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Effects of protected areas on survival of threatened gibbons in China

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Abstract: Establishing protected areas (PAs) is an essential strategy to reduce biodiversity loss. However, many PAs do not provide adequate protection due to poor funding, inadequate staffing and equipment, and ineffective management. As part of China's recent economic growth, the Chinese government has significantly increased investment in nature reserves over the past 20 years, providing a unique opportunity to evaluate whether PAs can protect threatened species effectively. We compiled data from published literature on populations of gibbons (Hylobatidae), a threatened taxon with cultural significance, that occurred in Chinese reserves after 1980. We evaluated the ability of these PAs to maintain gibbon habitat and populations by comparing forest cover and human disturbance between reserves and their surrounding areas and modeling the impact of reserve characteristics on gibbon population trends. We also assessed the perspective of reserve staff concerning PA management effectiveness through an online survey. Reserves effectively protected gibbon habitat by reducing forest loss and human disturbance; however, half the reserves lost their gibbon populations since being established. Gibbons were more likely to survive in reserves established more recently, at higher elevation, with less forest loss and lower human impact, and that have been relatively well studied. A larger initial population size in the 1980s was positively associated with gibbon persistence. Although staff of all reserves reported increased investment and improved management over the past 20–30 years, no relationship was found between management effectiveness and gibbon population trends. We suggest early and emphatic intervention is critical to stop population decline and prevent extinction.

Keywords: brake effect, gibbon, habitat, Hylobatidae, nature reserve, population trends, protected area management effectiveness

Efectos de las Áreas Protegidas sobre la Supervivencia de Gibones Amenazados en China

Resumen: El establecimiento de áreas protegidas (APs) es una estrategia esencial para la reducción de la pérdida de la biodiversidad. Sin embargo, muchas APs no proporcionan una protección adecuada debido a un mal financiamiento, personal y equipamientos inadecuados y un manejo poco efectivo. Como parte del reciente crecimiento económico en China, el gobierno del país ha incrementado significativamente la inversión en las reservas naturales durante los últimos 20 años, proporcionando así una oportunidad única para evaluar si las APs pueden proteger a las especies amenazadas de manera efectiva. Recopilamos datos de la literatura publicada sobre las poblaciones de gibones (Hylobatidae), un taxón amenazado que cuenta con importancia cultural, que se presentaron en las reservas chinas después de 1980. Evaluamos la habilidad de estas APs para mantener el hábitat y las poblaciones de gibones al comparar la cobertura del bosque y la perturbación humana entre las reservas y las áreas vecinas y al modelar el impacto de las características de la reserva sobre las tendencias poblacionales de los gibones. También evaluamos la perspectiva del personal de la reserva con respecto a la efectividad en el manejo de la AP por medio de una encuesta en línea. Las reservas protegieron efectivamente al hábitat de los gibones

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mediante la reducción de la pérdida del bosque y de la perturbación humana; sin embargo, la mitad de las reservas perdieron su población de gibones desde su establecimiento. Los gibones tuvieron mayores probabilidades de sobrevivir en las reservas establecidas más recientemente, a una elevación más alta, con menor pérdida de bosque y menor impacto humano, y las cuales han sido relativamente bien estudiadas. Un tamaño de población inicial mayor durante la década de 1980 estuvo asociado positivamente con la permanencia de los gibones. Aunque el personal de todas las reservas reportó un incremento en la inversión y mejoras en el manejo durante los últimos 20–30 años, no encontramos una relación entre la efectividad en el manejo y las tendencias poblacionales de los gibones. Sugerimos que una intervención temprana y empática es crítica para detener la declinación poblacional y prevenir la extinción.

Palabras Clave: efectividad en el manejo de áreas protegidas, efecto de frenado, gibón, hábitat, Hylobatidae, reserva natural, tendencias poblacionales

