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Original Research Article

Effects of human population density on the pattern of terrestrial nature reserves in China

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ABSTRACT

An increasing number of studies showed that coverage of existing protected areas is not enough to protect biodiversity. However, to what extent and how human population density influence the geographical pattern of protected areas are not clear. Based on 2644 terrestrial nature reserves (NRs) in mainland China in 2015, correlation analysis showed that there was a significantly negative relationship between human density and area ($R = -0.52$, $P < 0.001$) and coverage of NRs ($R = -0.21$, $P < 0.001$), and a positive one between human density and density of NRs at county level ($R = 0.64$, $P < 0.001$) (all sample size n = 1171). These relationships could also be observed at provincial level. Counties with NRs had significantly lower human density (mean = 95 persons km^{-2}) than those without (mean = 289 persons km^{-2}) ($P < 0.001$, n = 31) across China. Both percentage of agricultural land and road density significantly and negatively correlated with area and coverage of NRs, and positively with human density and density of NRs at provincial level (all $P < 0.01$, n = 31). The relationships between human and NRs varied among 31 provinces, three conservation objectives of ecosystems, species and others, three hierarchical managements of national, provincial, and city-county levels, and two jurisdictional departments of forestry and non-forestry. But the general pattern of such relationships did not change. In addition, human density and density of NRs significantly positively, and area and coverage of NRs negatively correlated with density of IUCN red-list high plants and vertebrates excluding fishes at provincial level (all $P < 0.05$, n = 31). These results suggested that human density had substantial impacts on the geographical distribution of NRs when their sites were designated, elucidating the mechanism responsible for the low effectiveness of NRs in representing biodiversity.

1. Introduction

Over the past two decades, a growing number of studies revealed that coverage of existing terrestrial protected areas (PAs) was not adequate to represent biodiversity (Scott et al., 2001; Oldfield et al., 2004; Wu et al., 2011a and b; Jenkins et al., 2013;

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Geldmann et al., 2013; Jenkins et al., 2015; Guo et al., 2015; Huang et al., 2016; Lü et al., 2017; Xu et al., 2018). In other words, PAs are often small in size in regions of high biodiversity. Understanding this is challenging for a number of reasons. First, biodiversity in itself does not distribute evenly in space. Second, regions that are less valuable for commercial uses or remote, unproductive for agricultural lands, are usually easy to be set aside for protection (Lan and Dunbar, 2000; Scott et al., 2001; Luck, 2007; Wu et al., 2011b). Third, PA establishment is a complex process related to diverse conservation objectives, managements and jurisdictions as well as laws and policies (Scott et al., 2001; Liu et al., 2003; Wu et al., 2011b; Zheng and Cao, 2015; Zhang et al., 2017). Despite of the challenges, to improve effectiveness of PAs in representing biodiversity, it is urgent to explore what and how factors dominate the geographical pattern of terrestrial PAs.

Human population density is a surrogate measure of human impacts to biodiversity (Brotherton, 1996; Harcourt et al., 2001; Parks and Harcourt, 2002; Luck, 2007; Vačkář et al., 2012; de Marques et al., 2016). In order to reduce or minimize human impacts on biodiversity in PAs, they were designed to be located in regions where human density was as low as possible (Kerr and Currie, 1995; Brotherton, 1996; Harcourt et al., 2001; Luck, 2007). To improve conservation, accordingly, area (area size) of PAs should be large, coverage (percentage of the area of PA (s) per area) of PAs should be high, and density of PAs (number density of PAs per area) should be low in regions of low human density. Alternatively, if biodiversity is high, area of PAs might be small and density of PAs might be high in regions despite of high human density (Araújo and Rahbek, 2007; McCarthy et al., 2011; Lü et al., 2017). In view of the importance of these issues in conservation science, there were many attempts on effects of human density on area (Harcourt et al., 2001; Parks and Harcourt, 2002; Luck, 2007; Vačkář et al., 2012), coverage of PAs (Wu et al., 2011a and b), and density (Wu et al., 2011b). These attempts are informative, but put too much weight on the effectiveness of PAs in representing biodiversity. And less attention was paied to the effects of human density on the pattern of PAs as a whole. Thus, knowledge on the effects of human on PAs is incomplete.

Mainland China (hereafter China) is one of the world's megabiodiversity countries. Nature reserves (NRs) are the mainstay in PA system in China. There were up to 2740 NRs with a total area of 1.47×10^6 km^2 by the end of 2015 (Ministry of Ecology and Environment of China, i.e., MEE, 2016). Conservation objectives of NRs involve ecosystems (i.e., forest, wetland, grassland, desert, ocean-sea), species (i.e., wild plant and animal) and others (i.e., ancient organism remains and geological relics). NRs are classified into national, provincial, city and county levels for hierarchical managements by the approval of corresponding governments (e.g., Guo and Cui, 2015). For example, establishment of national NRs need the approval of the State Council of China. Before 2018, NRs are under the jurisdiction of 8 departments such as State Forestry Administration (SFA), MEE and so on, but most of NRs are under the jurisdiction of SFA (Liu et al., 2003; MEE, 2016). In China, all of 22 provinces, 5 autonomous regions and 4 municipalities (hereafter the 31 provinces) were involved in establishment of terrestrial NRs. Terrestrial NRs covered lands including inland waters varied from 1.6% in Zhejiang province to 33.7% in Xizang autonomous region (MEE, 2016). This suggests that China might face a great challenge in the effectiveness of NRs in representing biodiversity (Liu et al., 2003; Zhang, 2015; Volis, 2018).

