodiversity framework states that PAs should be expanded to cover at least 30 % of the planet by 2030 (Convention of Biological Diversity, 2020; *https://www.iucn.org/resources/issues-briefs/post-2020-global-biodiversity-frameworkhttps://www.iucn.org/resources/issues-briefs/post-2020-global-biodiversity-framework*). Therefore. the area coverage of PAs (i.e., the percentage of conserved terrestrial lands and oceans) is one of the most important criteria for assessing the conservation status at the global scale and in different countries. However, the evaluation of conservation status solely based on PA coverage become increasingly controversial. Many scientific communities found that the role of area-based conservation is diminished because of ineffective management (Visconti et al., 2019; Maxwell et al., 2020). Our study and previous assessments of global PAs (Jones

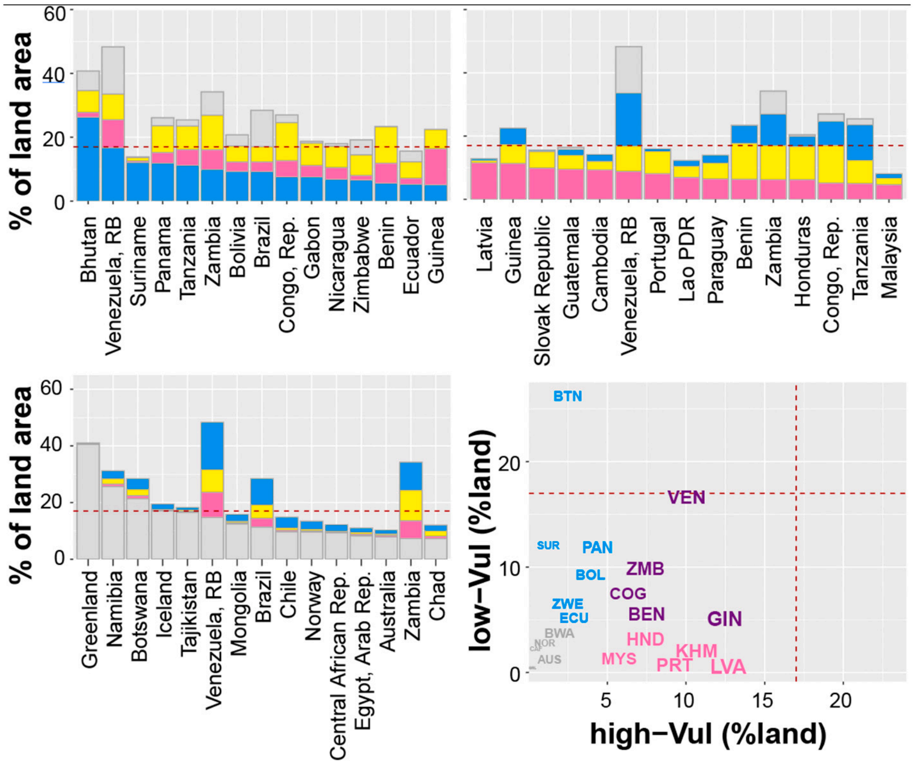

Fig. 4. The proportion of PAs with different vulnerability levels in different countries. To make the figures easier for reading, only countries larger than 40,000 km^2 and with PA coverage high than 5 % were included in this figure. See Appendix S1 for complete information of all countries evaluated. Bar plots (a-c) showed the proportion of PAs belonging to different vulnerability categories for (a) the top 15 countries with the highest proportion of low-vulnerability PAs, (b) the top 15 countries with the highest proportion of high-vulnerability PAs, and (c) the top 15 countries with the highest proportion of wilderness PAs. Colors in (a-c) represent the vulnerability groups: magenta, high-vulnerability PAs; yellow, moderate-vulnerability PAs; blue, low-vulnerability PAs; and gray, wilderness PAs. (d) Covariation between the proportion of high-vulnerability PAs (high-Vul, x-axis) and those of low-vulnerability PAs (low-Vul, y-axis) in different countries. The country names in (d) follow the ISO country codes, and the font size of these names is proportional to the rank of country size. Colors in (d) represent different country classifications: blue, countries shown in (a); magenta, countries shown in (b); gray, countries shown in (c); purple, the intersected countries shown in (a&b or a&b&c). No other special color assigned to the intersected countries shown in (a&c) to simplify the figure. ISO country codes: AUS, Australia; BEN, Benin; BTN, Bhutan; BOL, Bolivia; BWA, Botswana; BRA, Brazil; KHM, Cambodia; CAF, Central African Republic; TCD, Chile; CHL, Chile; COG, Congo, Rep.; ECU, Ecuador; EGY, Egypt; GAB, Gabon; GRL, Greenland; GTM, Guatemala; GIN, Guinea; HND, Honduras; ISL, Iceland; LAO, Lao PDR; LVA, Lativia; MYS, Malaysia; MNG, Mongolia; NAM, Namibia; NIC, Nicaragua; NOR, Norway; PAN, Panama; PRY, Paraguay; PRT, Portugal; SVK, Slovak Republic; SUR, Suriname; TJK, Tajikistan; TZA, Tanzania; VEN, Venezuela, RB; ZMB, Zambia; ZWE, Zimbabwe. The dashed lines represent 17 % PA coverage of the global land areas.