摘要: 建立保护区是缓解生物多样性丧失的重要手段。然而, 因为缺乏资金、人员和设备, 以及缺乏有效的管理, 很多保护区并没有为生物多样性提供足够的保护。过去 20 年中, 随着中国经济的发展, 中国政府极大地增加了对保护区的投入, 为我们提供了独特的机会来评估保护区能否有效地保护濒危物种。长臂猿科的物种均属于濒危物种, 在中国具有重要的文化意义。我们从已发表的文献中收集了 1980 年后生活在保护区内的长臂猿种群相关数据, 并评估了这些保护区能否维持长臂猿的种群和栖息地。我们比较了保护区与其周边地区的森林覆盖率和人为干扰, 并使用模型分析了影响长臂猿种群变化的保护区特征。同时, 我们通过线上问卷调查了保护区员工对于其所在保护区管理有效性的评价。结果显示, 保护区通过减少森林丧失和人为干扰, 能够有效地保护长臂猿的栖息地; 然而同时, 长臂猿在将近一半的保护区中消失了。长臂猿更多地存活在在较近成立的, 具有更高的海拔、更少的森林丧失、更少的人为干扰, 以及更多的科学研究的保护区中, 80 年代起始种群更大的长臂猿种群也更有可能存活下来。虽然所有保护区的员工均表示在过去 20–30 年间, 其所在保护区的投入和管理有效性均在增加, 但我们没有发现管理有效性和长臂猿种群变化趋势之间存在相关性。我们建议, 对濒危物种进行尽早且有力的干预, 对于制止种群下降、防止灭绝具有重要的作用。

Introduction

Establishment of protected areas (PAs) is a fundamental global strategy to reduce biodiversity loss (Margules & Pressey 2000; Jenkins & Joppa 2009). Protected areas can be effective in reducing habitat loss and stopping declines of threatened wildlife populations (Geldmann et al. 2013). However, many PAs have not functioned as expected for various reasons, including lack of funding, staffing, equipment, and training and ineffective management (Laurance et al. 2012; Watson et al. 2014). The most extreme examples are PAs with little or no formal management that do not provide adequate protection for biodiversity and exist only at the legislative level (Curran et al. 2004). Therefore, in addition to increasing the number and area of PAs, improving their effectiveness is imperative to the success of biodiversity conservation.

China is a huge country with a diverse range of land-cover types that support exceptionally rich biodiversity, including over 6000 vertebrate species (Xu et al. 1999). However, it also has the world's largest human population and faces a serious biodiversity crisis following decades of rapid economic growth (Ouyang et al. 2016; Liu et al. 2018). To reduce biodiversity loss, China has established many nature reserves (the most common type of PA in China); as of 2017, 2750 nature reserves had been established (Xu et al. 2019). Together with other types of PAs, they cover 20% of China's terrestrial area (Ouyang et al. 2018), approximately equivalent to the area of Peru or 3 times the area of Spain or California. China has also increased financial investment in its reserves, US$5.50/ha in 2009 (Li et al. 2013). However, the effectiveness of China's reserves in conserving biodiversity has been evaluated rarely (Quan et al. 2011; Ren et al. 2015).

Among the few species in China for which the effectiveness of conservation actions has been evaluated is the iconic giant panda (*Ailuropoda melanoleuca*) (Kang & Li 2018). Giant pandas receive tremendous conservation investment (currently ~US$140 million/year for *in situ* conservation), are of great public interest, and are extremely well researched (Wei et al. 2012; Swaisgood et al. 2018; Li 2020). However, even the flagship reserves for pandas have not protected panda habitat effectively (Liu et al. 2001; Li et al. 2017). Although recent assessment shows that panda populations and habitats have benefited greatly from reserves (Wei et al. 2020), total panda population size and habitat area have not recovered to pre-1988 levels (Wei et al. 2018). This high-profile example raises concerns that conservation actions for species receiving less attention or investment may be even less effective.

Gibbons (Hylobatidae) are small arboreal apes that require intact forest canopy habitat. They were once widely distributed across China and were culturally significant animals in ancient China (Fan 2017; Turvey et al. 2018). Their distribution has contracted dramatically over the past 400 years due to habitat loss and hunting (Chatterjee et al. 2012; Turvey et al. 2015; Fan 2017). Populations of 6 gibbon species survived in fragmented forests in 3 southwestern Chinese provinces (Guangxi, Hainan, and Yunnan) into the 1980s (Fan 2017). To protect these remnant gibbon populations and their habitat, the Chinese government established dozens of reserves, and >80% of gibbon populations currently occur in PAs (Fan 2017). Since 1989, all gibbons have been listed as class I protected animals in China. Nonetheless, some populations continued to decline, and 2 species were recently extirpated in China (Grueter et al. 2009; Fan et al. 2014). It is therefore essential to evaluate the effectiveness of reserves for gibbon conservation in China and to assess why different conservation efforts have had such varying levels of success.

