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Range-wide assessment of the impact of China's nature reserves on giant panda habitat quality

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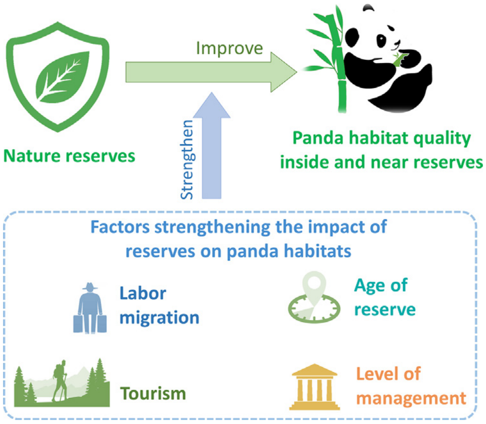
HIGHLIGHTS

- The impact of China's nature reserves on panda habitat quality was quantified.
- It is important to consider spatial heterogeneity of the impact in evaluation design.
- Most of habitat quality improvement in reserves is attributable to their protection.
- Nature reserves enhanced habitat quality beyond their boundaries.
- Labor migration and tourism helped to enhance the efficacy of nature reserves.

GRAPHICAL ABSTRACT



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ABSTRACT

Protected areas (PAs) form the backbone of global conservation efforts. Although many studies have evaluated the impact of PAs on land cover, human disturbances, and people's welfare, PAs' impact on wildlife habitat quality remains poorly understood. By integrating wildlife habitat mapping and information of 2183 rural households, we assessed the impacts of nature reserves (a type of PAs) across the entire geographic range of giant pandas (*Ailuropoda melanoleuca*) on panda habitat suitability change between 2001 and 2013 using the matching approach. We found the impact of nature reserves is concentrated in areas susceptible to human pressure, where 65% of the habitat suitability increase is attributable to the nature reserves' protection. The impact of nature reserves has spilled over to nearby unprotected areas and enhanced habitat suitability there. Nature reserves supported by the central government showed higher performance in improving habitat suitability than their counterparts supported by local governments. Older nature reserves perform better than those established more recently. Our results also show that local households' participation in tourism and labor migration (people temporarily leaving to work in cities) enhanced the ability of nature reserves

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Abbreviations: PAs, protected areas; GTGP, Grain-for-Green Program; NFCP, Natural Forest Conservation Program.

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to improve habitat suitability. These results and methods provide valuable information and tools to support effective management of PAs to enhance the habitat quality of giant pandas and other wildlife species in China and elsewhere.

1. Introduction

Establishing protected areas (PAs) is one of the most important strategies to curb the rapid loss of biodiversity worldwide (Watson et al., 2014). Under the auspices of the Convention on Biological Diversity, the international community has expanded the coverage of terrestrial protected areas from 9.0% in 2000 to 10.8% in 2010, and to 15.0% in 2020 (UNEP-WCMC and IUCN, 2020). New area designated as PAs over the past decade reached over 4 million km^2 (UNEP-WCMC and IUCN, 2020), an area larger than India. While the coverage of PAs remains insufficient in many places (Díaz et al., 2019), the number and extent of PAs increased rapidly around the world. However, global biodiversity is declining (Tittensor et al., 2014; WWF, 2018) and the effectiveness of PAs in delivering desired conservation outcomes has been questioned (Di Minin and Toivonen, 2015). Studies found that many PAs are challenged by inadequate government support and only 22% of PAs have “sound management” (Leverington et al., 2010; McCarthy et al., 2012). Meanwhile, the pressure of human activities is increasing inside and around PAs (Jones et al., 2018). Although some studies show PAs have helped to reduce forest loss and human disturbances (Schleicher et al., 2019), ecological degradation inside PAs has been documented even in some globally renowned PAs (Rada et al., 2019). The variable relationships between PAs and desired conservation outcomes have led to a growing call for empirical evaluation of PAs' impacts and reasons behind their success or failure (Baylis et al., 2015).

Many studies have estimated the impacts of PAs on land cover change (Feng et al., 2020), human disturbances (Geldmann et al., 2019), and people's welfare (Naidoo et al., 2019), but the impacts of PAs on wildlife habitat quality have not been widely evaluated. Although PAs' impact on land cover can provide some insights on how they affect wildlife habitats, the presence and quality of wildlife habitats are often determined by factors (e.g., forest composition, density, and age) more than land cover (Tuanmu et al., 2016). Therefore, we cannot reliably infer PAs' impact on wildlife habitats purely based on their effect on land cover. Furthermore, previous studies mostly focus on quantifying PAs' impacts while factors influencing PAs' performance in achieving conservation goals have not been investigated adequately (Yang et al., 2019; Zhao et al., 2021). For example, many studies (Kuriqi et al., 2019, 2020; Liu, 2017; Suwal et al., 2020) show that different places are increasingly interconnected through flows of people, energy, materials, and information, generating substantial impacts on ecosystem conservation. For PAs, the example flows may include inflow of tourists visiting PAs and outflows of labor migrants, which often generate substantial impacts on local livelihoods and shape human impacts on conservation. In addition to those external factors, some internal factors, such as management level (managed by central versus local governments) and establishment age (new versus old), are also known to influence PAs in achieving desired conservation goals (Zhao et al., 2019). Understanding the factors shaping PAs' impacts on desired ecological outcomes is critical for effective planning and management of PAs. Armed with this knowledge, conservation practitioners can design strategies accordingly to regulate the factors and enhance the ability of PAs to achieve conservation goals.