et al., 2018; Wolf et al., 2021) indicate that PAs can have high vulnerability to increasing human pressures. To improve the assessment of global and regional conservation status, PAs with different vulnerability levels should be differentiated. As high-vulnerability PAs may lack effective management to protect them from human pressures, they should not be included in the evaluation of the area coverage of PAs. Our results indicate that after excluding the high-vulnerability PAs (~12 % of global total PAs), the current global PAs cover ca. 13.8 % of global terrestrial land. Additionally, there are 47.8 % of global PAs belong to wilderness PAs and Greenland alone has contributed 11.5 % of wilderness PAs (Fig. 3 and Appendix S1). Previous studies have shown that these wilderness PAs cannot cover the biodiversity or the distribution of threatened species well (Pimm et al., 2018). This means that the effective PAs might be less than reported (i.e., 15.8 % global land).

4.2. *PAs experiencing intense human pressures*

Increasing evidence suggests that to improve the conservation coverage of global biodiversity, we should consider expanding PAs in regions with human pressures as these regions have stronger disturbances but fewer PAs compared with wilderness regions (Pimm et al., 2018; Wintle et al., 2018). Our results indicate that ca. 16.5 % of global PAs are experiencing intense current human pressures (HMcurrent $\geq$0.08); however, 49.9 % of these PAs have a low or moderate vulnerability, as the human pressures within them are decreasing or slowly increasing or lower than that in their counterfactual areas. Hence these PAs have been identified as overstrained PAs. These overstrained PAs have improved the performance of biodiversity conservation, considering they have fended off human threats from outside effectively (low values of HMrelative or ΔHMrelative) or reduced human pressures within them (low values of ΔHM). These results suggest that these overstrained PAs could act as refugia for biodiversity in regions experiencing intense human pressures (Wintle et al., 2018) if effective management could be assured. For example, the current PA system in Europe functions well in protecting biodiversity despite the high human pressures within PAs (Donald et al., 2007). As regions with high species and phylogenetic diversity are normally regions with high human population density and human activities (Balmford et al., 2001), these overstrained PAs allowing sustainable and low-level human activities will be critical in terms of filling gaps in the global PA system in the increasingly crowded world. In contrast, if the global PA system pursues only the proliferation of large protected areas with low human pressures, it may risk neglecting areas where protection is most urgently needed (Barnes et al., 2018; Pimm et al., 2018).

Our results indicate that more strictly protected categories (*I-II*) have lower proportions of high-vulnerability PAs (Fig. 3d), which suggests that the strictness of protection benefits the mitigation of human pressures within PAs. This result is consistent with previous studies (Laurance et al., 2004; Ahrends et al., 2010). In contrast, we find that the non-strictly protected PAs of the IUCN categories *III-VI* normally have high human pressures (HMcurrent) as sustainable use of natural resources in these PAs is allowed (Fig. 5d). However, these PAs do not necessarily have high anthropogenic vulnerability. Indeed, our results indicate that many of these PAs have a moderate or low vulnerability, and hence are identified as overstrained PAs (Fig. 5d). This is because 1) the increase of human pressures within these PAs is slow, and 2) the intensity and increase of human pressures within these PAs are both lower than those in their matched unprotected areas. These findings further suggest that the anthropogenic vulnerability assessment of global PAs should consider not only the intensity of human pressures within PAs but also the comparisons with those in the matched unprotected areas.