We compiled data on changes in site-specific population size for all 6 gibbon species that occurred after 1980 in China and assessed the effectiveness of reserves on preserving gibbon habitat and populations. We then surveyed staff across reserves with extirpated or extant gibbon populations to determine whether perceived effectiveness of management explained variation in gibbon population trends. We aimed to evaluate whether PAs have reversed population declines and halted loss of these species as an indicator of the success of PAs in China.

Methods

We compiled data on the distribution and status of all known recently extant (after 1980) gibbon populations in China and on the location, age, and administration level (national, provincial, and county) of all Chinese reserves where gibbons survive today or have recently occurred from published literature (Appendix S1). Some reserves consist of discrete management areas that were founded in different years or are managed by different agencies. We considered these areas separately. Reserve boundaries were downloaded from the World Database on Protected Areas (WDPA) (https://protectedplanet.net/) and were modified when necessary after consulting reserve staff.

Effects of Reserves on Gibbon Habitat

To test whether reserves have effectively conserved gibbon habitat, we obtained forest data at 30-m resolution from Global Forest Change 2000−2018 (https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.5.html). We compared overall forest cover in each reserve with forest cover in a 5-km area surrounding each reserve (hereafter buffer zone) in 2000 and calculated percent forest loss from 2000 to 2018. We also compared human footprint index (NASA Socioeconomic Data and Applications Center, https://sedac.ciesin.columbia.edu/data/set/wildareas-v3-1993-human-footprint) (a comprehensive index of human pressure on the environment at 1-km resolution) values for 1993 and 2009 between reserves and buffer zones. We used nonparametric Mann–Whitney *U* tests to conduct comparisons.

Effects of Characteristics of Reserves on Gibbon Populations

We used a logistic regression model to assess the impacts of reserve characteristics on presence or absence of gibbon populations after 2010 (dependent variable). Uncertain or unverified reports of local gibbon persistence (e.g., Turvey et al. 2017) were not accepted as evidence for continued gibbon survival. Reserves or specific management areas established after gibbons had been extirpated were excluded.

We selected 12 variables based on previous studies that showed a correlation with persistence of wildlife populations in PAs (Table 1). We calculated mean elevation and mean annual temperature of each reserve in ArcGIS 10.3.1, based on 90-m resolution DEM data from SRTM 4 (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp) and 30 arc-seconds resolution temperature data from WorldClim (http://worldclim.org/version2), respectively. We also calculated mean topographic ruggedness index (TRI) (Riley et al. 1999) derived from the DEM data. We collected publications about reserves and their gibbon populations by searching the China National Knowledge Infrastructure (http://www.cnki.net/) and Web of Science (http://apps.webofknowledge.com). The size of gibbon populations in the 1980s was obtained from published literature (Appendix S2).

All numerical independent variables were tested for collinearity prior to regression analysis. Elevation and temperature were significantly correlated ($r = -0.978$, $p < 0.001$), as were forest cover in 2000 and TRI ($r = -0.761$, $p < 0.001$). We retained elevation and forest cover in 2000 in the set of independent variables.

Because our sample size was small ($n = 18$), we considered only 1 variable for each model and calculated AICc values. Models with ≤ 2 ΔAICc were considered to have an equivalent support as the best model with the smallest AICc value (Burnham & Anderson 2002). We then calculated Akaike weight (ω_i) for each model. Because no single model had an ω_i over 0.9, we averaged top models that had a cumulative $\omega_i > 0.9$ to obtain the coefficient and SE for each variable that was contained in top models. Relative importance of variables was determined based on ω_i of the top models, and variables with SE larger than the absolute value of coefficient were excluded from the final model. We used the area under the receiver operating characteristic curve (AUC) to determine performance of the final model: 1.0 was perfect discrimination ability and 0.5 was no discrimination ability (Pearce & Ferrier 2000).

Table 1. Independent variables included in logistic regression models investigating characteristics of nature reserves associated with gibbon persistence into the 2010s.