Using the habitats of giant pandas (*Ailuropoda melanoleuca*) as an example, we quantified the impact of 36 nature reserves across the entire range of giant pandas on panda habitat suitability and assessed factors affecting the impact. Giant pandas are an icon of global conservation (Xu et al., 2017). Their habitats provide sanctuary to thousands of other species (Li and Pimm, 2016) and important ecosystem services worth between US$ 2.6 and US$ 6.9 billion/year (Wei et al., 2018), although different species have distinct habitat requirements (Wang et al., 2021). The Chinese government invested substantially in giant panda conservation. In addition to the establishment of nature reserves, the Chinese government has implemented a series of large-scale conservation programs covering the entire range of giant pandas (Huang et al., 2020; State Forestry Administration, 2015), including the Grain-to-Green Program (GTGP) and the Natural Forest Conservation Program (NFCP) since the early 2000s (Liu et al., 2008). The GTGP pays rural farmers to convert sloping cropland to vegetated land (Yang et al., 2018b), while the NFCP provides finance to local governments or forest enterprises for conservation-based forest management (Yin, 2009). Other changes in local communities, including the development of tourism and labor migration, may have also contributed to the improvement of panda habitat quality. As more households participated in tourism businesses or had members leave for temporary jobs in cities, human disturbances to panda habitat have decreased (Chen et al., 2012; Liu et al., 2012). Recent assessments show that the extent and suitability of giant panda habitat have increased since the early 2000s (State Forestry Administration, 2015; Xu et al., 2017; Yang et al., 2017). Given the concurrent beneficial impacts of these conservation programs and socioeconomic changes to the panda habitats (Chen et al., 2012; Liu et al., 2012; Yang et al., 2018b), a natural question is how much have the nature reserves contributed to the recovery of panda habitat?

Until now, the impact of the nature reserves on panda habitats remains unclear. A few studies (Viña and Liu, 2017; Wei et al., 2020; Xu et al., 2017) have compared changes in panda population, human disturbances, and vegetation cover inside and outside panda reserves. For example, Wei et al. (2020) found panda population exhibits more growth inside reserves than outside while human disturbances decreased more inside than outside nature reserves during the period from the early 2000s to the early 2010s (Wei et al., 2020). In contrast, Viña and Liu (2017) observed that there are more forest gains outside panda reserves than inside between 2000 and 2010 (Viña and Liu, 2017). Although those studies offered some insights on the role of nature reserves in protecting panda habitat, such simple inside-outside comparisons cannot reliably reflect the impact of the reserves. This is because there are other factors that need to be considered in those comparisons. The observed differences in the previous studies between inside and outside nature reserves might be caused by other factors, such as remoteness and terrain roughness, rather than the protection efficacy of nature reserves.

We addressed the limitations in those previous assessments and rigorously evaluated the impact of nature reserves on panda habitat quality. Specifically, we first quantified the impacts of all the 36 nature reserves established before 2001 on panda habitat suitability change between 2001 and 2013 using the matching approach (discussed more in Section 2.4). We then examined the spillover effect of the nature reserves on panda habitats surrounding nature reserves. To understand the factors shaping the impact, we also investigated the influences of four variables on the nature reserves' ability to improve panda habitat suitability, including the management level (national versus regional), establishment age (old versus new), tourism development (with versus without tourism), and labor migration (high versus low proportion of households having members leave for job in cities). Based on the results, we finally discussed the findings and provide some suggestions to improve the performance of nature reserves in giant panda habitat conservation.

2. Materials and methods

2.1. Conceptual framework

Our study was guided by the integrated framework of metacoupling (human-nature interactions within and between systems (Liu, 2017)). Systems here refers to nature reserves and other places that interact with the reserves (Fig. 1). Intracoupling refers to the interactions happening within the systems while intercoupling refers to the interactions among systems. For example, nature reserves may connect with cities far away via tourism and labor migration and interact with nearby areas via spillover effects (e.g., effects on wildlife habitat spill over to nearby areas). Humans and wildlife habitats within nature reserves may interact in different ways (intracoupling), such as farming, livestock husbandry, and forest harvesting. Based on the status of humans and wildlife habitats, policies are designed to regulate human activities and balance the needs for conservation and socioeconomic development. This intracoupling among humans, wildlife habitats, and policies affects and is affected by intercoupling. For example, income opportunities from tourism and labor migration may reduce local communities' dependence on natural resources for livelihoods, improve their well-being, and facilitate habitat recovery.

2.2. Study area

The geographic range of giant pandas encompasses six mountain ranges (Minshan, Qinling, Qionglai, Liangshan, Daxiangling, and Xiaoxiangling) in Gansu, Shaanxi, and Sichuan provinces of China, covering a total area of about 125,170 km^2 (Fig. 2). This region is characterized with high variation in elevation (ranging from 70 m to 6250 m) and climatic conditions (e.g., temperature) (Yang et al., 2017). The diverse biophysical conditions provide sanctuary to rich flora and fauna in this region and make it one of the most biologically diverse regions in the world (Myers et al., 2000). Besides the rich biodiversity, there are over 10 million people living in the panda range, most of whom are farmers depending on subsistence livelihoods (State Forestry Administration, 2015). Livelihood activities such as farming, logging, fuelwood collection, livestock husbandry, and road construction have been major threats to the conservation of giant panda habitats (Hull et al., 2011; Zhang et al., 2017b). The geographic range of giant pandas is also one of the most tectonically active regions of China (Xu et al., 2017). The region experienced several earthquakes over the past decades (Viña et al., 2011), including the devastating 2008 Wenchuan Earthquake that occurred in the Qionglai Mountain Range (Fig. 2). In addition to 69,227 deaths and 374,643 injuries, about 1221 km^2 of forest, grassland, and wetland were lost due to the earthquake (Xu et al., 2009; Yang et al., 2018a).

The first four nature reserves for panda conservation (Wolong, Baihe, Wanglang, and Labahe) were established in the early 1960s (Huang et al., 2020) and more were established in the following years. By the end of 2015, 67 nature reserves had been established for the conservation of giant pandas (State Forestry Administration, 2015). Despite the expansion of the network of nature reserves, the degradation of panda habitat continued until the early 2000s. From 1976 to 2001, the total panda habitat area across the range decreased by 4.9% (Xu et al., 2017). To address the imperiled status of giant pandas, the Chinese government implemented a series of conservation programs since the early 2000s, including payments for ecosystem services programs (i.e., NFCP and GTGP) and the establishment of 31 more nature reserves (Liu et al., 2016a; Tuanmu et al., 2016). The massive investments in those conservation efforts contributed to the recovery of panda habitat. The extent and suitability of giant panda habitat across the range started to improve since the early 2000s (Xu et al., 2017; Yang et al., 2017).