Previous studies showed that a number of factors could influence the establishment of NRs. Geographical heterogeneity can often be found in the pattern of terrestrial NRs. For example, area of NRs is large on inland regions but small in coastal regions in China (Ma et al., 2019). Area of NRs could be associated with different conservation objectives (Guo and Cui, 2015). NRs with the objective of ecosystem are often large with thousands of square kilometers, while NRs of ancient organism remains and geological relics are usually small with several hectares (Guo and Cui, 2015). Area of NRs may also be different among hierarchical managements and jurisdictional departments. For example, on average area of NNRs, PNRs and CCNRs was 2329 km^2, 405 km^2 and 13 km^2, respectively. Qiangtang NNR under SFA jurisdiction is near 2.98×10^5 km^2, while Shapotou NNR under MEE jurisdiction 1.40×10^2 km^2 (MEE, 2015a). Thus, to better our understanding of effects of human on NRs, it is necessary to take these factors into account. Fortunately, laws and policies on NRs are the same among the 31 provinces, and then effects of laws and policies on the pattern of NRs could be ignored among different provinces (Liu et al., 2003; de Marques et al., 2016; Zhang et al., 2017; Volis, 2018).

Our aim was to examine the effects of human density on the pattern of terrestrial NRs. Correlation analysis has the potential to obtain the extent relationship between two individual variables (Harcourt et al., 2001; Parks and Harcourt, 2002; Wu et al., 2011a, 2011b; Luck, 2007; Vačkář et al., 2012). More specifically, using China as a case by correlation analysis, we addressed the following three questions. First, did area and coverage NRs negatively, and density of NRs positively correlate with human density? Second, were these relationships influenced by geographical regions, conservation objectives, hierarchical managements and jurisdictional departments? Third, what were the consequences of the effects of human density on the pattern of NRs?

We compiled databases with datasets on human density and terrestrial NRs to examine the relationships between human and NRs at county level. To better understand the relationships, we conducted correlation analysis between human density, area, coverage and density of NRs, and percentage of agricultural land and road density at provincial level. To the second question, factors of geographical regions, conservation objectives, hierarchical managements and jurisdictional departments were considered to test their effects on the relationships between human and NRs. IUCN red-list species of high plants and vertebrates are one of the pre-eminent criteria for biodiversity conservation (López-Pujol and Zhao, 2004; Jenkins et al 2013, 2015). To the third question, we examined the relationships between human density, area, coverage and density NRs and density of IUCN red-list species of high plants and vertebrates.

2. Materials and methods

2.1. Data sources

A plenty of studies on NRs in China could be found in literature (e.g., Guo and Cui, 2015). Detail information on NRs in 2015 was obtained from the official website of MEE (namely Ministry Environment Protection of China before 2018) (MEE, 2015a). The base year of 2015 was selected because there was not detail information on NRs published after that year. The information included geographical scope (detailed to county level of administrative division), area, conservation objectives, hierarchical managements, jurisdictional departments and so on for NRs (MEE, 2015a). Each of NRs was related to at least one county-level administrative area (hereafter county unit). NRs with conservation objectives of ocean-seas or species in the ocean-seas were excluded, because ocean-seas was not settled by human (Luck et al., 2010). Moreover, area of NRs on ocean-seas was less than 7158.3 km^2 in total, which was far smaller than that of terrestrial NRs (MEE, 2016).

The 31 provinces could be sorted into three regions of East, Central and West China (see Fig. 2). In addition to the 31 provinces, China had 1506 of 2850 county units with terrestrial NRs. For each county unit, data on human population and area of terrestrial lands including inland waters could be obtained from the official website of Ministry of Civil Affairs of China (http://xzqh.mca.gov.cn/map). The data of human population and land area of county unit was the most detailed data by the official release. Data of agricultural land including farmland, garden, tea and vegetable plots of the 31 provinces was from the official website of Ministry of Natural Resources of China (http://tddc.mnr.gov.cn/to_Login). Data on road mileage of landway, railway and inland waterway was from the official website of National Bureau of Statistics of China (http://data.stats.gov.cn/easyquery.htm?cn=E0103).

Data on IUCN red-list high plants and vertebrates was from the assessment report on China's biodiversity by MEE (MEE, 2013 and 2015b). Based on IUCN Red List Categories and Criteria (Version 3.1) and Application of the IUCN Red list Criteria at regional levels (Version 3.0) for high plants, and IUCN Red List Categories and Criteria (Version 3.1), Guidelines for Using the IUCN Red List Categories and Criteria (Version 8.1) and Guidelines for Application of IUCN Red List Criteria at Regional and National Levels (Version 4.0) for vertebrates, IUCN red-list species were assessed by scientists from Chinese Academy of Sciences, universities, and other agencies. Both high plants and vertebrates were classified into 9 groups of Extinct, Extinct in the Wild, Regional Extinct, Critically Endangered, Endangered, Vulnerable, Near Threatened, Least Concern and data Deficient. High plants with bryophyta, pteridophyta, gymnosperm and angiosperm, and vertebrates with mammals, birds, reptiles, and