Reserve variable	*Abbreviation*	*Prediction*	*Reference*	*Data source, resolution*
Administrative level: national, provincial, county*	LEV	High-level reserves have stricter regulations and so provide greater protection to gibbon populations.	Dudley 2008	reserve websites, NA
Age (years)	AGE	Age of reserve positively correlates with gibbon population survival.	Claudet et al. 2008; Phoonjampa et al. 2011	reserve websites, NA
Mean elevation of reserve (m)	ELE	High elevation has negative impact on gibbon populations due to food limitation.	Fan & Jiang 2010	SRTM v4, 90 m
Mean topographic ruggedness index within reserve	TRI	More rugged terrain is beneficial to gibbon survival.	Li et al. 2014; O'Neil et al. 2020	calculated from SRTM DEM v4, 90 m
Mean annual temperature (°C)	TEM	Low temperature has negative impact on gibbon populations.	Fan et al. 2013	WorldClim, 30 arc-seconds
Forest cover in 2000	FOR	High forest cover provides better quality habitat for gibbons.	Phoonjampa et al. 2011	Global Forest Change 2000−2018, 30m
Forest loss during 2000–2018 (%)	FOL	Forest loss has a negative impact on gibbon populations.	Phoonjampa et al. 2011	Global Forest Change 2000−2018, 30 m
Human footprint index change 1993–2009 (%)	HFI	Human disturbance has a negative impact on gibbon populations.	Fan & Jiang 2010	NASA Socioeconomic Data and Applications Center, 1km
Number of papers published in Chinese and English referring to reserve and its gibbon population	PAP	Scientific research benefits threatened species conservation.	Hu et al. 2019	China National Knowledge Infrastructure, Web of Science, NA
Size of gibbon populations in the 1980s	POP	Small populations are more likely to become extinct.	Saccheri et al. 1998	published literature (Appendix S1)

**Including 3 variables: current administration level, level at reserve establishment, and whether reserve had been upgraded.*

Effects of Reserve Management Effectiveness on Gibbon Populations

We conducted an online survey of PA staff on reserve management effectiveness (https://wj.qq.com/s2/4828422/a27a/; Appendix S3). The survey was voluntary and anonymous, and we followed ethical guidelines provided by Vanclay et al. (2013).

The questions were based on the Management Effectiveness Tracking Tool, one of the most widely used systems to assess management effectiveness of PAs, and on the Technical Regulations for the Management Effectiveness Evaluation of Nature Reserves (LY/T 1726–2008) published by the State Forestry Administration of the People's Republic of China. We included 39 questions in 4 groupings (following Geldmann et al. 2017): group A, design and planning (9 questions); group B, monitoring and enforcement (11 questions); group C, capacity and resources (9 questions); and group D, decision-making arrangement (10 questions). We contacted reserve staff and asked them to recall information from the 1980s, 1990s, 2000s, and 2010s and then to fill out the questionnaire by self-scoring the performance of their reserves during each decade. Scores were integers and represented reserve performance from worst (0) to best (3). We provided a criterion for each score alongside the questions.

We aimed to find 3 respondents from each reserve and recorded the years when they were employed. For each participant, we summed the scores of all 39 questions, and the scores of questions included in each of the 4 groupings during each decade. We included scores only from participants for the decades during which they worked at their reserve. We calculated mean scores across all participants from the same area and used these values as indices of management effectiveness. We used a Friedman rank-sum test with a post hoc Conover test to compare these scores across different decades to determine change in reserve management effectiveness over time. Because only 5 areas had staff who had worked there since the 1980s, data from these 5 sites only were used to compare scores from the 1980s onward. Data for more reserves or management areas were available from the 1990s onward, so we conducted an additional comparison for this time series.

We then assessed the relationship between change of management effectiveness scores and gibbon population trends. Population trends were determined by comparing available estimates of gibbon populations between contiguous decades (based on data listed in Appendix S1) and classified as decreasing (estimates in the latter decade were smaller than those in the former decade without range overlap), stable (estimates with range overlap), or increasing (estimates in the latter decade were larger without range overlap). Because there were very few population trends classified as stable or increasing, we combined these 2 categories as not decreasing. We then calculated change of management scores, as well as percent change between those contiguous decades in which gibbon population trends were determined. We used a Mann–Whitney U test to compare mean scores for all questions and for questions in the 4 groupings between decreasing and not decreasing trends.

All analyses were conducted in R 3.5.0 (R Core Team 2016) with the packages ggplot2 (Wickham 2016), MuMIn (Bartoń 2016), usdm (Naimi et al. 2014), PMCMR (Pohlert 2014), raster (Hijmans 2020), and ROCR (Sing et al. 2005).