2.3. Spatiotemporal dynamics of giant panda habitat suitability

We obtained two habitat suitability maps covering the entire geographic range of giant pandas in 2001 and 2013 from our previous study (Yang et al., 2017). The maps were produced by integrating time-series satellite imagery, field survey data, and the Maximum

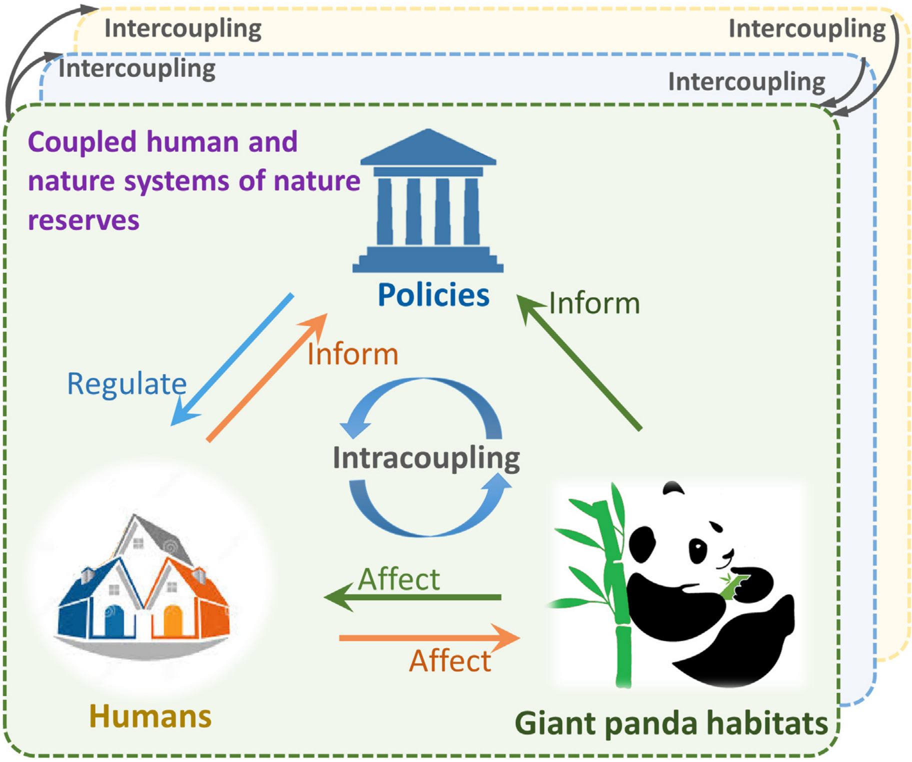

Fig. 1. Conceptual framework for studying the impact of nature reserves on giant panda habitats.

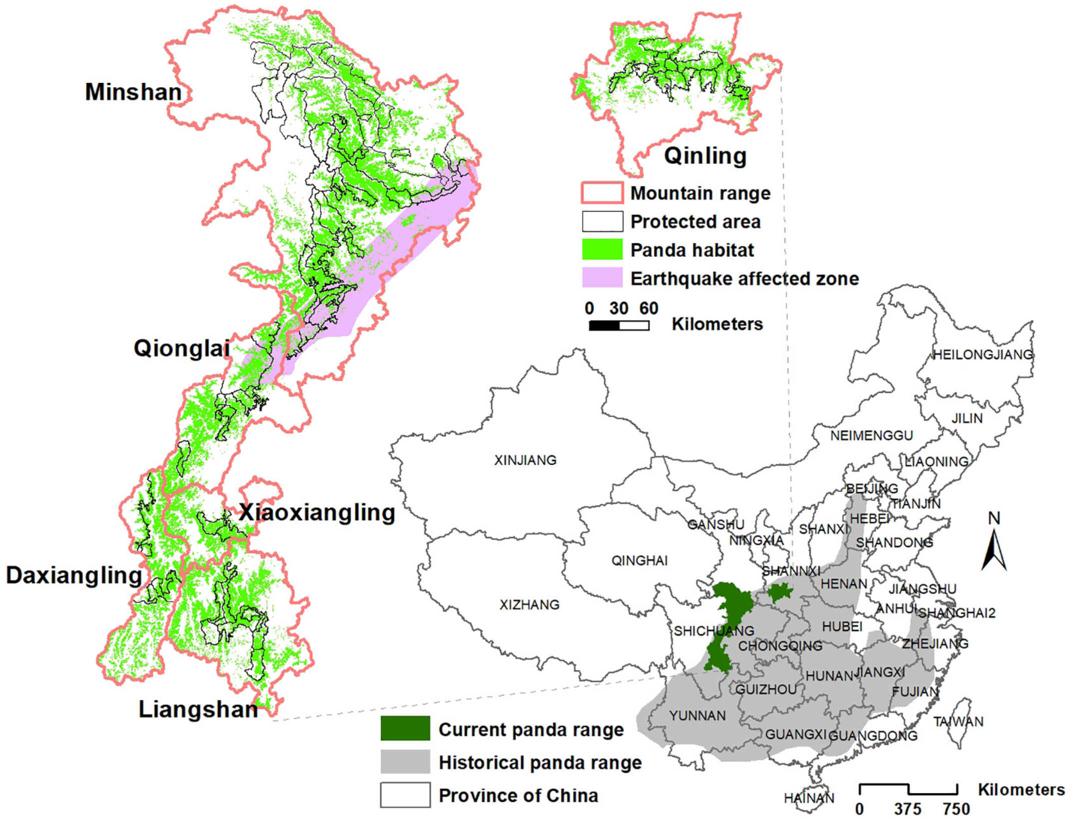

Fig. 2. The geographic range of giant pandas in Southwest China. The current geographic range of the species encompasses six mountain ranges, including Qinling, Minshan, Qionglai, Daxiangling, Xiaoxiangling, and Liangshan, across Sichuan, Gansu, and Shaanxi provinces.