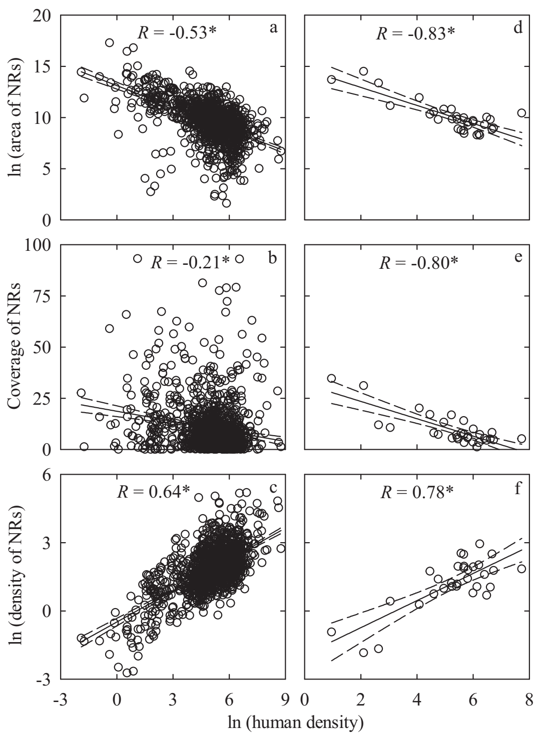

Fig. 1. Results of correlation analysis between human density (persons km^{-2}) and area (ha, a and d), coverage of terrestrial NRs (%, b and e), and density (number of NRs per area, 10^{-4} km^{-2}, c and f) and across mainland China in 2015. Each hollow circle represented a case of dataset of human density and NR and/or NRs at county-level (sample size n = 1171 for a, b and c), and a group of dataset of human density and terrestrial NR and/or NRs at provincial level (n = 31 for d, e and f). Solid strait lines were drawn from the simulation of linear regression model. Short dash lines symbolized the 95% CI of line regression model. *R* was correlation coefficient, and "*" indicated the statistical value of significance at $P < 0.001$.

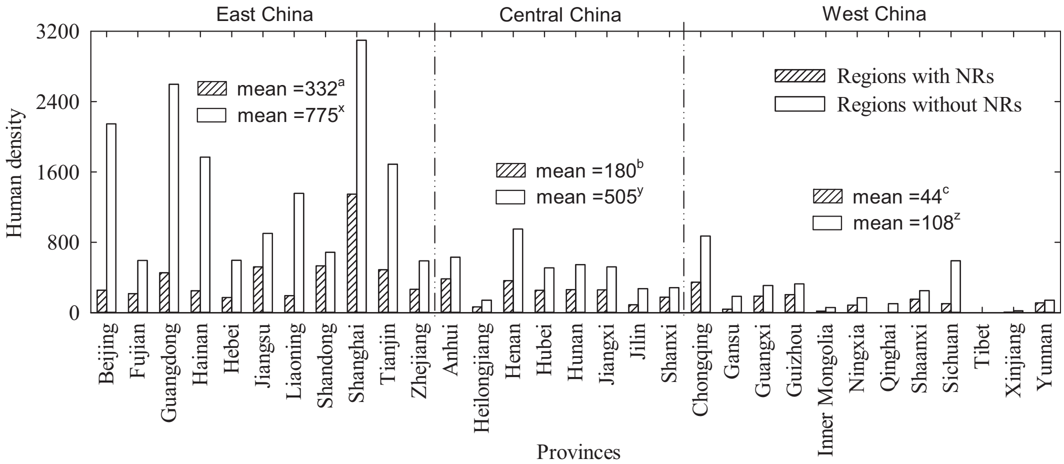

Fig. 2. Human density (persons km^{-2}) in regions with NRs and without NRs across 31 provinces of China in 2015. Different letter between a and x, b and y, and c and z indicated the significant differences in regions with NRs and without NRs among East, Central and West China at $P < 0.05$ level, respectively. Different letter among a, b and c, and among x, y and z indicated the significant differences among East, Central and West China at $P < 0.05$ level, respectively.

amphibians were assessed in all of the 31 provinces. Fish assessment was not based on the 31 provinces but on river basins. Thus, the data of IUCN red-list vertebrates did not include fishes in our study.

2.2. Data analyses

NRs were sorted into four cases: (1) one NR in one county unit, (2) many NRs in one county unit; (3) one NR in many county units, and (4) many NRs in many county units. For the last case, although NRs do not overlap with each other on their boundaries, the geographic scope of one NR may be across two or several county units, and at least one of these county units may has one or several NRs. This sorting method could avoid double-counting for impacts of human density on the pattern of NRs, although sample size got smaller than the number of terrestrial NRs in total in the same province. After this sortation, as a result, sample size was 1171 in total across China. There were four provinces of Beijing, Tianjin, Shanghai and Qinghai with a sample size of $\leq$6. Beijing, Tianjin and their adjacent Hebei provinces were merged into one, Shanghai and Jiangsu into one, and Qinghai and Gansu into one. In each sample size, area, coverage and density of NRs were calculated by area and number of NRs, land area of county unit (s) by simple arithmetic method, respectively. Human density was calculated by household registration population and land area in the county unit (s). Percentage of agricultural land and road density were calculated by area of agricultural land, and road mileage and land area in each of the 31 provinces, respectively. Density of IUCN red-list high plants and vertebrates was calculated by the number of the IUCN red-list high plants and vertebrates excluding fishes and land area in each of the 31 provinces, respectively.