Results

Change in Gibbon Survival and Population Size in Reserves

Gibbon populations recently occurred in areas covered today by 24 reserves or 32 distinct reserve management areas (Appendix S1). Huanglianshan used to contain both northern white-cheeked gibbon (*Nomascus leucogenys*) and western black crested gibbon (*N. concolor*), but both species are now extirpated. Nangunhe used to contain both lar gibbon (*Hylobates lar*) and *N. concolor* in separate areas, but now it contains only about 2 groups of *N. concolor*. Other reserves or management areas have only, or used to have only, 1 gibbon species.

Most reserves or management areas (63%) were established in the 1980s; 7 were established after gibbons were extirpated in previous decades. The status of gibbon populations could not be determined at the time of establishment of 4 reserves or management areas. Gibbons were extirpated in 10 areas after their establishment. Only 11 areas retained gibbons into the 2010s.

Among the 32 management areas, 21 had been upgraded since their establishment. Twenty of these were upgraded from provincial to national reserves, and 1 was upgraded from a county to a provincial reserve (Appendix S1). Upgrades occurred 13.7 (SE 1.7, range: 3−28) years after reserves were founded in 1999 (SE 2, range: 1986−2014). Among the 10 areas where gibbons were extirpated after reserve establishment, 6 had been upgraded. However, gibbons were extirpated in 4 areas before reserves were upgraded. Eight out of 11 areas where gibbons survived into the 2010s had been upgraded, and the percentage of upgraded reserves in this group was not different from that in the group of reserves where gibbons were extirpated ($\chi^2 = 0.077$, $df = 1, p = 0.782$).

Effects of Reserves on Gibbon Habitat

Forest cover in 2000 was higher in reserves than in the buffer zones surrounding each reserve (mean

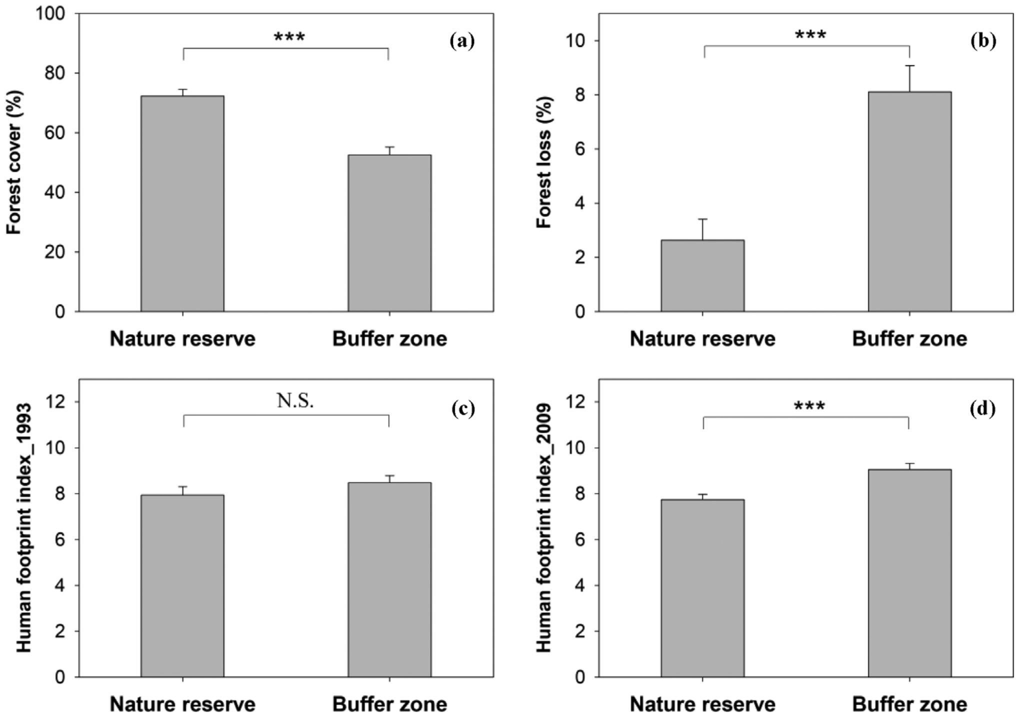

*Figure 1. (a) Forest cover in 2000, (b) percent forest loss from 2000 to 2018, and human footprint index in (c) 1993 and (d) 2009 in nature reserves and within 5 km of their borders (***, significant difference at $p < 0.001$; N.S., no significant difference).*

[SD] = 72.3 [2.2] vs. 52.6 [2.6], $W = 867$, $p < 0.001$) (Fig. 1a), and percent forest loss was higher in buffer zones than in reserves (mean [SD] = 2.63 [0.78] vs. 8.11 [0.97], $W = 128$, $p < 0.001$) (Fig. 1b). We found no difference in human footprint index between reserves and buffer zones in 1993 (mean [SD] = 7.95 [0.36] vs. 8.48 [0.31], $W = 423$, $p = 0.234$) (Fig. 1c), but there was a significant difference in 2009 ($p < 0.001$) (Fig. 1d); human impact in reserves (7.74 [0.23]) was less than in buffer zones (9.05 [0.26]).