Entropy (Maxent) modeling approach (Phillips et al., 2006). This approach can help map wildlife habitat quality at the range-wide scale efficiently (Yang et al., 2017). The input data for the panda habitat modeling included elevation, 11 remotely sensed vegetation phenology metrics from time-series remote sensing data, and 3239 panda presence records from the national giant panda field survey (Yang et al., 2017). Previous studies (Hull et al., 2016; Tuanmu et al., 2010, 2011) show that the vegetation phenology metrics and elevation variables can provide crucial information on key determinants of panda habitat suitability, such as forest cover and presence of bamboo. The output of the habitat modeling (occurrence probability of giant pandas) provides a measurement of habitat suitability of every 250 × 250 m pixel across the panda range, with the value ranging from 0 (lowest suitability) to 1 (highest suitability). We calculated the habitat suitability change from 2001 to 2013 and used it as the outcome variable in the evaluation of panda nature reserves' impact. Technical details regarding construction, validation, and application of the panda habitat suitability maps can be found in the previous study (Yang et al., 2017).

2.4. Estimating the impact of nature reserves on panda habitat suitability change

Land inside and outside nature reserves often have systematic differences in their biophysical conditions, such as their initial habitat status, elevation, and remoteness. Therefore, the habitat suitability changes inside and outside nature reserves are often not directly comparable. We addressed the issue and estimated the impact of panda reserves on habitat suitability change from 2001 to 2013 using the multivariate matching approach (Rubin, 1973). The purpose of using the matching method is to control for observable differences between protected pixels inside nature reserves and unprotected pixels outside nature reserves to ensure an “apple-to-apple” comparison. As compared with other approaches, such as regression and difference-in-differences, the matching method is more robust to model misspecification, has less strict assumptions, and is therefore more reliable for evaluating the impacts of PAs (Ferraro and Hanauer, 2014). The approach has been increasingly used in recent years to evaluate the impacts of PAs on land cover, poverty, and human well-being (e.g., Andam et al., 2008; Ferraro et al., 2013; Naidoo et al., 2019). These studies lay a good foundation for our research design. The matching approach also has limitations. First, the effect of control variables on the outcome (wildlife habitat quality change in this case) cannot be studied. Second, the matching approach often requires a large sample size and baseline characteristics to ensure an “apple-to-apple” comparison. However, the impact of controlled factors (e.g., elevation and terrain roughness) on habitat quality is not a focus of our study. The habitat suitability maps we obtained allow us to generate a large sample and baseline habitat suitability for reliable impact evaluation. Therefore, those limitations will not have major impacts on our study.

We randomly selected 503,927 pixels (25% of the total number of pixels) across the entire geographic range of giant pandas. We excluded pixels in the regions affected by the Wenchuan Earthquake because the earthquake generated substantial damage to panda habitats and might have affected pixels inside and outside nature reserves differently, which can bias our impact estimation. We also exclude pixels of three land cover types that are unlikely to become giant panda habitats, including water bodies, built-up areas, and barren land above the tree line. The land cover information for this exclusion was obtained from a previous study (Xu et al., 2017). Since our study focuses on the impact of nature reserves on habitat suitability change from 2001 to 2013, reserves established after 2000 ($n = 31$) were excluded from our analysis. Previous studies show that the impact of PAs may spill over to nearby unprotected land (Fuller et al., 2019). To avoid the spillover effect of nature reserves on our evaluation results, we excluded pixels close to panda reserves (distance to reserve boundary <20 km) from our evaluation. We chose 20 km as the threshold because our analysis (see Section 2.5) indicates pixels beyond this distance are unlikely to be affected by the spillover effects of nature reserves. After those exclusions, a total of 122,150 pixels were left for further analyses.

We tried two different study designs to quantify the impact of nature reserves on panda habitat suitability. In the first design, we followed previous studies (e.g., Andam et al., 2008; Zhao et al., 2019) and used all the remaining 122,150 pixels for the evaluation (Fig. 3A). One possible limitation of this design is that our study area is a mountainous region and a considerable amount of land is beyond the accessibility of people. The protection of nature reserves in those areas can generate little added value on habitat suitability due to the extremely low level of human disturbances there. Including a significant number of pixels from the land with little human disturbances in the evaluation may average out the impacts of nature reserves, make the reserves' impacts less detectable, and mask possible significant contributions of nature reserves to habitat suitability in areas susceptible to anthropogenic pressure. To address this limitation, we tried the second design and only included pixels within 5 km straight-line distance from the roads inside and outside the nature reserves ($n = 49{,}555$) to construct the groups of protected and unprotected pixels for the impact evaluation (Fig. 3B). We chose 5 km as the threshold because human residents in our study region live close to roads and a previous study (Chen et al., 2014) shows that human uses of natural resources (e.g., agricultural production and fuelwood collection) in this region mostly happen within 5 km from roads.

For each pixel within nature reserves, our matching method found a counterpart outside the reserves that is similar in terms of nine attribute variables, including habitat suitability in 2001, distance to habitat edge, elevation, slope, terrain roughness, distance to roads, distance to the nearest county capital, distance to cropland, and annual mean temperature (Table 1). To improve the matching quality, a caliper was used to constrain the difference in each of the nine covariates between protected and unprotected forest pixels to within the 0.5 standard deviation. The matching was done with replacement. Using the matched protected and unprotected pixels, the impact of the nature reserves on panda habitat suitability change was estimated by subtracting habitat suitability of unprotected pixels from that of protected pixels (also called average treatment effect on the treated). A bias-adjustment estimator (Abadie and Imbens, 2006) was used to address the potential bias in the impact estimation due to the remaining differences in the nine variables of pixel attributes between matched pixels inside and outside nature reserves.