To reduce the heteroscedasticity, data on area and density of NRs, human density, density of IUCN red-list species was normalized by natural logarithm (base *e*). Autocorrelation analysis was performed between two variables among human, NRs, agricultural land, road, and IUCN red-list species (Wu et al., 2011a, 2011b; Harcourt et al., 2001; Parks and Harcourt, 2002; Luck, 2007). Linear and non-linear models were conducted to improve model fit. Statistical values of *F*, *R* and *P* were used to indicate whether any given model was the best one for the correrelation analysis. At last, linear regression model was employed for all the analyses. Correlation analysis between human and NRs was performed at both national and provincial scales in consideration of the geographical heterogeneity. According to the conservation objectives, NRs were grouped into three types of ecosystem, species and others (Guo and Cui, 2015; MEE, 2015a). According to the hierarchical managements, NRs were classified into NNRs, PNRs and CCNRs. According to the jurisdictional departments, NRs were classified into two kinds of forestry and non-forestry. Correlation analysis was also conducted between human density and area, coverage and density of NRs after these classifications.

To further understand effects of geographical heterogeneity on effects of human on NRs, each of 31 provinces was classified into two regions with NRs and without NRs. Human density was calculated by total human population and total land area in each of the two regions. T-test for dependent samples was used to examine the effects of human density on NRs. The 31 provinces of China were sorted into East, Central and West China. T-test for independent samples was used to examine the effects of regions on human density, area, coverage and density of NRs, percentage of agricultural land, road density, and density of IUCN red-list species among East, Central and West China.

Correlation coefficient might be sensitive to outlying points, and thus Dixon's Q-test was used to exclude outliers based on the ratio between independent and dependent variables at $\alpha = 0.05$ (Liao et al., 2012). Statistical significance was set at both *P* value < 0.05 level and 95% Confidence Intervals (CI).

3. Results

3.1. Relationships between human density and area, coverage and density of NRs

In China, there were totally 2644 terrestrial NRs after NRs of ocean-seas were excluded. Sample size (n) was 1171 after sortation and mergence of the 2644 terrestrial NRs. Correlation analysis showed a significantly negative and linear relationship between human density and area ($R = -0.52$, $P < 0.001$; Fig. 1a) and coverage ($R = -0.21$, $P < 0.001$; Fig. 1b), and a positive one between human density and density of NRs at county level ($R = 0.64$, $P < 0.001$; Fig. 1c). These relationships could also be observed at provincial level (n = 31; Fig. 1d, e, f). Thus, area and coverage of NRs decreased, but density of NRs increased, with the increase of human density across China. Our data showed that there was a significantly positive relationship between area and coverage ($R \geq 0.57$, $P < 0.001$), and a negative one between area, coverage and density at county level (both $R \leq -0.36$, $P < 0.001$). These suggested that the three variables standing for the biogeographical pattern of terrestrial NRs were interacted with each other. T-test for dependent samples showed that human density was significantly lower in regions with NRs than that in ones without NRs ($t = 4.5$, $P < 0.001$, $n = 31$; Fig. 2). These results suggested that human density had significant impacts on the pattern of NRs.

Moreover, percentage of agricultural land and road density significantly and positively correlated with human density and density of NRs (all $R > 0.55$, $P < 0.01$, Fig. 3a, d, e and h), and negatively with area and coverage of NRs at provincial level in China (all $R < -0.56$, $P < 0.001$, n = 31, Fig. 3b, c, f and g). These suggested that regions that are more productive for agricultural lands and less remote, are of higher human density, and thus are much easier to be set aside for protection.

3.2. Effects of factors on the relationships between human and NRs

The relationships between human density and area, coverage and density of NRs varied among the 31 provinces. Negative correlation between human density and area of NRs in 9 provinces (including Beijing, Tianjin and Qinghai) was observed at significant level of $P < 0.001$, in 4 at $0.001 < P < 0.01$, in 11 at $0.01 < P < 0.05$, but in 3 at $P > 0.05$ (Fig. 4a). Negative correlation between human density and coverage of NRs in 4 provinces was at $P < 0.001$, in 7 at $0.01 < P < 0.05$, while in 16 at $P > 0.05$ (Fig. 4b). Positive correlation between human density and density of NRs in 12 provinces was at $P < 0.001$, in 3 at $0.001 < P < 0.01$, in 6 at $0.01 < P < 0.05$, but in 6 at $P > 0.05$ (Fig. 4c).

Across three types of conservation objectives, three groups of hierarchical mamagements and two kinds of jurisdictional departments, significantly negative correlation between human density and area of NRs (all $P < 0.001$; Fig. 5a, d, g), and positive one between human density and density of NRs were observed (all $P < 0.001$; Fig. 5c, f, i). Negative correlation between human density and coverage of NRs was in conservation objectives of ecosystem and species (all $P < 0.01$) (Fig. 5b), in NNRs (Fig. 5e), and in forestry department (Fig. 5h).

3.3. Consequences of human impacts on the pattern of NRs

Across the 31 provinces, human density (both $P < 0.05$; Figs. 6a and 7a) and density of NRs (both $P < 0.01$; Figs. 6d and 7d) significantly and positively, and area (both $P < 0.01$; Figs. 6b and 7b) and coverage of NRs (both $P < 0.05$; Figs. 6c and 7c) negatively correlated with density of IUCN red-list high plants (Fig. 6) and vertebrates excluding fishes (Fig. 7). T-test for independent samples showed that provinces in East China often had smaller area and lower coverage of NRs, but higher human density, density of NRs, percentage of agricultural land, road density and density of IUCN red-list high plants and vertebrates excluding fishes than those in Central and West China, respectively (all $P < 0.05$).