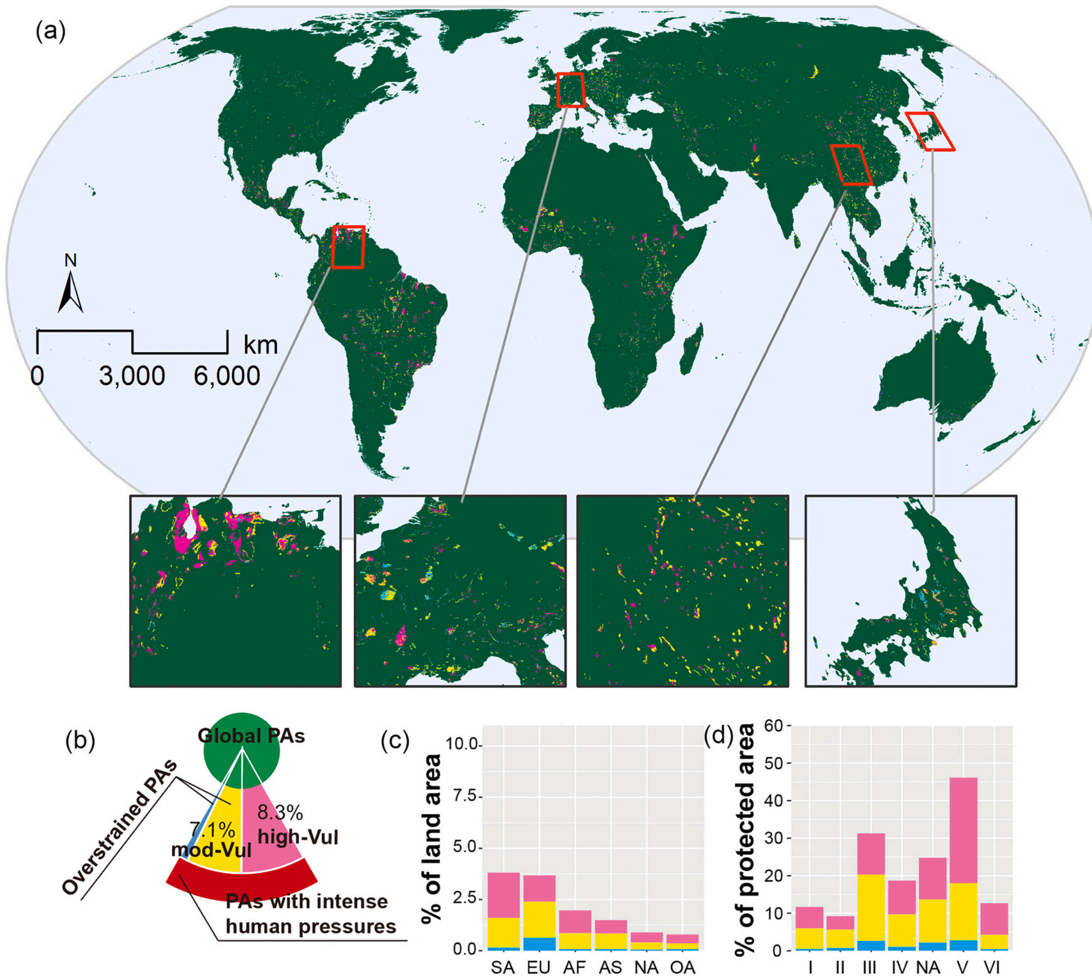

Fig. 5. Vulnerability of protected areas (PAs) experiencing intense human pressures across continents and the IUCN protection categories. PAs experiencing intense human pressures were defined as those with a current human modification index ≥0.08 following the method of Jones et al. (2018). (a, b) The spatial distribution (a) and (b) proportion of overstrained PAs (PAs that are experiencing intense absolute human pressures but don't have high vulnerability) shown together with high-vulnerability PAs experiencing intense human pressures at the global scale. Among the PAs experiencing intense human pressures (ca. 16.5 % of global PAs), ca. 49.9 % were evaluated as being overstrained (ca. 8.2 % of global PAs), and only ca.50.1 % were evaluated as being high-vulnerability PAs. (c, d) The proportion of the PAs experiencing intense absolute human pressures in different continents (c) and different IUCN protection categories (d). AF, Africa; EU, Europe; AS, Asia; SA, South America; NA, North America, and OA, Oceania. The color schemes in (a,c and d) are the same as that in (b).