2.5. Evaluating the spillover effect of nature reserves

To evaluate the spillover effect of the nature reserves on panda habitat suitability on nearby land, we compared habitat suitability changes of pixels within different distance ranges from the boundaries of the 36 nature reserves as suggested by previous studies (Ewers and Rodrigues, 2008; Fuller et al., 2019). Based on the distance to the boundaries of nature reserves, we classified all pixels outside reserves into five buffer groups: 0–5 km, 5–10 km, 10–15 km, 15–20 km, and > 20 km. We

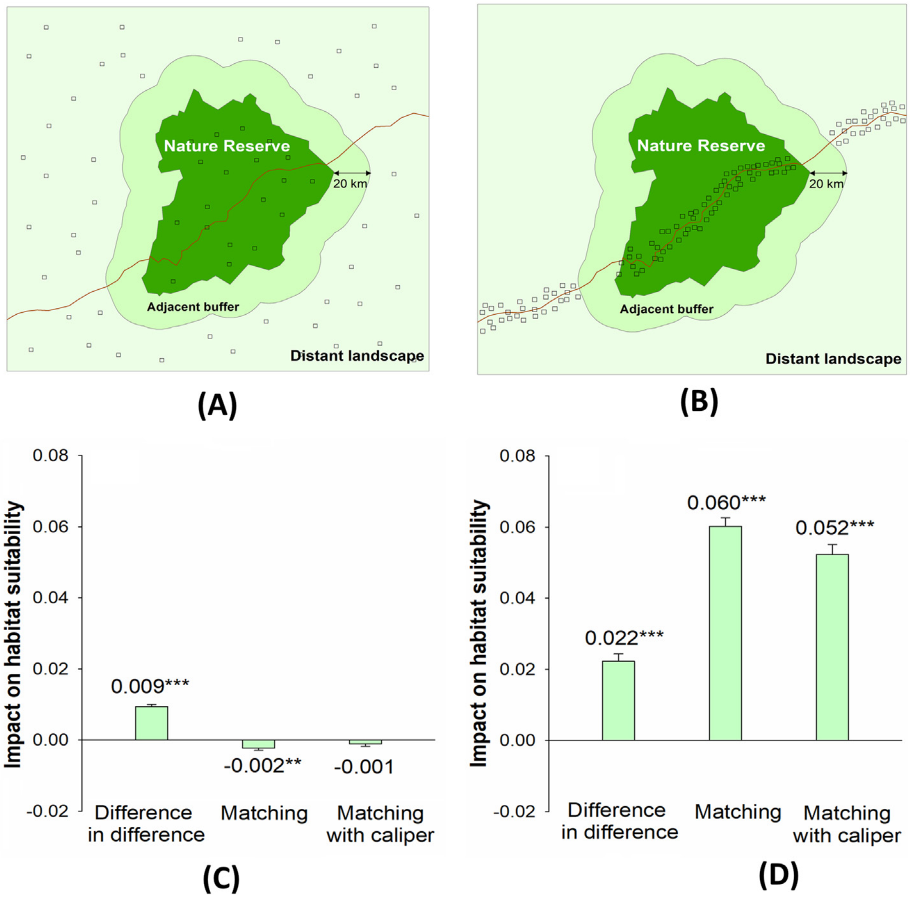

Fig. 3. Different schemes of sampling random pixel (A–B) and the corresponding impact evaluation results (C–D). (A) Sampling random pixels across the entire landscape inside and outside nature reserves; (B) Only sampling random pixels within the 5-km distance from the roads inside and outside the nature reserves. Black squares in (A)–(B) represent selected random pixels. (C) The estimated impact on habitat suitability change using the sampling scheme shown in (A). (D) The estimated impact on habitat suitability change using the sampling scheme shown in (B). The impact was estimated using difference-in-differences (comparing mean changes of two pooled samples of pixels without matchings), matching, and matching with caliper, respectively. A positive (negative) sign of the impact values indicates that the nature reserves facilitated (did not facilitate) the habitat suitability increase.

Table 1
Description of spatial data used to generate the socioeconomic and biophysical attributes of sample pixels for evaluating the impact of panda nature reserves on habitat suitability change.

Data layer	Unit	Description	Data source/format
Initial habitat suitability	Dimensionless	The habitat suitability index value in 2001.	(Yang et al., 2017)/Raster (250 m)
Distance to habitat edge	m	Straight-line distance to edge of habitat patches in 2001.	
Elevation	m	Elevation of GDEM pixels.	Aster Global Digital Elevation Map (GDEM)/Raster (30 m)
Slope	Radian	Slope calculated using GDEM elevation.	
Terrain Roughness	m	Standard deviation of GDEM elevation.	
Distance to roads	m	Straight-line distance to paved roads.	National Geomatics Center of China/Shapefile
Distance to the nearest county capital	m	Straight-line distance to the nearest county capital	
Distance to cropland	m	Straight-line distance to the nearest cropland	(Ouyang et al., 2016)/Raster (30 m)
Annual mean temperature	°C	Average annual mean temperature from 1970 to 2000.	(Fick and Hijmans, 2017)/Raster (1 km)

compared habitat suitability change in each of the first four close-range groups with that in the furthest range group (distance >20 km) using the matching approach. In each of the four comparisons, we only included pixels within 5 km from the roads. The matching procedure is the same as that used to compare protected and unprotected pixels to quantify the impact of nature reserves on habitat suitability changes. For each pixel in one of the first four close ranges, the matching method found a similar counterpart pixel in the furthest range similar in terms of nine attribute variables to estimate the difference, including initial habitat suitability, distance to habitat edge, elevation, slope, terrain roughness, distance to roads, distance to the nearest county capital, distance to cropland, and annual mean temperature. There is a spillover effect from the nature reserves if (1) statistically significant differences in habitat suitability change exist between the close ranges and the furthest range; and (2) the magnitude of the difference diminishes as distances to the nature reserves increase. To examine the robustness of the results to the distance interval used to define the pixel groups, we tried two other distance intervals, 3 km and 4 km, to define buffer groups and see whether the findings still hold. When using 3 km as the interval, we got six buffer groups (0–3 km, 3–6 km, 6–9 km, 9–12 km, 12–15 km, and 15–18 km) and compared pixels in each of them to the that in furthest range group (distance >20 km) using matching approach. When 4 km was used as the interval, we got five buffer groups (0–4 km, 4–8 km, 8–12 km, 12–16 km, and 16–20 km) and compared pixels in each of them to that in furthest range group (distance >20 km).