4. Discussion

4.1. Effects of human density on the pattern of NRs

Area, coverage and density are characteristics of the geographical pattern of terrestrial NRs in conservation biology (Diamond, 1975; Pressey et al., 1993; Brotherton, 1996; Boecklen, 1997). Our result about the negative correlation between human density and area of NRs was supported by a previous review on nine field studies (Luck, 2007). But the negative correlation was not observed in study at the Czech Republic (Vačkář et al., 2012), and this study did not present detail information on PAs. Our results about the relationships between human density, and coverage and density of NRs across China (Fig. 1b and c) were in accord with a previous study at 53 ecoregions of China, respectively (Wu et al., 2011a). However, a moderate negative correlation between human density and coverage of NRs ($R = -0.41$) was found in studies by Wu et al. (2011a), and a weak one in our study ($R = -0.21$, Fig. 1b). This might differ from scale dependence (Pautasso, 2007; Qian and Kissling, 2010). Scope of China in our study is much larger than that of the 53 ecoregions of China. Moreover, the difference might also be caused by different methods. Data on human density in study Wu et al. (2011b) came from raster data with a 1-km resolution, and boundaries of NRs were defined using coordinates measured in the field via the Global Positioning System.

We did not mean that human density itself has direct effects on the biogeographical pattern of terrestrial NRs. Our results showed that human density is a good indicator of human activities or pressures like percentage of agricultural land and road densty that might have negative impacts on the pattern of NRs (Fig. 3) (e.g., Prendergast et al., 1999; Hansen and DeFries,

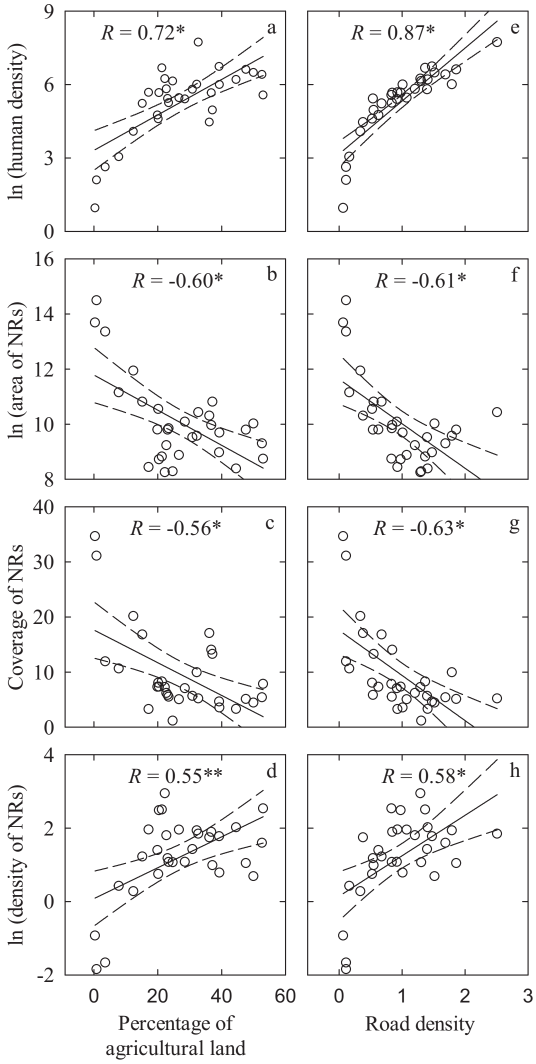

Fig. 3. Results of correlation analysis between percentage of agricultural land (%, a-d), road density (km km^{-2}, e-f), human density (persons km^{-2}, a and e), area (ha, b and f), coverage of NRs (%, c and f), and density (number of NRs per area, 10^{-4} km^{-2}, d and h) at provincial level in China in 2015 (n = 31). Solid strait lines were drawn from the simulation of linear regression model. Short dash lines symbolized the 95% CI of line regression model. *R* was correlation coefficient, "*" indicated the statistical value of significance at $P < 0.001$, and "**" at $P < 0.01$.

2007). Specifically, on the one hand, China is with a long history of agriculture. The majority of lands comprising or close to human settlements were designated for agricultural development. Thus, it was only possible to set remote lands aside for large NRs in regions of low human density (Brotherton, 1996; Luck, 2007). For instance, large NRs such as Qiangtang (2.98×10^5 km^2) and Sanjiangyuan (1.52×10^5 km^2) were seated at an elevation of over 4000 m and 3500 m on average, respectively, where human density was less than 3 persons km^{-2} (MEE, 2015a).

On the other hand, since the late 1970s, China's central government has attached great importance to the rapid decline of biodiversity, taking many measures to solve it. One of the most important measures was Wildlife Conservation and Nature Reserve Development Program, and the number and the area of NRs increased rapidly till the early this century (Liu et al., 2003; Ma et al., 2019). However, China with 1.3 billon citizens was a relatively poor nation. Its per capita gross domestic product in 2004 was estimated at roughly US$ 1500, only one fifth of the world average (Fang and Kiang, 2006). For governments, it was not easy to balance between development and conservation under the huge human pressure. Establishment of NRs meant that local people might be deprived of traditional use of resources. The most important of all was that land use changes were limited (see Regulations of the People's Republic of China on Nature Reserves). This might cause local people to suffer economic hardship in developing regions (Maikhuri et al., 2000; Weladji and Tchamba, 2003; Liu et al., 2010; McShane et al., 2011). In this context, only small NRs were possibly established at regions of high biodiversity despite of surroungding high human density. For example, there are 22 NRs with an average size of 11 km^2 in Shouning county of human density of 190 people km^{-2} in Fujian province of China (MEE, 2015a).