Effects of Reserve Characteristics on Gibbon Populations

Six of the 10 independent variables had significant impacts on gibbon survival into the 2010s and were retained in the final models (Tables 2 & 3). The AUC for the final model was 0.975, indicating good discriminatory ability. In general, gibbons were more likely to survive in more recently established reserves and in reserves at higher elevations. Percent forest loss and percent human footprint index change were negatively correlated with gibbon survival, and number of papers published was positively correlated with gibbon survival. Gibbon populations with a larger initial size in the 1980s were also more likely to survive into the 2010s. Forest cover and reserve administration level (either current or at establishment) and whether a reserve had been upgraded were not correlated with gibbon survival.

Effects of Reserve Management Effectiveness on Gibbon Populations

Sixty people from 21 reserves or management areas participated in our survey. Excluding records without clear reserve or management area identification, we retained 49 records from 19 areas (mean = 2.6 participants/area, range: 1–6). Participants had worked in their reserves for a mean (SE) of 14.7 (1.5) years.

Management-effectiveness scores increased over time (all $p \leq 0.003$) from the 1980s onward (5 areas) (Fig. 2a; Appendix S4) and from the 1990s onward (13 areas) (Fig. 2b; Appendix S4). No changes in score or percent changes between contiguous decades (either of all questions or of question groupings) differed between decreasing ($n = 8$) and not decreasing ($n = 4$) gibbon populations in corresponding decades (all $p > 0.05$) (Appendix S5). This result indicated there was no significant relationship between trends of gibbon populations and change or percent change of management scores (of all questions or of question groupings).

Discussion

Over 80% of China's gibbons now live inside reserves (Fan 2017). Although we found that reserves were effective in protecting gibbon habitat by reducing forest loss

Table 2. Logistic regression models[a] explaining presence or absence of gibbons in 18 reserves or management areas after 2010 based on 10 independent variables.

Variable	*Log likelihood*	AIC_c	ΔAIC^b	$\omega_i{}^c$
Elevation (m)	−9.37	23.535	0.000	0.228
Reserve age (years)	−9.38	23.555	0.019	0.226
No. of peer-reviewed articles	−9.45	23.707	0.171	0.210
Forest loss (%)	−9.93	24.660	1.125	0.130
Gibbon population size in 1980s	−10.32	25.448	1.913	0.088
Human footprint index change (%)	−10.71	26.213	2.678	0.060
Forest cover in 2000 (%	−10.98	26.750	3.215	0.046
Administration level when founded	−11.75	28.308	4.773	0.020
Whether reserve had been upgraded[d]	−12.14	29.074	5.538	0.014
Current-day administration level	−12.34	29.475	5.940	0.011

[a] *Ranked by Akaike information criterion with small-sample correction (AIC_c).*
[b] *Difference in AICc values between each model and the best model.*
[c] *Akaike weight.*
[d] *Administration level of many reserves upgraded during 1980s to 2010s (e.g., from county to provincial, from provincial to national).*

Table 3. Model-averaged coefficients and relative importance of variables for logistic regression models analyzing variables associated with presence or absence of gibbons in 18 reserves or management areas after 2010.

Variable	*Coefficient*	*SE*	*Relative importance based on* $\omega_i{}^*$
Intercept	0.312	2.881	
Elevation (m)	0.002	0.001	0.242
Reserve age (years)	−0.113	0.062	0.240
No. of peer-reviewed articles	0.370	0.304	0.223
Forest loss (%)	−0.941	0.588	0.138
Gibbon population size in 1980s	0.018	0.012	0.093
Human footprint index change (%)	−9.968	6.111	0.064