2.6. Comparing habitat suitability change in nature reserves with contrasting attributes

To understand the effects of nature reserves' attributes on their ability to enhance panda habitat suitability, we compared the habitat suitability changes in nature reserves with different management levels (national versus regional) and establishment age (old versus new) using the matching approach. National nature reserves are supervised by national government agencies while regional nature reserves are supervised by provincial, municipal, or county government agencies. Previous studies (e.g., Zhang et al., 2017a; Zhao et al., 2019) show that national nature reserves in China are often better funded and under stricter protection rules than regional nature reserves. The establishment age of nature reserves is another important attribute of PAs. Some studies suggest that newer PAs are better at conservation than older ones (Bowker et al., 2017) while others indicate otherwise (Andam et al., 2008). We categorized the 36 nature reserves into old and new groups for comparison using the medium establishment age (8 years as of 2001) as the threshold.

To understand the influence of livelihoods of local communities on the ability of nature reserves to enhance panda habitat suitability, we categorized and compared nature reserves based on their neighboring households' involvement in two important livelihoods: nature-based tourism and labor migration. We chose those two livelihoods because they are globally common, and previous studies (e.g., Chen et al., 2012; Yang et al., 2018b) show they can considerably affect ecosystem conservation. We included 26 nature reserves from which we collected household data. In 2015, we conducted a survey to collect information on households in communities located inside or within 10 km from the boundaries of the 26 panda nature reserves. For each community, we randomly selected about 20% of households and selected households' heads as our interviewees. The survey collected detailed household information including whether the household has member(s) participating in tourism business (e.g., operating farmer's house, working in hotels or as a tour guide) or leave to work in cities. A total of 2183 households completed our survey. The households all live close to roads (distance to roads <5 km). We categorized the 26 nature reserves into tourism and non-tourism groups based on whether there are households involved in tourism businesses. If the local community has households participating in tourism, we classified the reserve as a tourism reserve, otherwise as a non-tourism reserve. All 26 nature reserves have households with labor migrants. We therefore categorized the 26 nature reserves into groups with high and low labor migration using the medium value of proportion (0.54) of households having labor migrants across the 26 nature reserves as the threshold. Nature reserves where the local community has more than 54% of households with at least one labor migrant were classified as the high labor migration group, and the other as low labor migration group.

We compared the habitat suitability changes of the random pixels in the nature reserves with contrasting attributes (national versus regional, old versus new, tourism versus non-tourism, high versus low labor migration) using the matching method. Similar to estimating the impact of nature reserves on panda habitat suitability, the goal of the matching method in the comparison of pixels in nature reserves with contrasting attributes is to ensure they are comparable. The attributes we controlled for in each comparison are the same as in the impact evaluation as listed in Table 1. Only pixels within 5 km from the roads were included in the comparisons. The major steps of data analyses were summarized in Fig. 4. We performed all the matching analyses in R (R Core Team, 2020) using the 'Matching' package (Sekhon, 2011). After matching, the differences in the covariates in each of the analyses substantially decreased toward zero (Tables S1–S10), indicating good matching quality for reliable estimation.

3. Results

3.1. Impact of nature reserves on habitat suitability

Our results (Fig. 3) show that using random pixels across the entire landscape in the impact evaluations can mask the significant contribution nature reserves make to habitat suitability in areas susceptible to human disturbances. Results of the study design that used random pixels across the entire panda range show that nature reserves did not have any positive impact on habitat suitability (Fig. 3C). The impact estimates using the matching approach with and without caliper are negative and small (−0.002 and −0.001 respectively), suggesting the nature reserve did not improve habitat suitability. In the design that only used pixels with distance to roads smaller than 5 km, the impact