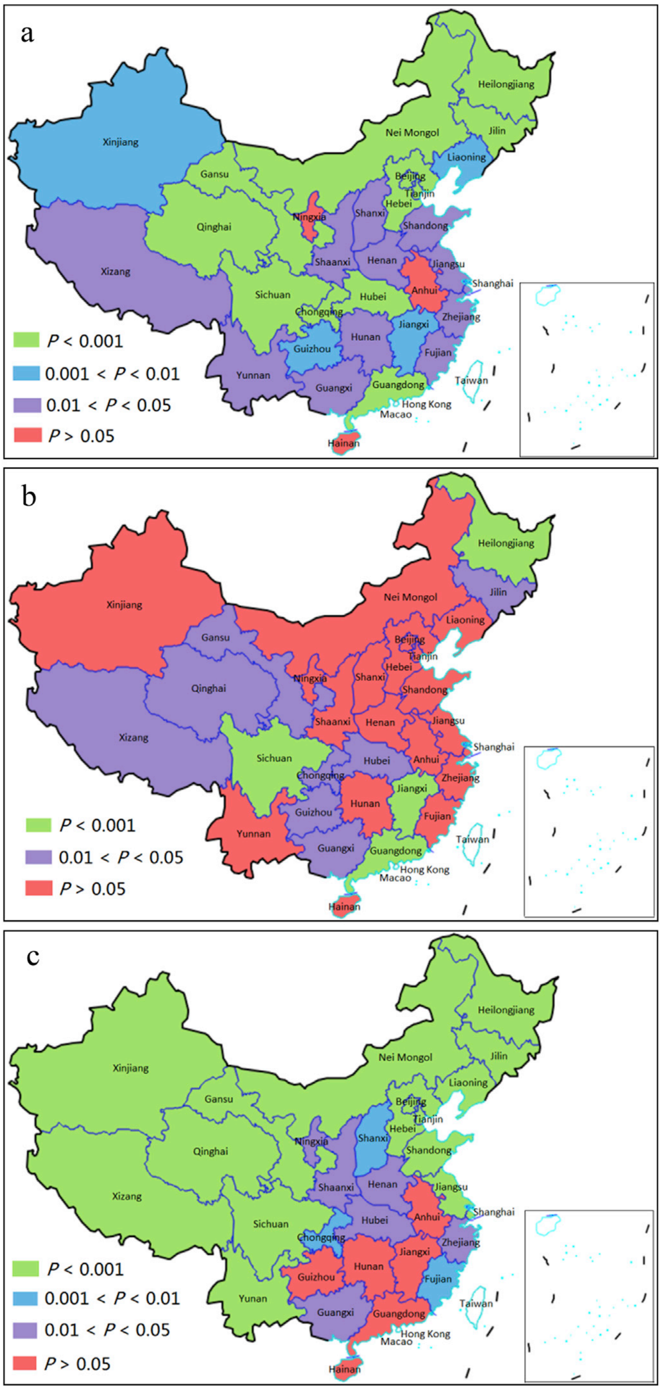

Fig. 4. Results of correlation analysis between human density (persons km^{-2}) and area (ha) (a), coverage (%, b) and density (number of NRs per area, 10^{-4} km^{-2}, c) of NRs in the 31 provinces of China in 2015. *P* was the statistical value of significance.

4.2. Variability in effects of human density on the distribution of NRs

The relationships between human density and area, coverage and density of terrestrial NRs revealed here varied among provinces, conservation objectives, hierarchical managements and jurisdictional departments. So the examination of how these relationships change with factors were required. The variation reflected diverse effects of human density on the pattern of NRs in a given region, and thus pointed to the need for caution in predicting the relationships between human and NRs.