4.3. Associations of anthropogenic vulnerability of PAs with PA characteristics and socioeconomic factors

At the PA level, we find that the anthropogenic vulnerability of PAs significantly differs across PAs with different elevations, establishment years and sizes (Fig. 6). Specifically, we find that the elevation of PAs is negatively associated with the proportions of high-vulnerability PAs and positively associated with the proportions of wilderness PAs. This result is consistent with the phenomenon that human population density is negatively associated with elevation. Additionally, we find that PA size is positively associated with the proportions of low-vulnerability and wilderness PAs. Two reasons may have contributed to this result: (1) large PAs normally have reduced edge effects (Ewers and Didham, 2007), and (2) large PAs are more likely to be established in lands with low human pressure (Barnes et al., 2017). Moreover, we also find that the proportion of wilderness PAs increases with the establishment year of PAs, suggesting that the recently-established PAs are more likely to be located in wilderness areas. This is likely due to the low economic expenses to establish wilderness PAs compared with establishing PAs in more economically developed regions. However, this trend reflects an urgent concern on global conservation as many important areas for biodiversity conservation are located in developed regions that cannot be covered by wilderness PAs (Pimm et al., 2018).

We find that the vulnerability levels of PAs have no significant relationships with the GDP per capita, HDI and WGI of a country. The effects of socioeconomic factors on PA effectiveness have generated widespread discussion. Some studies suggest that a country with higher GDP per capita, higher development and governance level is more likely to fund PA management and ensures the implementation of PA policies (Amano et al., 2018; Geldmann et al., 2019). In contrast, other studies raise concerns about the possible negative effects of socioeconomic development on biodiversity (Lees et al., 2016; Marques et al., 2019; Newbold et al., 2015). Our finding could be explained by the trade-offs between the positive and negative outcomes of socioeconomic development (Oldekop et al., 2016). Lately, some studies have proved the significance to reconcile socioeconomic development and nature conservation (Paul et al., 2020). Our findings and previous studies suggest that the advantages of development should pay more attention to mitigate the impact of human pressures on biodiversity through reasonable management to lower the anthropogenic vulnerability of PAs (Sanchez-Fernandez et al., 2018). In addition, our results suggest that different countries should have different priorities to improve the effectiveness of their PA systems (Fig. 4) (Tilman et al., 2017). Specifically, countries with few PAs should give high priority to expanding