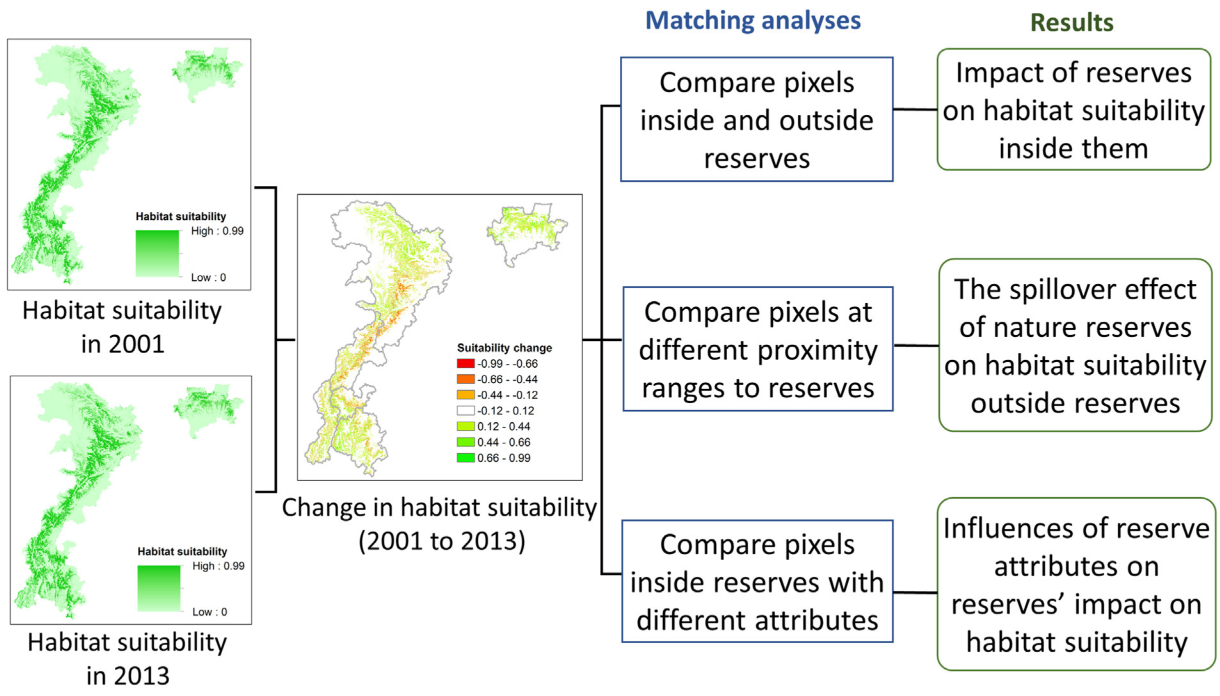

Fig. 4. Methodological steps. Flow chart depicting the major steps in the procedures used in the study. For details, see Materials and methods.

estimates using matching with and without caliper imply that protection by nature reserves significantly increased the habitat suitability by 0.052 and 0.06 respectively ($p < 0.001$) (Fig. 3D), which accounts for 65% and 75% of the total habitat suitability increase from 2001 to 2013 (0.08) inside the nature reserves respectively. The distinct results from the two study designs indicate that using random pixels across the entire landscape can mask the significant contribution of nature reserves provide to habitat suitability in areas susceptible to human disturbances. We also found the impact estimated using the traditional difference-in-differences approach (comparing means of two pooled samples of pixels without matchings) is small (0.022) (Fig. 3D). It is less than half of that using the matching approach, suggesting it is important to control for systematic differences between protected and unprotected land to avoid biased impact estimations.

3.2. Spillover effect of nature reserves on habitat suitability

The nature reserves generated a positive spillover impact on habitat suitability in nearby land. The results (Fig. 5) show that the habitat suitability in the first three close ranges (distance to reserves smaller than 5 km, from 5 km to 10 km, and 10 km to 15 km) increased significantly more than in the furthest range (distance to reserves >20 km). As the distance to nature reserves increase, the magnitude of the difference decreases rapidly and become statistically non-significant ($p > 0.05$), indicating the nature reserves generated a positive spillover effect on the habitat suitability. In other words, the establishment of nature reserves not only benefited panda habitat inside them but also the habitat on the nearby unprotected land. The results using 3 km and 4 km to define the buffer groups yield a similar pattern (Fig. S2): the impact of being close to reserves on habitat suitability is positive and the magnitude of the impact diminishes as the distance to the reserves increases. This indicates our finding that the nature reserves generated positive spillover effect on panda habitats outside nature reserves are robust to the way we define the pixel groups to evaluate the spillover effect.

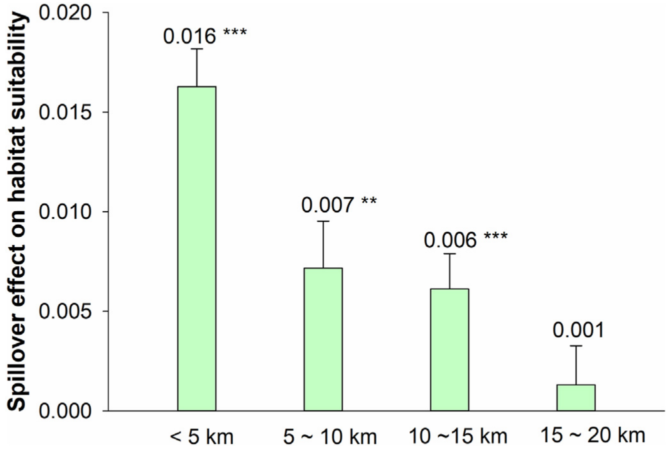

Fig. 5. Spillover effects on habitat suitability change at different proximity ranges to the boundaries of nature reserves. Statistical significance: *** $p < 0.001$, ** $p < 0.01$.

3.3. Habitat suitability changes in reserves with contrasting attributes

The attributes of panda nature reserves showed significant influences on their performance in improving panda habitat suitability. The national nature reserves or older reserves showed higher habitat suitability increases than their counterparts that are supervised by local governments or established more recently. Being a national nature reserve on average increased the habitat suitability by 0.022 (Table 2), which accounts for 21.9% of the total suitability increase in national nature reserves (0.1) ($p < 0.001$). The habitat suitability increase of older nature reserves is higher than in the newer ones by 0.014 ($p < 0.001$) (Table 2), accounting for 16% of the habitat suitability increase in the older reserves.

The intercouplings linking the panda nature reserves and other places, including the inflow of tourists and outflow of labor migrants, also have significant influence on nature reserves' impacts on habitat quality. Local households' involvement in tourism and labor migration showed positive influences on nature reserves' ability to enhance habitat suitability. Habitat suitability increase in nature reserves with households participating in tourism business or that have more labor migration is significantly higher than in non-tourism nature reserves ($p < 0.001$) or nature reserves with less labor migration ($p < 0.01$) (Table 2).

4. Discussion

Our results suggested that China's nature reserves played an important role in improving panda habitat sunitability. Although previous studies (Viña and Liu, 2017; Yang et al., 2017) show more gains in forest and panda habitats outside nature reserves than inside, our study shows that panda reserves significantly increased panda habitat quality, highlighting the importance to control confounding factors in the impact evaluation. We also found the impact of nature reserves is concentrated in areas susceptible to human pressure (distance to roads <5 km), where 65% of the habitat suitability gains are attributable to reserve protection. Furthermore, we found the impacts of nature reserves spilled over to nearby areas and improved habitat suitability beyond their boundaries. Possible reasons behind the positive spillover effect of nature reserves might include improvement in the environmental awareness of neighboring communities, which may have reduced the collection of natural resources. Another reason might be the development of tourism in nature reserves, which may have promoted the livelihood shifts of the neighboring communities from on-farm to off-farm activities and reduced human disturbances to panda habitats (Liu et al., 2016b; Yang et al., 2018b). These results provide important evidence to justify the unique value of nature reserves and the establishment of the new Giant Panda National Park. The new park will receive substantial investment from the central government to combine and expand the existing panda nature reserves to increase their coverage and consolidate the conservation management (Huang et al., 2020; Li et al., 2016).