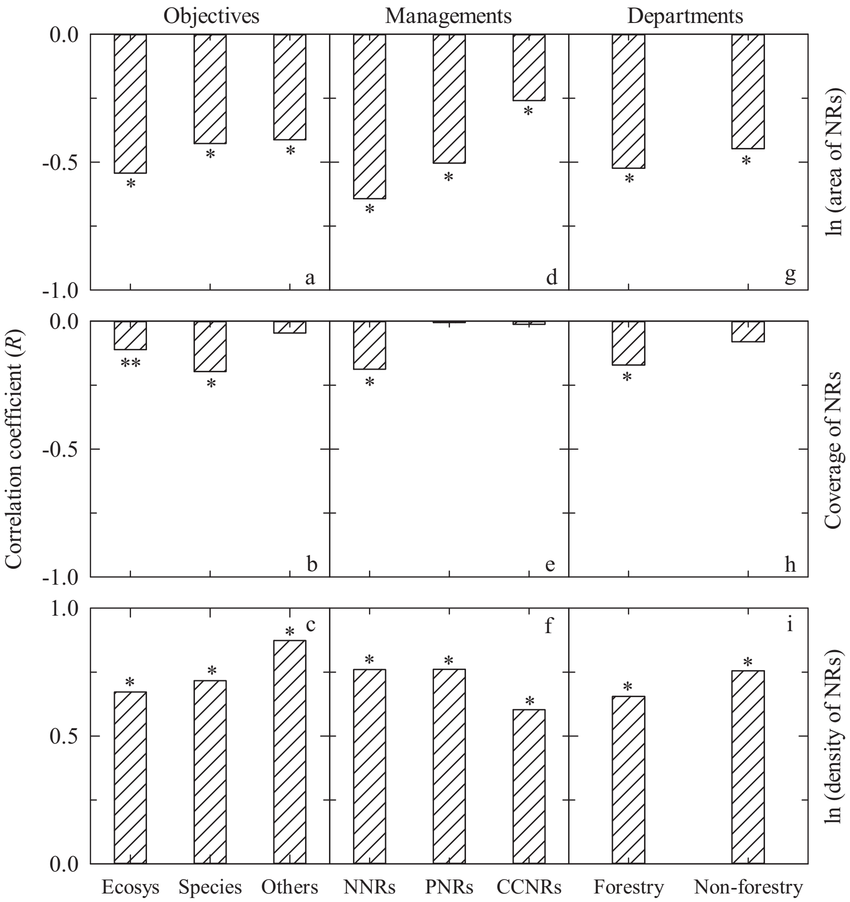

Fig. 5. Pattern of correlation coefficient (R) between ln (human density) (persons km^{-2}) and ln (area of NRs) (ha, a, d and g), coverage of NRs (%, b, e and h) and ln (density of NRs) (number of NRs per area, 10^{-4} km^{-2}, c, f and i) among conservation objectives (a–c), hierarchical managements (d–f), and jurisdictional departments (g–i) in China in 2015. Ecosystem was abbreviated to Ecosys. NNRs, PNRs and CCNRs were national, provincial, and city and county nature reserves, respectively. Sample size (n) was 982 for ecosystems, 429 for species and 98 for others with respect to conservation objective, 346 for NNRs, 663 for PNRs and CCRs with respect to hierarchical managements, and 1018 for forestry and 418 non-forestry with respect to jurisdictional departments. "*" indicated the statistical value of significance at $P < 0.001$, and "**" at $P < 0.01$.

The variation among provinces might result from three aspects. Firstly, geographical patterns of human density and biodiversity themselves were not even in topography from local to regional scale (Qian and Kissling, 2010; Zhao et al., 2016). Secondly, generally, establishment of NRs was based on the conservation values of not only species richness but also of habitat and ecosystem representativeness (Kerr and Currie, 1995; Margules and Pressey, 2000; Luck, 2007). Geographical patterns of species richness often coincide with human density (e.g., Araújo and Rahbek, 2007; Pautasso, 2007). But representativeness such as originality, rarity and vulnerability and human density are different metrics, and the former might not be very closed to the latter. Thirdly, China's NR system was built up within a short term of three decades, and site selection for many NRs was opportunistical, and lacked systematic planning and an adequate conceptual base (Wu et al., 2011a; Liu et al., 2003; Ma et al., 2019). Therefore, one or a combination of these aspects could possilbly result in uncertainty in effects of human density on the pattern of NRs in a given region. The variation among regions was also found in study on 22 African countries by Harcourt et al. (2001). They thought that each country in Africa was a political unit for decisions concerning conservation, and their attention was paied to the continent-wide relationship of human density and area of PAs.

Each classified group of conservation objectives, hierarchical managements and jurisdictional departments in this study was involved in conservation values, geographical heterogeneity and site selection. All factors that affect area of NRs might influence coverage, and density of NRs. Thus, any differential effects resulting from the differences in conservation values, geographical heterogeneity and site selection among classifications might have been swamped.

4.3. Consequences of effects of human density on the pattern of NRs

Our study showed that human density had substantial impacts on the pattern of terrestrial NRs. It would be a great potential for better elucidating the mechanism that coverage of NRs were not enough to protect biodiversity. The significant

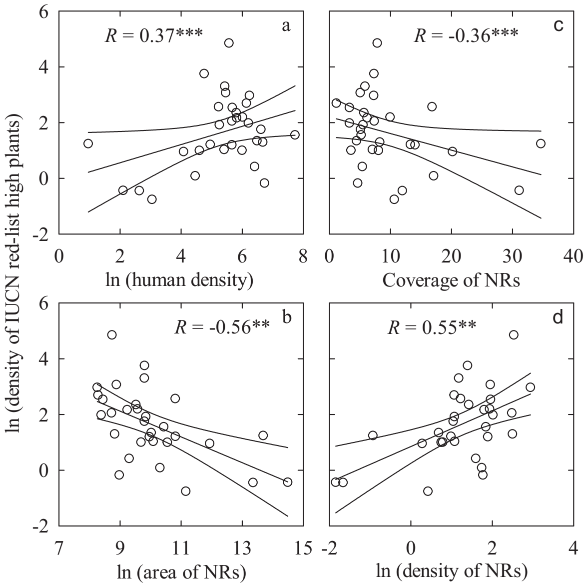

Fig. 6. Results of correlation analysis between human density (persons km^{-2}, a), area (ha, b), coverage of NRs on lands (%, c), density (number of NRs per area, 10^{-4} km^{-2}, d) and density of IUCN red-list high plants (number of species per area, 10^{-4} km^{-2}) across China in 2015. Each hollow circle represented a province (n = 31). Solid strait lines were drawn from the simulation of linear regression model. Dash lines symbolized the 95% CI of line regression model. *R* was correlation coefficient. "**" indicated the statistical value of significance at $P < 0.01$, and "***"$P < 0.05$.

and positive relationships between human, high plants and vertebrates suggest that high human density could result in high density of IUCN red-list speces. But provinces of high human density would be often associated with small area and low coverage of NRs. Moreover, provinces of high density of IUCN red-list species were also associated with small area and low coverage of NRs, leading to the low effectiveness of NRs in representing biodiversity (e.g., Lan and Dunbar, 2000; Wu et al., 2011a and b; Xu et al., 2018). The most likely explaination could be that when it came to select priority areas with regard to biodiversity conservation in regions of high human density, conservation values were less taken into account in planning and designing for NRs (e.g., Lan and Dunbar, 2000; Scott et al., 2001; Liu et al., 2003; Luck, 2007; Araújo and Rahbek, 2007). Therefore, some regions of high density of IUCN red-list speces were absent from protection, while others were over-represented (Wu et al., 2011a and b; Lü et al., 2017).