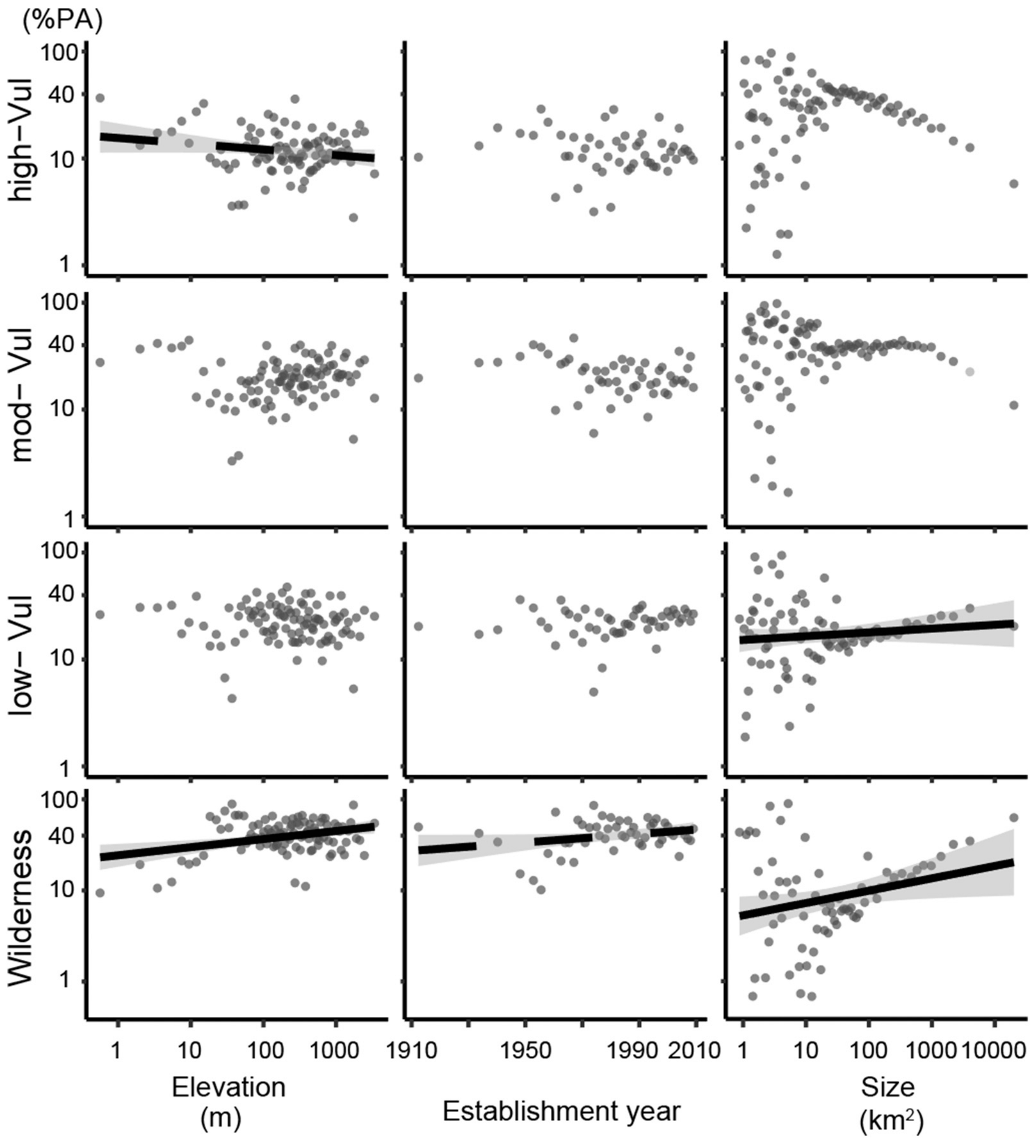

Fig. 6. Effects of PA characteristic variables on the proportion of protected areas (PAs) belonging to different vulnerability categories. For top-down, the y-axes of the four rows represent the proportion of high-vulnerability PAs (high-Vul), moderate-vulnerability PAs (mod-Vul), low-vulnerability PAs (low-Vul) and Wilderness PAs. From left to right, the x-axes represent the mean elevation, the establishment year and the size of the PA. To avoid too many points participating in the statistic, we grouped the three variables by one hundred quantiles with the same number of PAs in each group. The proportion of the vulnerability of PAs, elevation and PA size were log-transformed. A solid line was drawn if the corresponding regression was significant ($p < 0.05$) and a dotted line was drawn if $p < 0.1$.

their PA coverage, while countries with a high proportion of high-vulnerability PAs should give high priority to PA management to recondition the high-vulnerability PAs, and those with a high proportion of low-vulnerability PAs can focus on improving biodiversity outcomes.

CRediT authorship contribution statement

Jiahui Meng: Conceptualization, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Yaoqi Li:** Writing – original draft, Writing – review & editing. **Yuhao Feng:** Software. **Fangyuan Hua:** Writing – original draft, Writing – review & editing. **Xiaoli Shen:** Writing – review & editing. **Sheng Li:** Writing – review & editing. **Nawal Shrestha:** Writing – review & editing. **Shijia Peng:** Writing – review & editing. **Carsten Rahbek:** Conceptualization, Writing – review & editing. **Zhiheng Wang:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We declare that we have no conflict of interest. The work is all original research carried out by the authors. All authors agree with the contents of the manuscript and its submission to the journal.

No part of the research has been published in any form elsewhere, unless it is fully acknowledged in the manuscript. The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal. Any research in the paper not carried out by the authors is fully acknowledged in the manuscript. All sources of funding are acknowledged in the manuscript, and we have declared any direct financial benefits that could result from publication.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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