Our study also highlights the importance of considering the spatial heterogeneity of the impact of PAs in the impact evaluation design. Comparing socioecological outcomes inside and outside PAs is a major approach for evaluating their impacts. However, the impact of PAs can be highly heterogeneous across the landscape. If a large amount of land with little human pressure were included in the evaluation of PAs' impact, the impact may be averaged out and generate misleading conclusions. In our case, the nature reserves cover a large amount of remote land where the protection of nature reserves can make little difference in panda habitat suitability change. Our results show that including those areas in the impact evaluation can mask the significant contribution of nature reserves to panda habitat suitability in areas with high anthropogenic pressure and lead us to conclude that the reserves have little impact on panda habitat suitability. However, we note that nature reserves may prevent habitat degradation on currently remote land in the future. Therefore, keeping remote land under protection remains important for giant panda conservation in the long term.

Management level and establishment age of nature reserves played a role in their ability to improve panda habitat suitability. Our results show that national nature reserves had a larger impact on panda habitat suitability than regional ones. This might be because national nature reserves are often managed more rigorously and received more manpower and financial sources than regional nature reserves (Wu et al., 2018). The new Giant Panda National Park will integrate all the existing nature reserves and will report directly to a new management agency, the National Park Administration in the central government (Huang et al., 2020). This structural reform may help panda conservation receive more support and achieve better panda habitat suitability improvement, especially for the areas previously managed by regional nature reserves (Huang et al., 2020). Our results also show that older nature reserves exhibited higher performance in improving habitat suitability than newer ones. This difference suggests there might be a time lag in the impact of panda nature reserves on habitat suitability. One possible reason for the delay in the impact is that it often takes time for nature reserves to fully function and for local households to know and follow the new regulations of the nature reserves.

Livelihoods of neighboring households exhibited significant influence on nature reserves' impact, which highlights the importance of socioeconomic management for improving the performance of PAs. To maximize the beneficial impact of nature-based tourism and labor migration on the panda habitats which was found in this study, we would suggest government help local farmers overcome the barriers that prevent them from benefiting from those off-farm activities. For example, previous studies (e.g., Wong et al., 2007; Zhong et al., 2016) show that migrant workers in cities usually find it hard to bear the high living expenses, confront an unfair education system for their children, and lack a sense of belonging. Studies on nature-based tourism (He et al., 2008; Kiss, 2004) suggest that benefits from tourism development often go to tourism companies and government rather than local communities because local communities often lack the skills, knowledge, and financial support to benefit from tourism. Therefore, management interventions that can help to overcome these barriers may enhance the beneficial effects of tourism and labor migration on the performance of nature reserves. Example measures may include providing training to households to develop skills necessary for them to start their own tourism businesses and investing more resources for better education of labor migrants' children in cities. Those measures may also reduce households' dependence on farming and livestock husbandry and diminish the risk of human-wildlife conflicts, such as crop raiding and livestock predation. This is important because the recovery of panda habitats also facilitates the population growth of other species that may cause human-wildlife conflicts such as wild boar (*Sus scrofa*) and Asian black bear (*Ursus thibetanus*) (Yang et al., 2020).

5. Conclusion

With the escalating pressures from human activities, it is essential to evaluate the performance of PAs in achieving desired conservation outcomes and understanding the factors shaping their performance. Wildlife habitat quality is critical for biodiversity conservation, but the impact of PAs on habitat quality has not been adequately evaluated. By integrating wildlife habitat mapping and information of 2183 rural households, we provide an integrated assessment of the impact of China's nature reserves on the habitat suitability change of giant pandas. We found the nature reserves have played a unique role in enhancing the habitat quality even beyond their boundaries. The impact of the nature reserves was influenced by their attributes as well as the livelihood activities of their neighboring communities. Those findings have implications for guiding PAs to take explicit measures to improve their performance in protecting the habitats of giant pandas. While the impacts of PAs on habitats of other species will vary across places, the evaluation

Table 2
Influence of four attributes of nature reserves on their ability to improve panda habitat suitability, including the management level (national versus regional), establishment age (old versus new), tourism development (with versus without tourism), and labor migration (high versus low proportion of households having members leaving for job in cities).

Type of nature reserves	Number of nature reserve in each type	Mean habitat suitability change	Difference in habitat suitability change
National vs. regional	[17, 19]	[0.10, 0.036]	0.022^{***}
Old vs. new	[16, 20]	[0.085, 0.066]	0.014^{***}
With tourism vs. without tourism	[13,13]	[0.070, 0.052]	0.021^{***}
High vs. low labor migration	[12, 14]	[0.092, 0.049]	0.030^{**}

$^{***}p < 0.001$, $^{**}p < 0.01$. The difference in habitat suitability change from 2001 to 2013 (column 4) was estimated using the matching approach, which controlled the biophysical differences between the pixels in different types of nature reserves in each of the four comparisons. Positive difference values indicate that nature reserves in the first categories outperformed in the second categories in improving the panda habitat suitability.

approach used in this study can be easily adapted to other contexts and inform conservation management in China and many other places around the world.

CRediT authorship contribution statement

Hongbo Yang: Conceptualization, Methodology, Data curation, Formal analysis, Writing- original draft. **Qiongyu Huang:** Investigation, Writing – review & editing, Project administration. **Jindong Zhang:** Data curation, Writing – review & editing. **Melissa Songer:** Writing – review & editing, Investigation, Supervision. **Jianguo Liu:** Conceptualization, Data curation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors have no conflict of interest to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145081.

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