**Akaike weight.*

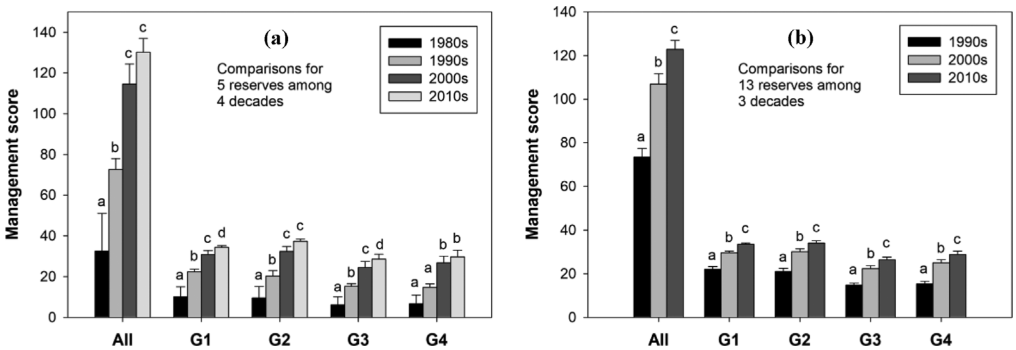

Figure 2. Mean management scores based on responses of nature reserve staff to an online survey for all questions and for 4 question groupings (G1, design and planning; G2, monitoring and enforcement; G3, capacity and resources; G4, decision-making arrangement) over time. Differing lowercase letters indicate significant differences at $p < 0.05$.

and human impacts, they were not protecting gibbon populations well. Almost half of the reserves in China that formerly contained gibbons have lost these populations in the few decades since they were established, and gibbons never recolonized a reserve in China once they were extirpated.

Effectiveness of Reserves for Conserving Gibbon Habitat and Populations

We found that forest cover inside gibbon reserves was higher than in the buffer zones and forest loss and human impacts were lower inside these reserves than in buffer zones. This result indicates that reserves have been effective at protecting habitat relative to the protection offered in the surrounding landscapes (cf. Geldmann et al. 2013). Some regional case studies have demonstrated that PAs are not always effective at maintaining habitat (Brower et al. 2002; Curran et al. 2004), and further steps are required to fulfill their conservation potential (Watson et al. 2014). However, many PAs are effective in reducing forest loss and anthropogenic activities inside their boundaries, including other PAs in China (Wei et al. 2020).

These reserves generally protected gibbon habitat, but they were not effective at protecting gibbon populations. Gibbons were extirpated in almost half of the reserves or management areas since they were established. We identified several reserve characteristics that affected gibbon survival (Table 3). Initial population size of gibbons in the 1980s was positively associated with gibbon survival into the 2010s. This result is in accordance with the common pattern that small populations are more likely to become extinct due to inbreeding, genetic drift, and demographic stochasticity, as well as increased vulnerability to hunting or other anthropogenic disturbance (e.g., Saccheri et al. 1998; Legendre et al. 1999). The Hainan gibbon (*Nomascus hainanus*) population at Bawangling was an exception to this general pattern. This population decreased from 7 to 9 known individuals in 1989 (Liu et al. 1989) and contained only 13 known individuals in 2003 (Zhou et al. 2005), but it has now increased to over 30 individuals (Chan et al. 2020). Nevertheless, the relative importance of initial population size was low (Table 3), suggesting that other variables have been more influential in determining gibbon survival in Chinese reserves.

Although forest loss in reserves was lower than in their surrounding buffer zones, loss still occurred inside reserves (see also Zhang et al. 2010), and percent forest loss was inversely correlated with gibbon survival. Furthermore, we assessed overall forest cover but not forest quality. Gibbons rely heavily on mature, undisturbed evergreen forest (Phoonjampa et al. 2011), and specific anthropogenic activities, such as cardamom planting, reduce the quality of gibbon habitat (Yuan et al. 2014). Such changes in habitat quality may explain why we found no correlation between forest cover and gibbon survival. Further investigation of both quantity and quality of gibbon habitat is needed.

We found that gibbons were more likely to survive in reserves at higher elevations (and with lower temperatures). This finding is consistent with longer term patterns of local survival and extirpation of gibbon populations across China during recent centuries (Chatterjee et al. 2012; Turvey et al. 2015). These patterns likely reflect the fact that lower elevation landscapes typically have higher human populations and more anthropogenic pressures, including poaching, agricultural encroachment, and livestock grazing (Fan & Jiang 2010). The likelihood of this is supported by our additional result that increased human footprint index in reserves, a measure of the negative impacts associated with anthropogenic activities, was negatively associated with gibbon survival.