There were 60% of terrestrial NRs in number with an area lower than 100 km^2 in China. Small NRs tended to be located in regions of high human density. These suggested that, of course, despite of small NRs, local governments took an active part in establishment of NRs in the regions of high human density. These small NRs could make an important contribution to reduce a large of habitats loss and prevent massive fragile ecosystems from degradation. Based on the theory of complementarity, that high density of NRs occurred in regions of high human density could be the best way to biodiversity conservation at minimum costs (Pressey et al., 1993; Kati et al., 2004; Araújo and Rahbek, 2007; Pautasso, 2007). However, small NRs might also suffer from double jeopardies of not only their size but also their situation in especially adverse surrounds (Harcourt et al., 2001; Parks and Harcourt, 2002), and had higher rates of species loss than larger ones (e.g., Rivard et al., 2000). Human activities adjoining NRs might have strong edge effects on the NRs (e.g., Woodroffe and Ginsberg, 1998; Sih et al., 2000). Edge effect of NRs is the major cause of mortality in wild species (Brashares et al., 2001). Thus, small NRs might be at a high risk in protecting biodiversity.

4.4. Implications

Our findings have several implications for conservation planning and managements. First, it is well known that the geographical pattern of human density has developed for thousands of years, while the "newborn" NRs are with a short history of several decades in China. The pattern of human density has significant impacts on area, coverage and density of terrestrial NRs, and then influence on effectiveness of NRs in representing biodiversity. Second, the relationships between human and NRs suggest that it is both a challenge to biodiversity conservation and an oppoutunity to harmonious coexistence between people and nature. China's top leaders have recognized that lucid waters and lush mountains are invaluable assets. For example, the urbanization has reduced rural human population from 8.32×10^8 persons in 1998 to 5.77×10^8 persons in 2017 in China (seen from National data of Mational Bureau of Statistics of China). The decrease in human density in large rural areas would be beneficial to improve conservation (Boecklen, 1997). Third, large NRs could better safeguard biodiversity than small ones (Harcourt et al., 2001; Parks and Harcourt, 2002; Rivard et al., 2000). However, a large number of small NRs and

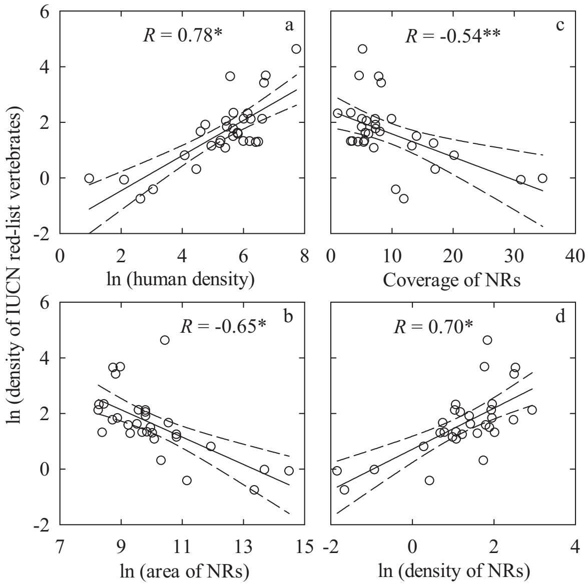

Fig. 7. Results of correlation analysis between human density (persons km^{-2}, a), area (ha, b), coverage of NRs on lands (%, c), density (number of NRs per area 10^{-4} km^{-2}, d) and density of IUCN red-list vertebrates excluding fishes (number of species per area, 10^{-4} km^{-2}) across China in 2015. Each hollow circle represented a province (n = 31). Solid strait lines were drawn from the simulation of linear regression model. Dash lines symbolized the 95% CI of line regression model. *R* was correlation coefficient. "*" indicated the statistical value of significance at $P < 0.001$, and "**" at $P < 0.01$.

high density of NRs tend to occur in regions of high human density. Regions of small NRs are often associated with high density of IUCN red-list vertebrates. Such congruences highlight the importance of enlarging scope of small NRs, and creating habitat corridors for wildlife to enhance connectivity between small NRs (Huang et al., 2016; Saura et al., 2018). Fourth, the human-density-dominated pattern of NRs would keep for a long time, suggesting that it is urgent to take more measures such as conservation education, family planning, job training and alternative livelihood to reduce the conflicts between human and NRs, to improve conservation (Lan and Dunbar, 2000; Liu et al., 2003; Fang and Kiang, 2006; Zhang, 2015; Zheng and Cao, 2015; Zhang et al., 2017). Last but not least, China is reforming PA system at present, and governments shoud pay more attention to provinces of small NRs and high density of NRs, because those provinces often have high human density and high density of IUCN red-list high plants and vertebrates.

5. Conclusions

Our results support the hypotheses that area and coverage of NRs significantly and negatively, and density of NRs positively correlated with human density at county and provincial levels across China. At the same time, human density, area, coverage and density of NRs significantly correlated with percentage of agricultural land and road density at provincial level. Despite of the variation among provinces, the relationships between human and NRs were significant across different conservation objectives, hierarchical managements and jurisdictional departments. These suggested that human density could have substantial impacts on the pattern of NRs. The relationships between human and NRs shed light on the mechanisms responsible for the low effectiveness of NRs in representing biodiversity. High density of IUCN red-list high plants and vertebrates was associated with small NRs and low coverage of NRs across the 31 provinces.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00762.

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