The number of articles published on gibbons and their reserves was positively correlated with gibbon presence. It is possible that researchers have conducted more studies in areas where gibbon populations are healthy and well managed. Alternatively, scientific research helps wildlife conservation by raising public awareness and concerns about threatened species, improving management of reserves through science-based decision making, and attracting additional funding (Pusey et al. 2007; Hu et al. 2019). More importantly, gibbon studies, especially behavioral ones, usually require long-term fieldwork, and the presence of researchers and research sites in forests may be one of the most effective ways to prevent poaching (Piel et al. 2015; Chapman et al. 2017). We therefore encourage more long-term field studies, not only to improve understanding of the conservation status and requirements of threatened populations, but also to support their practical protection.

We found that age of reserve was negatively associated with gibbon survival, contrary to our prediction that the earlier a landscape received protection, the greater the likelihood that populations would persist (Friedlander et al. 2017). This result clearly demonstrated that establishment of a reserve does not mean that its gibbons immediately received effective protection. Reserves founded several decades ago may not have received sufficient investment, and initial management effectiveness may have been low (Han 2000; Li et al. 2013). Our results also showed that human impacts in reserves did not differ from surrounding buffer zones in 1993, but were lower than in buffer zones in 2009, indicating low management effectiveness in earlier stages but improved effectiveness later on. Other factors, such as traditional ecological knowledge and strict local regulation on guns, may also have contributed to survival of gibbon populations in some unprotected landscapes before reserves were established and continued to influence local gibbon survival after reserve establishment (Ma et al. 2019; Zhang et al. 2020).

We found no relationship between reserve administration level (current-day level, level at foundation, and whether reserve had been upgraded) and gibbon survival. A higher level of administration usually means more investment and probably more effective management

(Quan et al. 2011). However, our findings suggest that administration level does not reflect management effectiveness for specific gibbon populations. Gibbons have a low reproductive rate; females breed every 3–5 years and are thus very sensitive to poaching (Fan & Jiang 2007; Phoonjampa & Brockelman 2008). Although poaching is strictly prohibited across Chinese reserves, it does occur in many reserves in China, including national-level reserves (Gong et al. 2017). For sensitive gibbon populations, any management improvement brought by upgraded administration level can be counteracted by a single poaching event.

Importance of Early Investment in Reserves for Species Conservation

Two-thirds of reserves or management areas had been upgraded, with most of them upgraded from provincial to national reserves. No areas were downgraded. On average, reserves were upgraded 14 years after establishment, and most were upgraded around 1999. Our findings are in accordance with other studies showing that China has dramatically increased investment in reserves since 2000 (Li et al. 2013). Similarly, reserve staff who participated in our questionnaire survey all reported management effectiveness scores that increased over time (Fig. 2). Comparisons of human footprint index between reserves and surrounding buffer zones also indicated an increased general management effectiveness of reserves, a pattern also seen in many other PAs around the world (Geldmann et al. 2015).

Nonetheless, this increase in management scores was not associated with positive gibbon population trends over time. This is concerning because it suggests that increased investment in existing reserves does not automatically increase survival prospects for gibbons. This lack of correlation may be because many reserves were established when gibbon populations were rapidly declining or already on the edge of extinction. However, our results also suggest that reserves established longer ago had limited investment and low management effectiveness. If effective investment during this crucial early time window was missed, subsequent increases in investment appeared to be unable to preserve gibbon populations.

Conservation Implications

We found that establishment of PAs has not ensured gibbon survival in China. Although it is not possible to determine the critical time window when there was a best last chance to save each of these now-extirpated gibbon populations, we argue that immediate investment at early stages (i.e., when PAs were established) is likely to be most helpful for the conservation of such small, threatened populations. Conservation practitioners must stop population decline at an early stage and take emphatic action to prevent extinction. Nevertheless, delayed investment is better than no investment; conservation efforts have saved many vertebrate species from extinction (Hoffmann et al. 2010), and even tiny remnant populations can recover, even if they have persisted at very low sizes for several decades (Crees et al. 2016). Indeed, such potential for conservation recovery is shown in our study by the Hainan gibbon, which—although still extremely rare and vulnerable—is showing encouraging signs of population recovery (Bryant et al. 2016; Chan et al. 2020). "Although time is running out, there is still an enormous amount of nature left to fight for" (Balmford 2012).

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Supporting Information

Additional information is available online in the Supporting Information section at the end of the online article. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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